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Design strength evaluation of RC beams under radiation environments for nuclear power plants

Won-Hee Kang[a], Tae-Hyun Kwon[b], Hyeong-Tae Kim[c], Kyoungsoo Park[c,*]

[a] *Institute for Infrastructure Engineering, University of Western Sydney, Penrith, NSW 2751, Australia*
[b] *Korea Atomic Energy Research Institute, Daejeon, South Korea*
[c] *Department of Civil and Environmental Engineering, Yonsei University, Seoul 120-749, South Korea*

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ABSTRACT

Neutron irradiation changes the behavior of construction materials such as strength and ductility, and thus structural design equations or their safety margins should accordingly be updated for the design of nuclear power plants (NPP) under irradiation. However, current design codes do not account for such changes in material strength. In this study, a framework is proposed to evaluate the change of the safety margins in design equations of reinforced concrete (RC) flexural members under radiation environments. Material strength changes are approximated on the basis of a collected test database, and the design strengths of RC beams are evaluated considering these material strength changes. The evaluation results demonstrate that the design strength of an under-reinforced flexural member can increase while the design strength of an over-reinforced member generally decreases. These results are associated with the material strength changes such that the yield strength of steel increases and the compressive strength of concrete decreases with the fluence of neutron radiation. Current NPP design codes need to further consider this un-conservative design possibility due to the design strength reduction of flexural members under irradiation.

1. Introduction

Neutron irradiation is one of the major concerns associated with the construction and operation of a nuclear power plant (NPP). Irradiation not only causes damage to living organisms but also changes the behaviors of construction materials, which can influence the structural performance of NPP. In relation to high radiation levels, this study focuses on typical light water reactor (LWR) configurations and considers reinforced concrete (RC) structures close to a reactor pressure vessel such as biological shield walls and reactor vessel supports. Field et al. (2015) conducted the radiation transport simulations and showed that the estimated neutron fluence exceeds the 1.0×10^{19} n/cm^2 at 40 years of a nominal design life at the surface of the biological shield, when fast neutron with energies above 0.1 MeV are considered as a conservative estimate.

There have been investigations on the behavior of construction materials under irradiation, especially concrete and steel. They have included experiments on the change of material behaviors under neutron and/or gamma irradiation such as the compressive and tensile strength of concrete (Field et al., 2015; Hilsdorf et al., 1978; Fujiwara et al., 2009; Kontani et al., 2010; Vodák et al., 2005), the porosity of cement paste (Vodák et al., 2010), the density of aggregates (Ichikawa and Koizumi, 2002), and the yield stress of mild steel (Murty, 1984a,b). Recently, Mirhosseini et al. (2014) investigated the effects of neutron irradiation on RC 2D panels while only considering the change of the concrete compressive strength. Therefore, most existing studies mainly focused on experimental and theoretical investigation of radiation effects on material properties, and their impact on the resistance and design of structural members has not been investigated experimentally or statistically. Consequently, these impacts have not been seriously considered in the design of structural members of NPP. For example, the observed material behavior changes due to irradiation have not yet been applied to current NPP design codes including ACI 349-06 (ACI 349-06, 2007), KTA-GS-78 (KTA-Sachstandsbericht., 2005), and DIN 25449 (DIN 25449, 2008).

Basically, the current NPP design codes (ACI 349-06, 2007; KTA-Sachstandsbericht., 2005; DIN 25449, 2008) require more conservative safety margins compared to the design standards for ordinary concrete structures (American Concrete Institute, 2011; Korea Concrete Institute, 2007; Standards Australia International Ltd, 2009) to avoid the catastrophic consequences of NPP failures. In these standards, more conservative safety margins are achieved by providing larger load factors only; the safety margins included

* Corresponding author. Tel.: +82 2 2123 5806.
E-mail address: k-park@yonsei.ac.kr (K. Park).

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in resistance models are kept the same as those for ordinary structures. The safety level achieved by the greater load factors are quantitatively well-supported by the literature including the work by Hwang et al. (1987), Han (1998), Han et al. (1991), and Han and Ang (1998). However, the current safety margins for resistance involve no consideration of the effects of long-term radiation exposure on the resistance of structural members. As mentioned earlier, the strength change of construction materials such as steel and concrete can affect the performance of structures, which can result in unsafe predictions of structural resistance and improper choices of safety margins. Therefore, design standards need to take into account the quantified effect of neutron radiation on the behavior of structural members and provide proper safety margins to ensure the integrity of the design standards of NPP.

In the present paper, the safety of flexural members is evaluated when steel and concrete are exposed to neutron radiation affecting the change of the material and structural strength. Then, the safety margins in current design standards are recalibrated by proposing a Eurocode-based statistical safety factor calibration framework that considers the effects of radiation exposure of structural materials. In this framework, the effects of neutron radiation on the material strengths of steel and concrete are represented by statistically approximating the material strength changes. The modeling error of design equations is estimated through using a collected experimental database of ordinary RC beams. We herein limit our application to the ultimate flexural failure of RC beams as a representative structural member type. The reliability analysis in this study is based on the ultimate state only, and the serviceability limit state is not considered following the practices in current structural design codes. The serviceability related long-term effects (Mohanty et al., 2003) need to be considered in the future work to reflect all failure modes realistically.

The remainder of this paper is organized as follows. In Section 2, literature on the material behavior of concrete and steel under neutron radiation is briefly reviewed, and prediction functions for the material strength changes of concrete and steel given the effects of radiation are developed. In Section 3, the nominal bending capacity of RC beam sections are evaluated with the developed prediction functions. In Section 4, a safety margin calibration method is proposed in order to ensure the applicability of current code provisions to extreme radiation environments. Section 5 provides a collected database of the ultimate flexural strength of RC beams which is used to estimate the modeling error of design equations. In Section 6, the safety margins in current design code equations are recalibrated in conjunction with the changes in material strength due to radiation exposure. Finally, conclusions and discussions are drawn in Section 7.

2. Material behavior under radiation environments

When construction materials such as concrete and steel are exposed to radiation, their mechanical properties generally change in accordance with the amount of irradiation (William et al., 2013), which in turn has an impact on the structural behavior of NPP. In this section, the effects of irradiation on concrete and reinforcing steel are reviewed focusing on the strength, and approximated expressions for their changes in strength are proposed.

