Transactions, SMiRT-24
BEXCO, Busan, Korea - August 20-25, 2017
Division IX (include assigned division number from I to X)

NUMERICAL EVALUATION OF NEUTRON IRRADIATION ON REINFORCED CONCRETE MEMBERS

Tae-Hyun Kwon[1], Kyoungsoo Park[2], Hyeong-Tae Kim[3], Sangho-Kim[4]

[1] Senior Researcher, Korea Atomic Energy Research Institute, Korea
[2] Associate Professor, Department of Civil and Environmental Engineering, Yonsei University, Korea
[3] Graduate Student, Department of Civil and Environmental Engineering, Yonsei University, Korea
[4] Senior Engineer, Plant Building and Structural Team, Hyundai Engineering Co., Korea

ABSTRACT

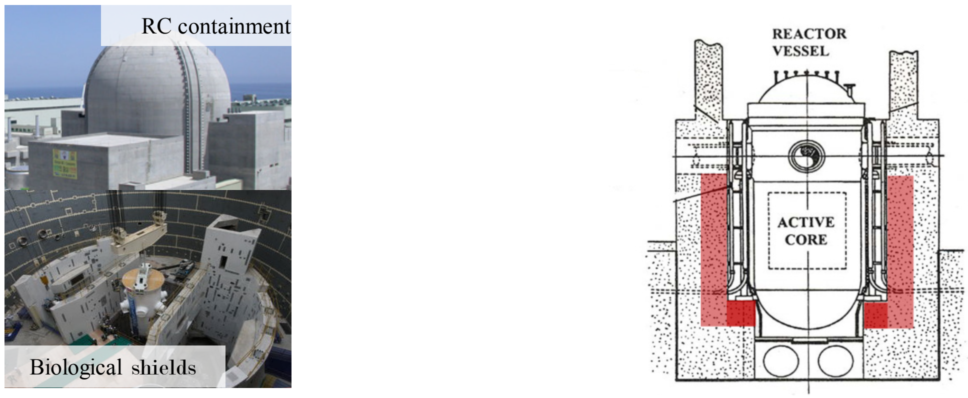
Reinforced concrete (RC) is the most widely used material to build a containment, biological shield, foundation, and support structures in nuclear power plants (NPPs). Age-related effects on such RC structures have been extensively studied in detail. However, the effect of neutron irradiation requires further studies because of its limited database. The biological shields and supports for a reactor vessel is located at closest proximity to a reactor core and expected to see the highest levels of irradiation over the lifetime. Any changes in the mechanical properties from long-term irradiation could be particularly significant. In this regard, the irradiation experiment of a capsule is planned to propose a reliable level of irradiation for concrete and reinforced steel material. In addition, the response of RC members is numerically evaluated with increasing levels of neutron irradiation. The structural response such as the beam-column interaction of a RC column and moment-shear interaction of a RC slab are investigated as the result of neutron irradiation.

INTRODUCTION

Reinforced concrete (RC) is a composite material in which concrete resists compression and steel bars as reinforcement are embedded in tensile regions to counteract the concrete's relative low tensile strength and ductility. RC is widely used as a containment, biological shield, foundation, and support structures in nuclear power plants (NPPs). Such RC structures are large and irreplaceable for the life extension. Therefore, the long-term durability of RC structures has been extensively studied in detail. Mechanical, chemical and material changes that can contribute to degradation of RC structures include sulfate attack, corrosion, freeze-thaw, elevated temperature, etc.

The radiation induced degradation, on the other hand, requires further studies because of its limited experimental data. Previous experimental results suggest that the effect of neutron radiation on RC structures is not significant if the neutron fluence is lower than $1.0 \times 10^{19} n/cm^2$ (Hilsdorf et al., 1978). Then, most of RC structures have been regarded as sound as the neutron fluence is below 1.0×10^{19} n/cm^2 in the design life of NPPs. Any reduction of strength from irradiation is not considered in periodic inspection programs. However, the experimental conditions described in the previous study are not consistent in terms of measured properties, concrete mixture, specimen size, temperature, and neutron energy (Field et al., 2015). It is critical to conduct a controlled experiment to propose a reliable reference level of neutron radiation.

