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Reliability of ductility requirements in concrete design codes

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ABSTRACT

Ductility is an important limit state for the design of reinforced concrete beams. Its implementation varies considerably between design codes. This is investigated using reliability-based assessment with ductility defined by strain ratio. The modelling uncertainty for the ductility limit state typically is much greater than that for structural strength limit state. This is reflected in the corresponding reliability indices of limit state defined for ductility. Some of these could be considered unacceptably low.

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1. Introduction

The design of reinforced concrete (RC) structures has long been predicated on the provision of adequate structural strength and adequate ductility [1], The preference for ductility is partly to try to obviate brittle and semi-brittle structural failure which because of its usual sudden nature tends to have very negative consequences. Ductility also has high-energy dissipation capability for withstanding dynamic loads, such as those caused by earthquakes. A comprehensive inelastic nonlinear analysis provides an accurate method for evaluating the adequacy of ductility of structural systems. However, such an analysis often is not practical in routine design, which usually relies heavily on meeting design code requirements. In current design codes, ductility is addressed only implicitly, usually expressed in parameters such as a maximum geometric reinforcement ratio, which is assumed to result in ductile and reliable designs. For RC beams, ductility usually is expressed as a curvature requirement. Reviews [2–6] of the suitability of design codes requirements for curvature ductility showed they were predominantly based on fixed targets. Some recommendations for modifying the code provisions have been proposed previously but these studies were conducted primarily in a deterministic framework.

There have been numerous studies performed on the strength of RC members, resulting in code calibrations that have now been implemented in many design codes [7–9]. In contrast, only limited research has been conducted regarding the probabilistic aspects of inelastic RC deformation and ductility. Costello and Chu [10] developed a methodology for assessing the failure probabilities of RC beams. Although they acknowledged many sources of uncertainty, they only considered variability in material properties. The limit state function for the ductility was defined as follows,

$$p_f = \Pr(\rho_b < \rho_{\max} = 0.75\rho_{bn}) \quad (1)$$

In Eq. (1), ρ_b is the geometric reinforcement ratio at the balance condition and ρ_{bn} is the balanced geometric reinforcement ratio given by the design code. A so-called 'balanced' condition is defined as the condition at which the tensile reinforcement reaches its yield strain just as the concrete in compression reaches its ultimate strain capacity. In the limit state shown in Eq. (1), ρ_b, which depends on material properties and sectional dimensions, was treated as a random variable. According to this limit state, a brittle failure is deemed to occur when this random ratio is less than the code-specified ratio. It was reported that the probability of compressive failure for a singly RC beam, designed based on maximum allowable reinforcement ratio of the ACI 318-63 code, is about 0.166. This means that on average one in six beams, designed with the maximum reinforcement ratio advised by the ACI 318-63 code, could be expected to fail in a brittle manner. Allen [11] conducted a probabilistic study on RC beams subjected to bending moment. The curvature ductility ratio was used to define the ductility limit state.

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Non-ductile failure was deemed to occur when this ratio becomes less than 1.0. It was shown that because of variability in concrete compressive strength and ultimate strain even when the section was under-reinforced, there was a significant probability of brittle failure. It was also reported that the variability in the curvature ductility is much higher than the variability of the ultimate moment. Ito and Sumikama [12] examined the appropriateness of the reduction coefficients for (i) the balanced steel ratio and (ii) that recommended for moment redistribution in continuous RC beams according to the ACI 318–83 code. The same limit state function used by Cotello and Chu was employed by Ito and Sumikama. It was shown that for a number of cases of RC beams designed to the ACI 318-83 maximum reinforcement ratio of $0.75\rho_{bn}$ the probability of compressive failure is high, ranging from 0.005 to 0.472 (depending on the level of variability in the steel and concrete materials). For calibrating the reduction coefficient to ensure ductile failure, a fixed target probability of failure of 0.01 was used, while to ensure the development of plastic hinge for the purpose of moment redistribution, a fixed value of 0.00135 was used. Using these values, the reduction coefficient (which reduces ρ_{bn}) was calibrated. From this, it was concluded that the code-specified values of 0.75 and 0.50 used to ensure ductile failure and development of plastic hinge respectively, could be reduced considerably. Other studies of ductility measures, especially in confined RC members, are available [13–15] but these do not deal directly with the reliability of ductility requirements in design codes.

The present paper examines the level of reliability delivered by the current design codes with regard to providing minimum ductility for RC beams. A limit state based on strain ductility is defined to permit separation of the ductile and brittle failure modes of an RC cross-section. Considering the uncertainty in all the main random variables and in the model error, statistics of the ductility measure are then derived and compared. For further comparison, the conventional strength limit state involving only dead load and flexural capacity is also considered. Finally, the reliability of ductility measures provided by some of the current design codes is investigated.