2.1. Irradiation effects on concrete

The compressive strength of concrete generally decreases when the amount of neutron irradiation increases (William et al., 2013), which can reduce the load carrying capacity of structural members. For a given neutron fluence (r_n, n/cm^2), the changed compressive strength of concrete $f_c{}'$ is approximated by introducing a ratio of the

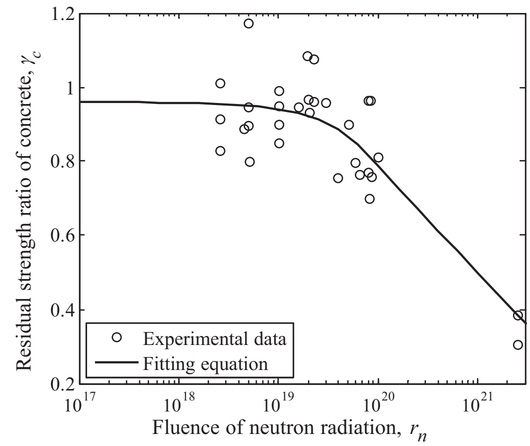

Fig. 1. Change of the compressive strength ratio of concrete with respect to the fluence of neutron radiation (Hilsdorf et al., 1978).

changed compressive strength to the original compressive strength (f'_{c0}), which is defined as the residual strength ratio of concrete, i.e., $\gamma_c = f'_c/f'_{c0}$. Fig. 1 shows the experimental results collected by Hilsdorf et al. (1978) for the compressive strength of concrete with respect to the fluence of neutron radiation (r_n). To these results, a fitting function for the strength ratio γ_c using linear and exponential functions is found as

$$\gamma_c = \begin{cases} 1 & r_n \le 10^0 \\ \left(0.96e^{-0.002} - 1\right) \log_{10} r_n^{1/18} + 1 & 10^0 \le r_n \le 10^{18} \\ 0.96e^{\left(-2\times10^{-21} r_n\right)} & 10^{18} \le r_n \le 10^{20} \end{cases} \quad (1)$$

In this function, when the neutron fluence is smaller than 1.0 n/cm^2, the strength ratio is assumed to be one. When the neutron fluence increases from 1.0 n/cm^2 to 1.0×10^{18} n/cm^2, the strength ratio linearly decreases from 1 to 0.958 in the logarithmic scale. When the neutron fluence is between 1.0×10^{18} n/cm^2 and 1.0×10^{20} n/cm^2, the strength ratio is fitted to an exponential function. If the neutron fluence is greater than 1.0×10^{20} n/cm^2, one can employ a linear function, as shown in Fig. 1, which leads to the significant decrement of the residual strength ratio of concrete. Note that such decrement is a result of the experiments for liquid glass with the neutron fluence of 2.0×10^{21} n/cm^2 and the temperature range of 200–550 °C (Dubrovskii et al., 1966). Fujiwara et al. (2009) and Kontani et al. (2010) indicated that such compressive strength reduction can be associated with the elevated temperature during fast neutron experiments. Thus, for the fitting of experimental data, we set the maximum radiation limit to be 1.0×10^{20} n/cm^2 in this study, which corresponds to the concrete residual strength ratio (γ_c) of 0.786. Note that such approximation well corresponds to the recent investigation on the compressive strength variation according to the neutron fluence (Field et al., 2015).

In addition, the amount of the neutron fluence can vary within a cross section of an RC beam, and thus the corresponding compressive strength may change. For example, the neutron fluence on the boundary can be greater than the fluence at the interior because of the radiation shielding effect of concrete. However, for a conservative evaluation of the strength of an RC beam, it is assumed that the compressive strength of concrete is uniform within a cross section.

2.2. Irradiation effects on steel

When mild steel is exposed to neutron radiation, it generally exhibits an increase in its yield strength and elastic modulus while a decrease in its ductility. To illustrate this, uniaxial tension test

Table 1
Statistics of the fitting errors of Eqs. (1) and (2).

	Ratio of the test results to the predictions	
	Mean	COV
Concrete compressive strength	1.00	0.11
Steel yield strength	0.98	0.07

results obtained by Murty (1984b) using different amounts of neutron radiation are presented in Fig. 2(a), which clearly demonstrates the increase of the yield stress and the reduction of ductility. Fig. 2(b) displays the experimental results (circles) showing the change of the steel yield strength with the amount of neutron radiation as follows: the yield strength slightly increases until the neutron fluence becomes $5.0 \times 10^{16}\ \mathrm{n/cm^2}$; then it increases approximately twice as fast until the neutron fluence becomes $1.0 \times 10^{19}\ \mathrm{n/cm^2}$. Based on these test results, the ratio of the increased yield stress (f_y) to the original yield stress (f_{y0}), named the irradiated yield stress ratio of steel (γ_s), can be approximated by using the following piecewise linear function:

$$\gamma_s = \begin{cases} 1 & r_n \le 10^0 \\ \left(0.3665 - \dfrac{6}{\log_{10}\left(5 \times 10^{16}\right)}\right) \log_{10} r_n + 1 & 10^0 \le r_n \le 5 \times 10^{16} \\ 0.3665 \log_{10} r_n - 5 & 5 \times 10^{16} \le r_n \le 10^{20} \end{cases} \quad (2)$$

This function is plotted as piecewise solid lines in Fig. 2(b). According to this function, for example, an original yield strength of 400 MPa can be increased to over 800 MPa within the range of neutron irradiation in consideration. However, this excessively large value may not be appropriate in the structural design of RC beams, because current design codes such as ACI 349 (ACI 349-06, 2007) and ACI 318 (American Concrete Institute, 2011) limit the allowed yield strength in design calculations by 60,000 psi (400 MPa) or by 80,000 psi (550 MPa), respectively, except for pre-stressing tendons because of serviceability issues in deflections and crack openings (American Concrete Institute, 2011; Soltani et al., 2013).

Most alloys display the increase of the elastic modulus according to the fluence of neutron radiation (Murty, 1984b). However, the change of the elastic modulus is not considered for the strength evaluation of an RC beam because of the following reasons. Experimental data of mild steel (Fig. 2(a)) shows a small change in the elastic modulus, and other experimental data for mild steel are limited. Next, the higher elastic modulus generally leads to a higher capacity of an RC member, and thus the change of the elastic modulus is not considered for the conservative design purpose.

2.3. Statistics of fitting curves

The proposed fitting functions in Eqs. (1) and (2) can be used to predict the reduced strength of concrete and the increased strength of steel, respectively, due to radiation exposure, and their fitting error statistics are provided in Table 1. These statistics are calculated based on the definition of the fitting error that is the ratio between the test results and the predictions by using the functions in Eqs. (1) and (2). The coefficients of variation of the fitting error of the concrete compressive strength ($V_{\mathrm{fitting},fc'}$) and the irradiated steel yield strength ($V_{\mathrm{fitting},fy}$) are 0.11 and 0.07, respectively.