In addition, the RC structures, such as biological shields and supports for a reactor vessel, are located in the closest proximity to a reactor core and expected to see the highest levels of irradiation over the lifetime (Park et al., 2016). The anchorages at a reactor vessel, especially, could be considered as the most critical due to its load bearing (Figure 1).



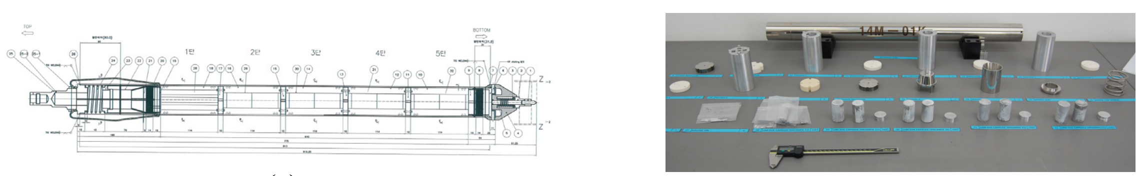
(a) (b)

Figure 1. RC as a biological shield and as load carrying support for the reactor vessel.

In this regard, an irradiation capsule containing mortar and reinforcement specimens are prepared to investigate the changes of strength in a controlled condition. Also, the response of RC members is numerically investigated as the results of neutron radiation.

TESTING OF IRRADIATION CAPSULE

The High-Flux Advanced Neutron Application Reactor (HANARO) is a 30MW multipurpose rsearch reactor for radioisotope production, irradiation services, neutron transmutation doping, neutron activation analysis, and neutron beam research. Material irradiation tests are commonly performed for specimen of reactore vessel, nuclear fuel, nuclear fuel cladding, and new materials. For concrete materials, because of a limited size of a capsule and elevated temparature, a mortar specimen with the size of ø30×50mm is prepared and installed as shown in Figure 2. For reinforcement bars, the typical plate-type tensile specimens with SD400 SD500, and SD600 are made for irradiation tests.



(a) (b)

Figure 2. (a) Capsule design for irradiation experiment, (b) Capsule components with mortar and reinforcement specimen.

At this time, the capsule containing the specimens is sealed to be ready for irradiation using HANARO. The capsule will be loaded into the one of irradiation holes in the core for about 28 effective full power days. It is expected that the peak fast neutron fluence would be $10x10^{19}n/cm^2$. Then, the capsule will be removed and transferred to the shielded facility, called hot cells. The irradiated mortar specimen will be tested for their compressive and tensile strength. For the irradiated specimens of reinforcement bars, uniaxial tensile test will be performed to obtain the change of stress-strain behaviour after irradiation.

NUMERICAL INVESTIGATION OF IRRADIATED RC MEMBERS

Experimental investigation with irradiated RC members is not applicable considering that even specimen testing is only available in miniaturization because of the tight space of a capsule. For a static response, the RC sections of column and slab member are evaluated.

P-M Interaction of RC Column

A nominal design lifetime of NPPs is 40 years and the total fluence can be assessed from a safety analysis report (SAR) of Shin-Kori NPP (Shin-Kori SAR). It was reported that the maximum neutron flux at 15.24cm (0.5ft) distant from the reactor vessel is 10^5 to 10^9 n/cm^2- sec, and the total fluence for 40 years then becomes about 10^{14} to 10^{18} n/cm^2. According to the estimation, the strain-stress relationship of concrete and mild steel could be conservatively considered up to a neutron flux of $1.0\text{x}10^{19}$ n/cm^2.

The stress-strain relationship for concrete can be assumed to be parabolic (ε_c' , f_c') as shown in Figure. 3. Note that the compressive strength (f_c') and its corresponding strain (ε_c') are 40MPa and 0.002, respectively.