2. Minimum ductility requirements of RC beams

In order to ensure that RC beam sections possess minimum ductility, design codes prescribe some limits, such as maximum geometric reinforcement ratio, ρ_{max}, maximum neutral axis depth, c_{max}, or minimum tensile rebar strain, ε_{smin}. Using the conventional equilibrium and compatibility equations, all these limits can be related. Fig. 1a shows a typical singly reinforced RC beam section with strain diagrams at the balance and design states shown in Fig. 1b and c, respectively. At the design state, by reducing the reinforcement area (to ensure ductile design), the neutral axis depth decreases and consequently the strain at tensile reinforcement increases from ε_y to ε_{smin}. The stress diagram at the design state is also shown in Fig. 1d. α_1 and β_1 are parameters of the equivalent rectangular stress block, and ε_{cu} is the maximum strain capacity of concrete at the ultimate state.

The normalised neutral axis depth, c/d, and tensile reinforcement ratio, $\rho = A_s/bd$, corresponding to the balance condition (c_b/d and ρ_b) can be used as a means to separate the ductile and non-ductile failures. By reducing the neutral axis depth or the reinforcement area i.e. using values of $(c/d)_{max}$ and $\rho_{max} = A_{smax}/bd$ lower than $(c/d)_b$ and ρ_b, a safety margin for ensuring minimum section ductility is imposed by design codes. Investigating the adequacy of this safety margin in a probabilistic manner is the main aim of the present paper. As shown in Table 1, the limiting ductility requirements vary between different design codes. Most of the current design codes employ the maximum neutral axis depth, c_{max}, as a limit for ensuring adequate section ductility.

The code-specified values for strain of concrete at the ultimate state, ε_{cu}, and equivalent rectangular stress block parameters are also shown in Table 1. The neutral axis parameter at the balance condition, $(c/d)_b$, depends on the ultimate strain of the concrete and the yield strain of tensile reinforcement. Referring to Figs. 1b–1d and using equilibrium and compatibility equations, the limiting expression for ductility can be written as shown in Eqs. (2a)–(2c).

$$\left(\frac{c}{d}\right)_b = \frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_y} \tag{2a}$$

$$\left(\frac{c}{d}\right)_{\max} = \frac{\varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{s\min}} \tag{2b}$$

$$\rho_{\max} = \frac{\alpha_1 \beta_1 f'_c}{f_y}\left(\frac{c}{d}\right)_{\max} \tag{2c}$$

As shown by Eq. (2c), the concept of limiting the neutral axis depth or the minimum strain at the tensile rebar is a means to limit the tensile geometric reinforcement ratio. Design codes that apply the strength reduction factor to material properties (ϕ_c for concrete and ϕ_s for steel) rather than the strength component [17,18] already consider part of the safety margin required for ductile design. In order to make the results of these design codes consistent with those of other design codes, the ratio ϕ_c/ϕ_s of should be multiplied in the limiting c/d values shown in Table 1. For the Canadian code [17], this ratio equals 0.65/0.85 = 0.765, while for the *fib* Model Code (MC) 2010 [18] this ratio equals (1/1.5)/(1/1.15) = 0.767. Table 2 shows the limiting ratios based on different design codes and steel and concrete strengths. It should be noted that in deriving the $\varepsilon_{smin}/\varepsilon_y$ ratio for each code, its own ultimate concrete strain (shown in Table 1) is used and a value of

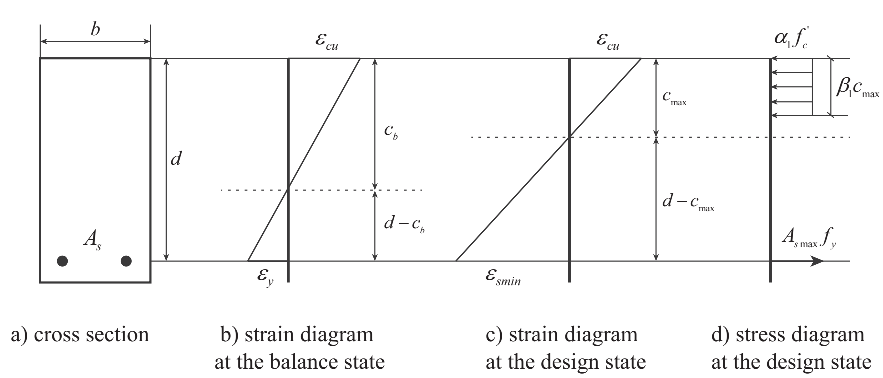

Fig. 1. Strain and stress diagrams at the balance and design states.

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