3. Nominal moment evaluation under radiation environments

Previous section demonstrated that concrete has decreasing compressive strength, while steel has increasing yield strength and

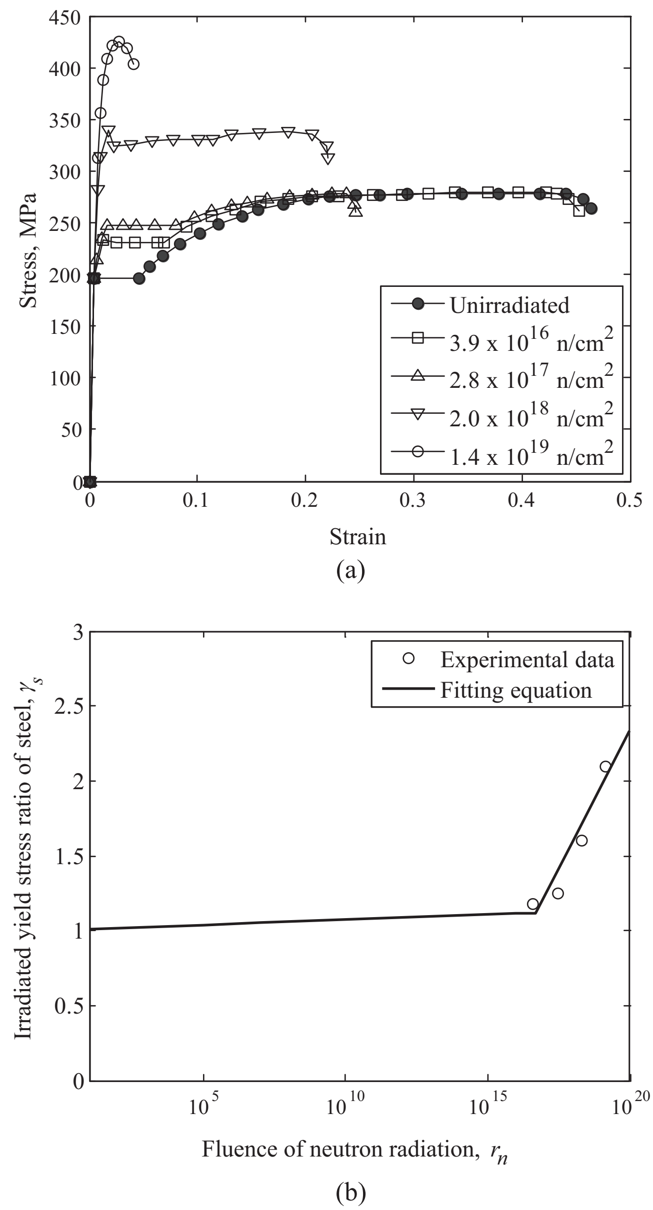

Fig. 2. (a) Uniaxial tension test results (Murty, 1984b) and (b) the yield strength ratio with respect to the fluence of neutron radiation.

decreasing ductility according to the increased amount of neutron irradiation. Such material changes will have influences on the nominal strength and design strength of RC beams. This section shows the evaluation of the nominal strength of RC beam sections by accounting for such material behavior changes. For the strength evaluation, two approaches are employed. The first evaluation approach is to utilize changed material strengths of concrete and steel. When using this approach, the change of failure type and the corresponding safety margin should be carefully considered. The increase of the yield strength of steel can be thought to be equivalent to the increase of the reinforcing steel area. Thus, the increase of steel yield strength can change the section failure mode from tension-controlled failure to compression-controlled failure. In addition, it should be noticed that this approach does not account for the serviceability issues of using high-strength steel such as long-term deflections and crack opening.

The second approach is to utilize the changed material strengths of concrete and steel with the use of the limited maximum yield strength of 400 MPa according to ACI-349 (ACI 349-06, 2007).

If this limit is applied, for example, the flexural capacity of an RC beam section will apparently decrease after the yield stress of the steel reaches 400 MPa due to the increase of the amount of neutron irradiation. The yield stress of reinforced steel will remain constant at the limited value of 400 MPa, and the compressive strength of concrete will continue decreasing with the increase of the neutron fluence. Thus, this design approach provides conservative estimation of the nominal moment, because the true yield stress of reinforcement may be greater than the limited yield stress of 400 MPa.

For a singly reinforced concrete beam, the nominal moment (M_n) is evaluated by utilizing the above mentioned two evaluation approaches. The depth (d) and the width (b) of a beam are 600 mm and 250 mm, respectively, with the original concrete compressive strength (f'_{c0}) of 30 MPa. An equivalent rectangular stress distribution on concrete is assumed, with the ultimate concrete strain of 0.003. The yield stress (f_{y0}) and the elastic modulus (E_s) of steel are 400 MPa and 200 GPa, respectively. The four reinforcement areas (A_s) are considered: 3500 mm^2, 3000 mm^2, 2500 mm^2, and 2000 mm^2. For the given cross sections and material properties, the steel area for the maximum reinforcement ratio is 3425 mm^2, which leads to the net tensile strain of 0.004. The steel area for the reinforcement ratio of the net tensile strain of 0.005 is 2997 mm^2, which results in the maximum strength reduction factor based on ACI and KCI design codes (American Concrete Institute, 2011; Korea Concrete Institute, 2007). All the geometric and material parameters are assumed to be nominal values. Then, the nominal moment is computed as

$$M_n = A_s f_a \left(d - \frac{a}{2} \right) \tag{3}$$

where, a is an equivalent compression zone. The stress of reinforcing steel (f_s) is calculated as min ($E_s\varepsilon_s$, $\gamma_s f_{y0}$) for the first approach and as min ($E_s\varepsilon_s$, $\gamma_s f_{y0}$, 400 MPa) for the second approach, where ε_s is the strain of reinforcing steel. Note that the irradiated yield stress ratio (γ_s) changes according to the fluence of neutron radiation (r_n), as shown in Eq (2).

The nominal moments according to the fluence of neutron radiation for the four different reinforcement areas are plotted in Fig. 3. When one does not limit the yield stress of reinforcement, the nominal moment slightly increases until the neutron fluence of 5.0×10^{16} n/cm^2 is reached (see Fig. 3(a)). After exposure to the neutron fluence of 5.0×10^{16} n/cm^2, the irradiated yield stress ratio increases notably (Eq. (2)), and thus the nominal moment also increases. Since the tensile strain on reinforcements decreases as the irradiated yield stress ratio increases, the RC section behavior eventually reaches the balanced strain condition, which corresponds to the maximum nominal moment in Fig. 3(a). After reaching the balanced condition, the nominal moment decreases because the compressive strength of concrete decreases, and the increase of the yield stress does not impact the nominal moment under the compression controlled failure. When a greater amount of reinforcement is placed, the balanced strain condition occurs even with a smaller amount of the neutron irradiation. Note that the nominal moment with a large neutron irradiation such as 1.0×10^{20} n/cm^2 can even be lower than the original nominal moment at no irradiation, and the reduction is more significant with larger amount of reinforcements.