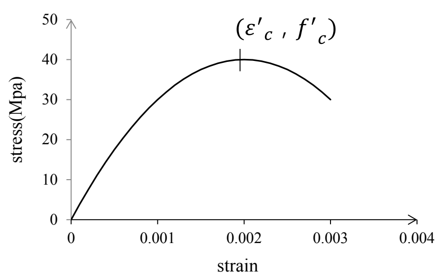


Figure 3. Assumed parabolic strain-stress curve.

A general assessment is that the compressive strength of concrete decreases under neutron radiation exposure, and the neutron fluence on the order of $1.0\text{x}10^{19}$ n/cm^2 was reported to become critical for concrete strength (Kontani et al., 2010 and William et al., 2013). The change in compressive strength is not significant for a neutron flux below $1\text{x}10^{19}$ n/cm^2 and thus the parabolic strain-stress relationship is fixed with incremental neutron irradiation.

The effect of irradiation also occurs in the reinforcement embedded in concrete. Material of reinforcement in RC is mild steel and it is expected to be exposed to environment due to long-term micro cracks around a concrete cover (Figure 4).

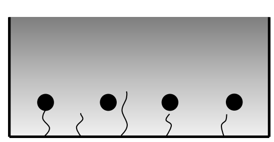


Figure 4. Conceptual figure for micro cracks around a concrete cover.

Reinforcement bars in RC is mostly mild steel. Murty et al. (1984) reported strain-stress relationships of the mild steel with incremental irradiations as shown in Figure 5. It shows that yield strength is increased 2.3 times and the ductility is 13-times less compared to the non-irradiated one.

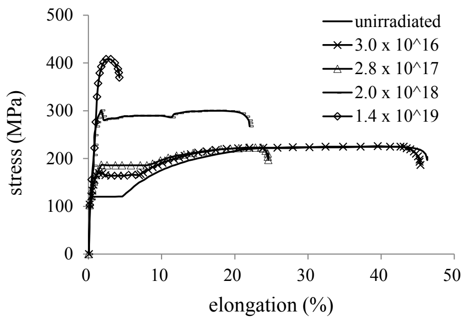


Figure 5. Digitized strain-stress curves of mile steel at room temperature with incremental neutron irradiation (Murty, 1984).

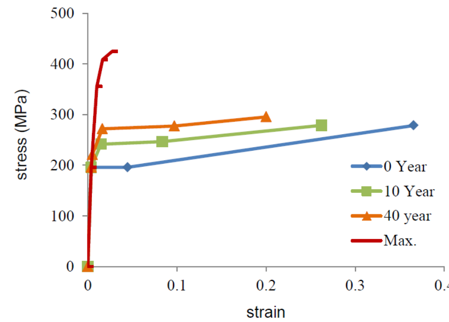


Figure 6. Scaled stress-strain curve for reinforcing steel with linear segmentation of yielding, stiffening, and ultimate points.

However, the results are obtained from a wire specimen atypical with a rebar specimen for RC. But, the experimental results are obtained from a wire specimen atypical with a rebar specimen for RC. Therefore, they are consistently scaled such that the yield strength becomes 450MPa and the young modulus 183,000MPa with linear segmentation of yielding, stiffening, and ultimate points (Figure 6). Then, they are interpolated to result in the relationships matching with the target years listed in Table 1. The strain-stress relationships for reinforcement are further simplified for numerical simulations using the program Response-2000 (Bentz, 2000).

Table 1: Estimated total neutron fluence at years of operation

Years of operation	Neutron fluence (n/cm^2)
0	0
10	1.95 x 10^{17}
40	7.8 x 10^{17}
Max.*	1.4 x 10^{19}

* A year that matches with available maximum neutron fluence in experimental data (Figure 1).

Figure 7 shows a typical RC column section and then, the behavior of beam-column interaction is numerically simulated using the program Response-2000. Response-2000 is based on fiber section model where an RC element is refined as a bundle of fibers represented by a uniaxial material model.