On the other hand, if one limits the yield stress at 400 MPa, the yield stress of reinforcement remains constant because the initial yield strength is 400 MPa in this example, and only the compressive strength of concrete decreases. It means that the nominal moment always decreases with the increase of neutron irradiation, as shown in Fig. 3(b). Note that the amount of decrement increases as a larger amount of reinforcement is placed. This is because the required resistance on concrete for the equilibrium between tension and compression increases when the reinforcing steel area increases, and thus, according to the fluence of neutron radiation, more decrement on concrete resistance is expected.

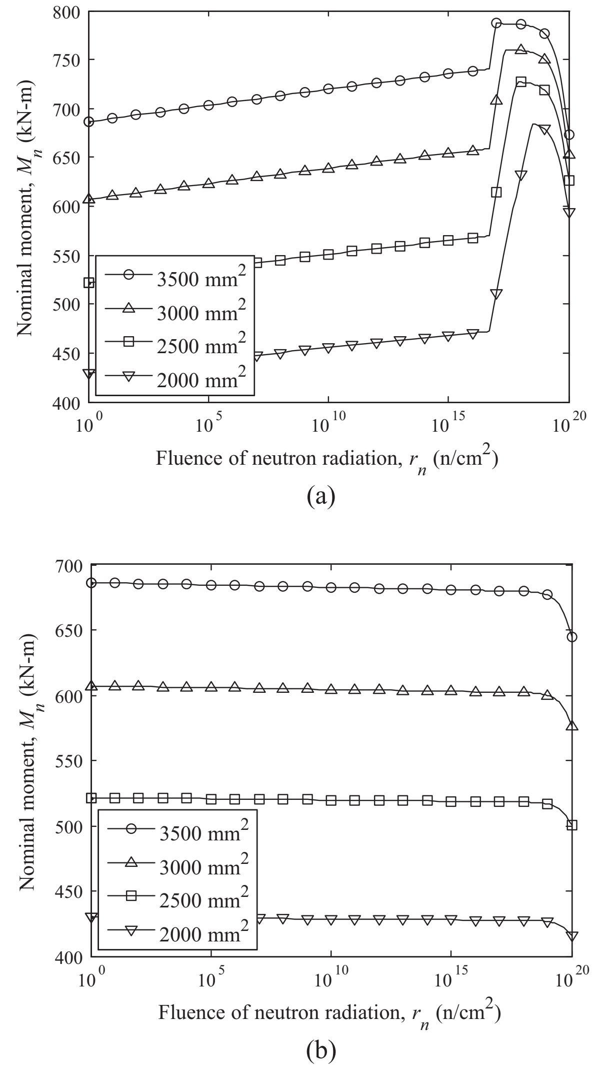

Fig. 3. Evaluation of the nominal moment (a) with the limited yielding stress, and (b) without limiting the yield stress.

4. Statistical resistance factor calibration

As demonstrated in the previous section, the flexural moment of an RC beam and its failure type are significantly affected by radiation exposure, and this is mainly due to the strength changes of concrete and steel. Current design codes for RC beams do not consider such material strength changes, and therefore, the resultant uncertainties and unsafety should be reassessed to ensure the adequacy of the safety margins given in the codes. In this context, this study proposes a safety margin calibration procedure for irradiated RC beams by modifying the Eurocode-based procedure for normal RC beams. When checking the adequacy of the safety margin in current design codes, we will use the term *resistance factor* to represent the safety margin for resistance prediction models, among various choices found in international codes: the safety margins for resistance are called *resistance factors* in the load and resistance factor design (LRFD) format, *strength reduction factors* in ACI and KCI, *partial safety factors for resistance* in the limit state design format in Eurocodes, and *capacity factors* in Australian standards.

The existing studies on the calibration of resistance and load factors for NPP are as follows. Bhattacharya et al. (2013) calibrated optimal partial safety factors for cracking and collapse limit states of structural elements in a typical inner containment shell of an Indian pressurized heavy water reactor. Han et al. (1991) calibrated partial safety factors for load combinations based on the target reliability required for NPP design and the serviceability limit state of the crack failure, which can cause radiation emission. Hwang et al. (1987) developed a reliability analysis method to determine the load and resistance factors for concrete containments and shear wall structures according to the LRFD format along with several limit states and target limit state probabilities. However, these studies do not consider material property changes due to irradiation in their calculations, as previously mentioned.

The proposed method in this study aims to evaluate the change of resistance factors of RC beams due to irradiation. The method modifies the statistical method given in EN 1990 Annex D.8 (European Committee for Standardization, 2002) in order to consider material behavior changes due to irradiation. These material behavior changes are considered by using the fitting functions in Eqs. (1) and (2) and their estimated fitting errors in terms of coefficients of variation. The EN 1990 based method provides procedures for calibrating a single resistance factor as the ratio of the design resistance to the nominal resistance, utilizing experimental data. The reasons for the choice of this method lie in its differences from other available resistance factor calibration methods, which are as follows: first, this method is based on the lognormal distribution models for resistance with the lower limit at zero, instead of a normal distribution, and this corresponds to reality (Gulvanesian and Holicky, 2005). The corresponding target reliability should be selected based on the same models and assumptions. Second, this method can calibrate the resistance factors separately from the load effects, by using the First Order Reliability Method (FORM) sensitivity factors. Third, the modeling error of a theoretical model is rigorously estimated from the comparison between the experimental observations and the theoretical predictions. Due to the second and third reasons, when evaluating modeling errors, we can fully utilize the database introduced in Section 5, which includes no information about uncertainties in loading models.

4.1. Calibration procedure

A resistance factor (ϕ) is calculated as the ratio of the design resistance (R_d) to the nominal resistance (R_n) of RC beams, i.e.,

$$\phi = \frac{R_\mathrm{d}}{R_\mathrm{n}} \tag{4}$$

The design resistance represents the target resistance having sufficient safety represented by the target reliability level. The estimation of R_d requires the identification of the statistical distribution of resistance, which can be obtained from distribution parameters defined by its constant bias and statistical variance. Based on this statistical distribution, the fractile representing the design resistance is determined according to the designated target reliability level. The nominal resistance represents the predicted resistance from design equations when its input parameters are taken as their nominal values and the resistance factor is taken as unity.

The design resistance, R_d, is calculated according to the following calibration procedures. Let $g_R(\boldsymbol{x})$ be a resistance prediction function in a design code, where $\boldsymbol{x}$ is a vector of input parameters with mean measured values. First, the intrinsic bias of this function is corrected by introducing the following bias-correction term:

$$\bar{b} = \frac{1}{N}\sum_{t=1}^{N}\left(\frac{R_{ei}}{R_{ti}}\right) \tag{5}$$

where, N is the number of test results in experimental database. Additionally, $R_{\mathrm{e}i}$ is the resistance observed from the i-th experimental result while $R_{\mathrm{t}i}$ is the theoretical resistance calculated from $g_R(\boldsymbol{x}_i)$ with a set of mean-measured input parameters ($\boldsymbol{x}_i$) used in the i-th experiment. By multiplying the resistance function by this bias correction term, the predicted resistance (R) for a given set of $\boldsymbol{x}$ after bias correction is unbiasedly predicted as follows:

$$R = \bar{b}g_R(x)\delta \tag{6}$$

where, δ is the prediction error of the unbiased resistance function. The error term for each test result, δ_i, is statistically given as

$$\delta_i = \frac{R_{\mathrm{e}i}}{\bar{b}R_{\mathrm{t}i}} \tag{7}$$

The coefficient of variation of R in Eq. (6) is obtained from the following two sources: the coefficient of variation of the prediction error term δ (V_δ) and the coefficient of variation of $g_R(\boldsymbol{x})$ based on the uncertainties in the input parameters $\boldsymbol{x}$ (V_{Rt}). Assuming that R in Eq. (6) follows a lognormal distribution, the coefficient of variation of R is estimated as follows:

$$V_R \cong \sqrt{\left(V_\delta^2 + V_{Rt}^2\right)} \tag{8}$$

where, V_δ can statistically be estimated from δ_i ($i = 1,\ldots,N$) in Eq. (7), and V_{Rt} can be estimated from each test result with the perturbation of input parameters according to their statistical distributions by using the Monte Carlo simulations or the first-order approximation of moments (Ang and Tang, 2007); this study uses Monte Carlo simulations. Under the lognormal assumption, the standard deviation of $\ln R(\sigma_{\ln R})$ is calculated as follows:

$$\sigma_{\ln R} = \sqrt{\ln\left(1 + V_R^2\right)} \tag{9}$$

This standard deviation is used to calculate the target design value of R_d for a target reliability index β as follows:

$$R_\mathrm{d} = [\bar{b}g_R(x_0)\exp(-k\sigma_{\ln R} - 0.5\sigma_{\ln R}^2)]C_\mathrm{m} \tag{10}$$

where, coefficients k and C_m are defined as

$$k = \frac{\left(k_\mathrm{d}V_\delta^2 + \beta V_{Rt}^2\right)}{V_R^2} \tag{11}$$

and

$$C_\mathrm{m} = \left(\frac{g_R(x)}{g_R(x_0)}\right) \tag{12}$$

where, k_d is the fractile factor corresponding to the target reliability index β at the 75% confidence level, determined for the number of test data from a non-central t-distribution. Here, β is the target reliability index achieved by resistance factors only, and it does not involve the safety in the load factors. However, in design standards such as ISO 2394 (International Organization for Standardization, 1998), the target reliability index β_t considering both resistance factors and load factors is provided instead of β. Therefore, β needs to be calculated by using the FORM sensitivity factor (α_R) taken as 0.8, which represents the partial resistance effect; β is defined as the product of α_R and β_t (International Organization for Standardization, 1998).

To account for the ignorance of the change of the strengths of irradiated materials in design codes, the resistance ratio constant C_m in Eq. (12) is introduced, which is defined by the ratio of the theoretical predictions with and without considering the material strength changes in terms of their mean measured values. The input parameters for these two cases are represented by $\boldsymbol{x}$ and $\boldsymbol{x}_0$, respectively. In the evaluation of $g_R(\boldsymbol{x})$, the prediction errors

Table 2
Statistical parameters of random variables.

Design parameters	Mean	COV	Distribution type	References
Section width, b	1 × nominal	0.01	Lognormal	Joint Committee on Structural Safety (2001)
Section depth, d	1 × nominal	0.01	Lognormal	Joint Committee on Structural Safety (2001)
Area of steel, A_s	1 × nominal	0.02	Lognormal	Joint Committee on Structural Safety (2001)
Steel yield strength, f_y	Mean-measured	$\sqrt{V_{f_y}^2 + (2V_{\text{fitting},f_y}(\log_{10}(r_n)/20))^2}$	Lognormal	Joint Committee on Structural Safety (2001)
Concrete compressive strength, f_c'	Mean-measured	$\sqrt{V_{f_c'}^2 + (2V_{\text{fitting},f_c'}(\log_{10}(r_n)/20))^2}$	Lognormal	Nowak and Szerszen (2003) and Szerszen and Nowak (2003)

where, V_{fy} = 0.07, $V_{\text{fitting},fy}$ = 0.07, $V_{fc'}$ = 0.10, and $V_{\text{fitting},fc'}$ = 0.11.

of the material strength changes are also included in the parametric uncertainties of the steel yield strength and the concrete compressive strength, as shown in Section 4.3.

Next, R_n is calculated by plugging in the nominal values of $\boldsymbol{x}_n$ into the resistance prediction model, i.e., $g_R(\boldsymbol{x}_n)$. When the experimental data do not provide information about the nominal values of the input parameters, the characteristic values based on the 5% fractile value of 1.64 are alternatively used to replace the nominal input parameters (International Organization for Standardization, 1998). For example, the characteristic strength of reinforcement steel (f_{yk}) is defined as

$$f_{yk} = f_{ym} \exp\left(-1.64\sigma_{\ln f_y} - 0.5\sigma_{\ln f_y}^2\right) \tag{13}$$

where, f_{ym} is the mean measured value of the yield strength and $\sigma_{\ln f_y}$ is the standard deviation of f_y with the lognormal distribution. The characteristic values for the concrete compressive strength can also be calculated in the same manner. In this study, the nominal values for the yield strength of steel and the compressive strength of concrete are calculated as these characteristic values, and the nominal values of geometric parameters are assumed to be equal to the mean measured values.

4.2. Target reliability index

The consequences of NPP failure and the corresponding radiation emission could be catastrophic, and the acceptable failure probability of such event needs to be determined in order to preserve public confidence (Bhattacharya et al., 2013; Cave and Kastenberg, 1991). Considering the severity of these consequences, very low failure probabilities are generally accepted in the literature. For example, proposed probabilities on the order of 10^{-8} per reactor year (Cave and Kastenberg, 1991) and 10^{-6} per reactor year (US Nuclear Regulatory Commission, 1973) are found in the literature, and ISO 2394 (International Organization for Standardization, 1998) proposes a value of 10^{-6} in comparison with risks resulting from other activities such as an individual lethal accident rate of 10^{-4}. This study assumes that such low failure probability is already achieved by high load factors, and a target reliability index, β (= $\alpha_R\beta_t$) = 3.04, is separately used for the resistance part where β_t corresponds to the failure probability of about 10^{-4}. This neglects the load effect to make a matching pair with the lognormally distributed resistance models according to the international design standards including ISO 2394 (International Organization for Standardization, 1998). This target reliability index is plugged into β in Eq. (11) to calculate the design resistance of un-irradiated or irradiated RC members.