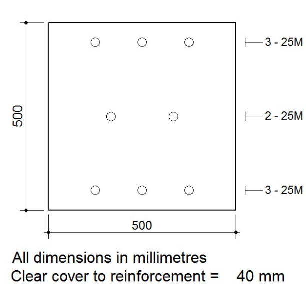
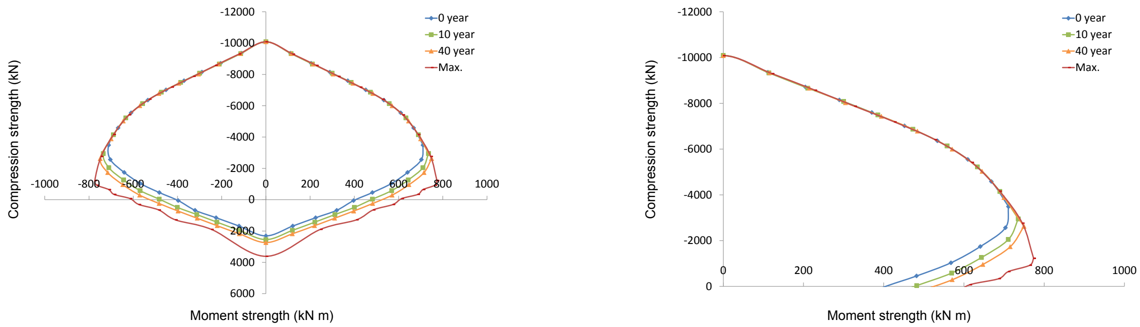


Figure 7. RC section for beam-column interaction.

The beam-column interaction can be characterized by a diagram called a P-M diagram (axial compression and bending moment strength interaction diagram). The numerical results with years of NPP operation are shown in Figure 8.



(a) (b)

Figure 8. (a) P-M diagram results from software Response-2000 (b) change of balanced compressive strength.

where, x-axis is the bending moment strength (kN·m) and y-axis is the axial compression strength (kN). In the first quadrant (the upper right part), the balanced compressive strength, Pb, moves lower as the irradiation progresses and, as a result, the compression controlled area becomes more dominant. This suggests that the member characteristic migrates to a more brittle region as the yield stress of the longitudinal steel increases.

The effect of neutron irradiation on beam-column interaction is evaluated. ACI318 requires the strength reduction factor, ϕ=0.70, for the compression controlled area and the higher up to 0.9 as the tensile strain in steel reinforcement goes higher. This concept works well with this example. However, this does not take into account the energy dissipation capacity of the member but it only expresses the ultimate strength. Therefore, the current strength evaluation concept may be misleading when the material behavior of steel reinforcement becomes brittle due to the neutron irradiation. In such case, even for the transient and tension controlled area, the strength reduction factor needs to be modified to account for the potential ductility loss.

Shear-Moment Interaction of RC Slab

The section of a typical one-way slab is defined by unit length in Figure 9. This figure shows the comparison of VM interactions in terms of irradiation time, which is obtained based on AASHTO LRFD.

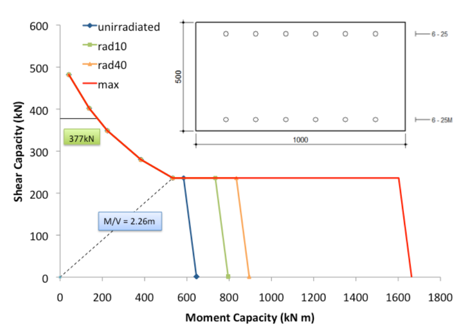


Figure 9. VM strength interaction diagram (w/o shear reinforcement, unit for the section is in mm).

Each dot represents the ultimate shear strength for a given bending moment or vice versa. The bending moment strength increases with a higher radiation exposure due to the increase of the steel strength (see the area below M/V=2.26m.) In this area the bending strength is determined only by the longitudinal reinforcement and compressive concrete with the plane-section assumption. In the area above this line, however, the beam capacity is governed by shear failure and the property change in the longitudinal reinforcement does not affect the beam capacity. It should be noted that this applies only to those beams without shear reinforcement.