4.3. Statistical parameters of random variables

To estimate the coefficient of variation of the resistance function, V_{Rt} in Eq. (8), the statistical distribution of the design parameters needs to be prepared. The design parameters, which are considered random variables in this study along with their statistical parameters, are reported in Table 2. It is assumed that all resistance-related parameters follow a lognormal distribution as they physically have non-negative values. Note that the variances of the strengths of steel and concrete are estimated by considering both the parameter uncertainties of material strengths and the fitting errors from the curve fitting processes in Eqs. (1) and (2). The prediction errors of the material strength changes are included by taking the square sum of the coefficients of variation of material strengths and fitting errors. V_{fy} and $V_{fc'}$ are for the steel yield strength and the concrete compressive strength, respectively; $V_{\text{fitting},fy}$ and $V_{\text{fitting},fc'}$ are for fitting errors of the irradiated steel yield strength and the concrete compressive strength, respectively. It is assumed that the coefficients of variation for fitting errors are zero when un-irradiated and linearly increase until the neutron fluence reaches 1.0×10^{20} n/cm^2 up to the values of 2 $V_{\text{fitting},fy}$ and 2 $V_{\text{fitting},fc'}$.

5. Test data and parameter distribution

To comparatively quantify the bias and modeling uncertainty of a resistance prediction model, experimental data on the flexural resistance of RC beams with rectangular sections have been collected. In this database, a total of 88 test results from the following 10 sources are included: Janney et al. (1956), Alami and Ferguson (1963), Kani (1966, 1967), Triantafillou and Plevris (1992), Ziara et al. (1995), Takeda et al. (1996), Brincker et al. (1999), Wu et al. (2011), and Talbot (2013). In this study, some irrelevant or outlying datasets are discarded.

The RC beam sections included in the collected test data are actually not for NPP design but for ordinary buildings. However, the reliability analysis results from these data can extensively be applied to NPP design based on the following arguments in (Ellingwood and Hwang, 1985): (i) the strength characteristics of reinforcing bars in nuclear power plants and those in ordinary buildings do not differ significantly. (ii) The strength of concrete in nuclear power plants has lower variance than those in ordinary buildings. (iii) The variance of geometric parameters in massive concrete members is negligible in reliability analysis. Based on these arguments, we can deduce that the modeling error of the resistance prediction model estimated from the comparison with the collected database is also valid for beams used in NPP design when material strength changes due to irradiation are not considered. In addition, because of a lack of experimental data for radiated RC beams, it is further assumed that the modeling error remains constant over material strength changes while the fitting error of material strength changes is included in parametric uncertainties.

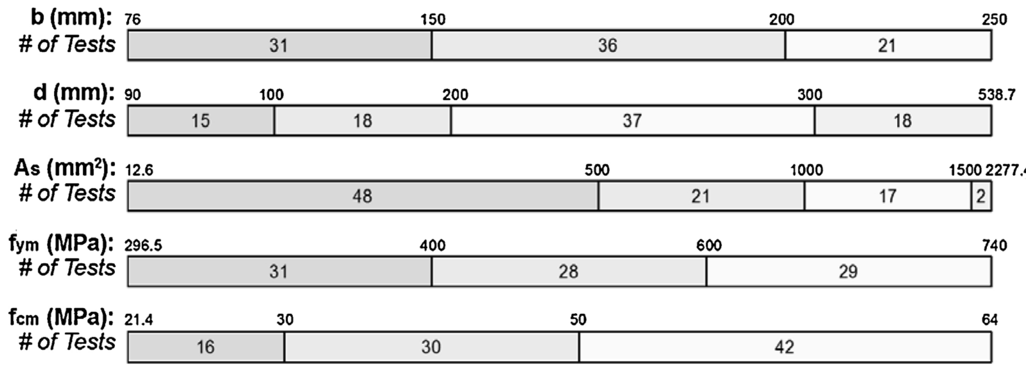

Fig. 4. The distributions of the values of design parameters.

Fig. 4 shows the distributions of the input parameters of $g_R(\boldsymbol{x})$ in the collected database: the width (b) and the depth (d) of the RC beams, the area of reinforcement (A_s), the mean measured yield strength of steel (f_{ym}), and the mean measured compressive strength of the concrete (f_{cm}). Because the collected experiments were originally conducted for research purposes, some cases may not represent the realistic conditions of existing structures. However, the comprehensiveness of the database enables us to cover a wide range of parameter values. Although the database generally has uniformity for all parameters, some of them lack it because their collections of test data were randomly assembled from numerous test results in the literature. For example, the range of the area of reinforcement covers values up to 2277 mm^2, but nonetheless, there are only two results in the range of 1500–2277 mm^2 in the database.

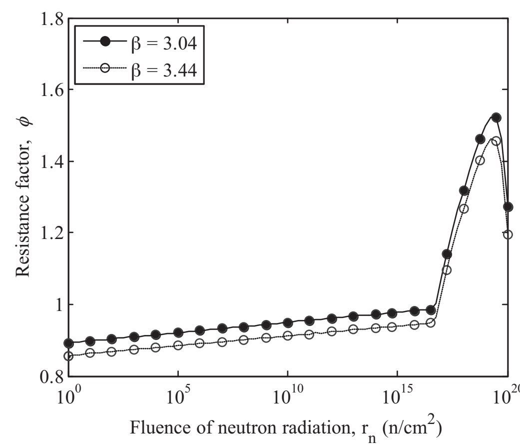

Fig. 5. Resistance factors for the target reliability indices, β = 3.04 and 3.44 considering tension-controlled failure data.

6. Estimation of resistance factors considering radiation effects

In this section, the average resistance factor of RC beams is calibrated for the increasing values of the fluence of neutron radiation ranging from 1.0 n/cm^2 to 1.0×10^{20} n/cm^2. The effects of the radiation exposure to the strengths of concrete and steel are considered by introducing the resistance ratio constant C_m in the design resistance (Eq. (12)) and the prediction error of the fitting curves (Table 1).

For the evaluation of the error between the design equation and experimental results, the database is sub-divided into three groups at the un-irradiated stage: (i) tension controlled failure, (ii) compression controlled failure, and (iii) the transition between the tension and compression controlled failures. Each group is defined on the basis of the net tensile strain of an RC beam. When the net tensile strain is greater than 0.005 at the nominal moment, the section behavior is considered to be tension controlled failure. If the net tensile strain is smaller than 0.002, the section behavior will display compression controlled failure. For the in-between net tensile strain, the section is assumed to be in the transition between the tension and compression controlled failures. Such classification corresponds to the design codes of ACI-318 (American Concrete Institute, 2011) and KCI-M-07 (Korea Concrete Institute, 2007). A resistance factor calibration is carried out for each group to follow the practices in current design codes.

In each group, the material strength changes due to radiation can lead to the change of a failure type from tension-controlled failure to compression controlled failure. The consequence of compression controlled failure is different from that of tension controlled failure, and two target reliability indices are employed to cover both failure types in any group. The values of the target reliability indices (β) 3.04 and 3.44 are utilized, which are obtained from the reliability indices (β_t) of 3.8 and 4.3, respectively. For example, all the RC beam sections in the group under tension controlled failure generally use the reliability index 3.04 when un-irradiated, but the failure types of some of the sections can change from the tension controlled failure to the compression controlled failure during radiation exposure due to the change in the strength ratio of steel to concrete. In this sense, the reliability index for compression controlled failure also needs to be considered for all groups. Note that the reliability index of 3.8 represents the target reliability index generally used to calibrate the resistance factors in lognormally distributed resistance models for ultimate limit state design according to European Committee for Standardization (2002) and International Organization for Standardization (1998), and of 4.3 is additionally selected to represent an increased target reliability index chosen in this study in order to account for the extra risk for a compression controlled failure, which is the largest value choice in European Committee for Standardization (2002) and International Organization for Standardization (1998).

6.1. Resistance factors for tension-controlled members

The resistance factor calibration results for the tension controlled failure members according to the radiation indices are shown in Fig. 5. This group includes 64 test results. The resistance factor for un-irradiated members (i.e., r_n = 1 n/cm^2) is calculated to be 0.9 for the reliability index of 3.04 for tension-controlled failures. This result confirms the reasonable safety of current design codes and the validity of the presented resistance factor calibration procedure. As the radiation exposure level increases, the resistance factors substantially increase for the range of radiation indices from

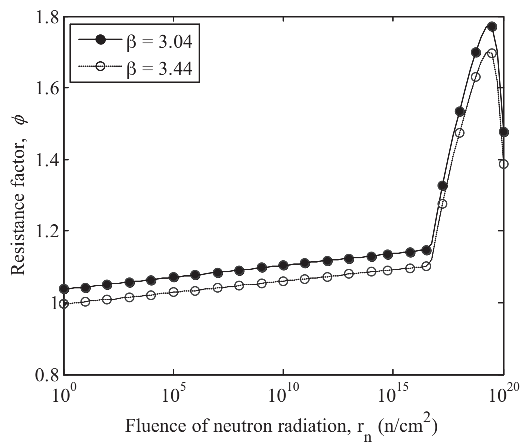

Fig. 6. Resistance factors for the target reliability indices, β = 3.04 and 3.44 considering tension-controlled failure data and the upper limit (400 MPa) for the design yield strength of steel.

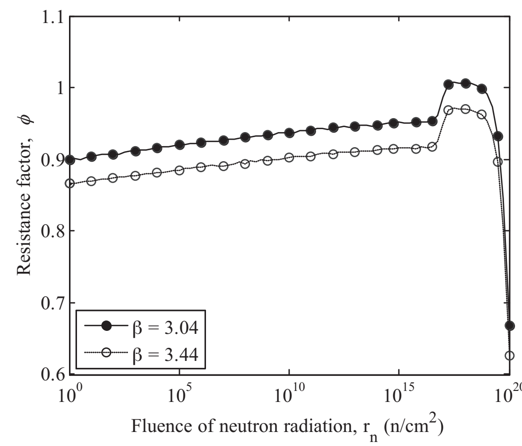

Fig. 7. Resistance factors for the target reliability indices, β = 3.04 and 3.44 considering the data in the transition range.

1.0×10^{17} n/cm^2 to 1.0×10^{19} n/cm^2 and reaches a value of around 1.5. This is mainly because of the increased strength of steel due to radiation exposure. Since current design codes do not consider the effect of the increased strength of steel, the additional safety achieved by this effect is included in the calibrated resistance factor. When the fluence of neutron radiation is greater than 10^{19} n/cm^2, the resistance factor starts decreasing but does not go below the un-irradiated value for both target reliability indices. For the target reliability index of 3.44, it is observed that the resistance factor 0.9 provided in most of the international design codes for RC beams offers reasonable safety even for very long-term radiation exposure, such as at the fluence of neutron radiation of 1.0×10^{20} n/cm^2, when the RC beam sections are under tension controlled failure.

The same analysis is repeated (see Fig. 6), but in this case, the maximum yield strength of steel is limited at 400 MPa according to ACI-349 (ACI 349-06, 2007). The result obviously shows much higher resistance factors for the overall range of the fluence of neutron radiation, because the limited steel yield strength at 400 MPa provides an extra safety to the design equations from the un-irradiated stage. This is associated with the additional conservatism introduced in current design codes in order to account for serviceability issues regarding deflection and crack width.

6.2. Resistance factors for the transition between tension-controlled and compression-controlled members

A similar calibration is repeated for the RC beam sections within the transition of the tension and compression controlled failures, as shown in Fig. 7. The test data includes 19 test results. The resistance factor at the initial stage for both the target reliability indices (3.04 and 3.44) is calculated to be around 0.9. As the radiation exposure level increases, the resistance factors slowly increase until the fluence of neutron radiation of 1.0×10^{18} n/cm^2 and decrease in the range of 1.0×10^{18} to 1.0×10^{19} n/cm^2. The increase is due to the strength changes of steel under radiation exposure. However, in this plot, as radiation effect increases, the resistance factor quickly decreases and goes below that of the un-irradiated state between the fluence of neutron radiation of 1.0×10^{19} n/cm^2 and 1.0×10^{20} n/cm^2. This is important because the application of current design code can underestimate the safety margin for resistance prediction of RC beams for a long-term radiation exposure. Therefore, it is needed to apply more conservative safety margins for a very long-term radiation exposure condition, or to improve the existing resistance prediction models based on the updated strength models for irradiated concrete and steel

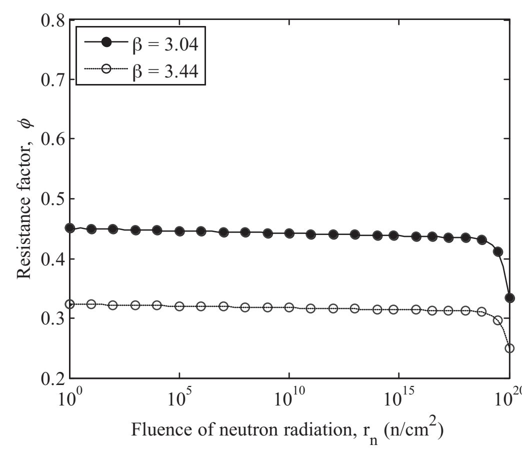

Fig. 8. Resistance factor for the target reliability indices, β = 3.04 and 3.44 considering compression-controlled failure data.

reinforcement to maintain the same resistance factor. The analysis with the upper limit of the yield strength of steel (400 MPa) is not performed because the nominal values of the steel yield strength are lower than 400 MPa for all the RC beam sections in the transition range within the collected database.

6.3. Resistance factors for compression-controlled members

For the RC beam sections under the compression-controlled failure mode, the calibration results are plotted in Fig. 8. It is difficult to collect the data with the RC beam sections under compression controlled failure because most RC beam section designs try to avoid compression controlled failure. Thus, in the collected dataset, only five test results are available in this range. As shown in Fig. 8, the resistance factors are calibrated as 0.45 and 0.32 for reliability indices 3.04 and 3.44, respectively, when the fluence of neutron radiation is 1 n/cm^2. These values are even smaller than those provided in current design codes, because the number of test data is quite small, which creates very large extra uncertainty due to the insufficient population for estimating distribution parameters in a t-distribution, suggesting a highly conservative resistance factor. By ignoring this extra uncertainty due to insufficient number of test data, an improved result can be obtained as shown in Fig. 9. This ignorance of the extra uncertainty is based on the assumption that by collecting more data on the RC beam sections under compression controlled failure, the statistical uncertainty can be reduced

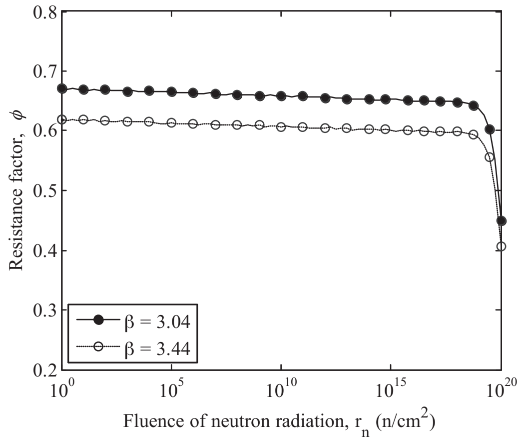

Fig. 9. Resistance factor for the target reliability indices, $\beta = 3.04$ and 3.44 considering compression-controlled data neglecting the uncertainties from the insufficient amount of data.

while the other modeling and parametric uncertainties remain the same. When the fluence of neutron radiation is 1.0 n/cm^2, the resistance factors are calculated to be 0.67 and 0.62 for reliability indices 3.04 and 3.44, respectively. These values are similar to the required values for compression controlled members in international codes, and this shows that further collection of data for compression controlled sections will increase the resistance factor value by reducing the extra uncertainties created from an insufficient amount of data. The reason for the smaller resistance factors for the compression controlled failure sections against the tension controlled failure sections is that the compressive strength of concrete has a larger variation compared to the yield strength of reinforcing steel and it dominantly contribute to the failure. Under the compression controlled failure, as the failure of concrete is more important than that of reinforcing steel, the larger variation in the concrete strength compared to the steel strength will increase the uncertainty in the RC beam sections, and more safety needs to be added to the resistance factors.

In both Figs. 8 and 9, the resistance factor starts gradually decreases until the fluence of neutron radiation of 1.0×10^{19} n/cm^2 and rapidly drops between 1.0×10^{19} and 1.0×10^{20} n/cm^2. This is because the steel bars cannot reach their yield strength due to the early failure of concrete, and concrete failure controls the failure of the RC beams. Therefore, for compression controlled sections, long-term radiation exposure, i.e., $r_n > 1.0 \times 10^{19}$ n/cm^2, will definitely create a risk of catastrophic failure but current design codes do not consider the effect of neutron radiation.

The analysis is not repeated for the upper limit of the yield strength of steel, i.e., 400 MPa, for the sections under compression controlled failure because the yield strength of such sections in the collected database is mostly lower than 400 MPa. Additionally, under compression controlled failure, the reinforcing bars usually cannot reach their yield strength because of the early failure of concrete.

7. Discussions and conclusions

The effects of neutron irradiation on structural design of flexural members are investigated. For this purpose, nominal moments of RC beam sections are evaluated, and the resistance factor for the design of those sections is re-calibrated based on the modification of the statistical method in EN 1990 Annex D.8 (European Committee for Standardization, 2002), with consideration given to the change of material properties with respect to the fluence of neutron radiation. It is found that the increase of the neutron irradiation results in the increased nominal moment and the resistance factor for a tension-controlled flexural member under radiation exposure. This is because the increase of the yield stress of reinforcing steel provides a more dominant effect to the section failure than the decrease of the compressive strength of concrete with respect to the fluence of the neutron radiation. However, in RC beam sections with a larger amount of reinforcement or under compression controlled failure, the neutron irradiation results in the decrease of both the nominal strength and the resistance factor, especially when the fluence of the neutron radiation is greater than 10^{19} n/cm^2. This is due to the early failure of weakened concrete before the reinforcement reaches the yield point.

The limitations and possible improvements of the current study include the following. The analysis in this study for the evaluation of the nominal moment and the resistance factor is based on ACI-349 (ACI 349-06, 2007), as a representative case; it is possible that there is a slight variation in the results when applying the proposed framework to other design standards such as AS3600 (Standards Australia International Ltd, 2009), Eurocode 2 (British Standards Institution, 2004), and KCI-M-07 (Korea Concrete Institute, 2007). In addition, the changes of the compressive strength of concrete and the yield stress of steel under irradiation are purely based on the currently available experimental test results, which are limited in terms of the amount of test data. The approximated equations, Eqs. (1) and (2), may not provide fully representative material behaviors, and the evaluated nominal moment for an irradiated flexural member can have more or less errors and uncertainties than that for an un-irradiated flexural member. Nonetheless, the proposed framework can still be used for evaluating the strength of flexural members and their reliability indices under irradiation. The calculated reliability indices can be used to verify the safety of the current design equations and to propose appropriate modifications on the design standards accounting for the irradiation effects on the properties of construction materials. The proposed safety margins are calibrated mainly for RC beams, but it has important ramifications for the design of other types of structural materials and members.

The proposed framework can be improved by collecting more experimental data and employing new irradiated material strength models, which will reduce the statistical and modeling uncertainties and strengthen the proposed framework. In addition, the present study does not consider the decrease of steel ductility with neutron radiation, which will create detrimental effects, such as reduced energy dissipation against an earthquake. Accordingly, further thorough investigations are desired for the safety evaluation of NPP design.

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