As presented in the earlier study (Part et al., 2016 and Kang et al., 2016), the bending behavior of a RC member becomes more brittle as it is exposed to neutron radiation. ACI318-11 requires a reduction factor in the strength evaluation of a member when a brittle behavior is expected. For example, the strength reduction factors for axial and shear are as small as 0.65 and 0.75, respectively and the strength reduction factor goes up to 0.9 if the tensile strain is greater than 2.5 times the yield strain. The strength reduction factors are to drive the system to ductile element yielding first before the brittle mode takes place. Therefore, it should be alarming if the element that was designed to be ductile becomes brittle. With this regard, the material penalty factor is introduced in terms of ductility loss ratio as shown in Table 2. The ductility is defined as the ultimate strain divided by the yield strain of the reinforcing steel, referring to Figure 6. The relative ductility of the steels is normalized and linearly interpolated between 0.75 and 1.0.

Table 2: Material penalty factor based on ductility loss ratio.

irradiation	yield strain (a)	ult. strain (b)	Ductility (b/a)	Ductility norm'ed	Factor (-)
0 year	0.0025	0.2210	88.4	1.0	1.00
10 years	0.0031	0.1589	51.5	0.58	0.90
40 years	0.0035	0.1212	34.9	0.40	0.85
Max.	0.0054	0.0167	3.1	0.03	0.76
Ref. point	-	-	0.0	0.00	0.75

The VM diagram (Figure 9) is reproduced in Figure 10 by applying the strength reduction factors calculated in Table 2.

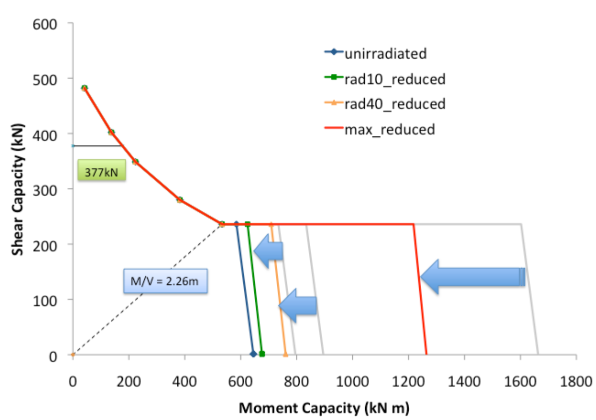


Figure 10. Modified VM strength interaction diagram modified by the strength reduction factors.

The effect of radiation on the behavior of one-way slab is presented by the shear and moment capacity interaction diagram. The results suggest that the yield strength increase of the longitudinal reinforcement barely affects the shear strength but it increases the bending strength significantly. This may be misleading, however, as the structural capacity to observe the energy from environmental loadings such as earthquake would be actually reducing. Therefore, the modified moment capacity is proposed by adopting the strength reduction factor that accounts the ductility loss. If the strength still exhibits an increase in the strength assessment as in this example, it is recommended that the original design strength (unirradiated) is used as the maximum limit strength. Otherwise, use the reduced strength

CONCLUSIONS

This study investigated the section responses of the RC members with incremental neutron radiation. The RC structures close to the reactor vessel could be considered as the most critical in estimating that the total fluence for 40 years becomes about 10^{14} to 10^{18} n/cm^2. The responses were investigated with the maximum neutron fluence up to 10^{19} n/cm^2 and it suggests the use of strength reduction factors, which is mainly contributed from the ductility loss of the reinforcing bars. It is noted that the effect of irradiation needs to be assessed as an age-related degradation. Furthermore, the current investigation will be extended to a structural fragility evaluation of NPPs.

REFERENCES

Hilsdorf, H.K., Kropp, J. and Koch, H.J. (1978) “The effects of nuclear radiation on the mechanical properties of concrete”, *ACI Special Publication*, 55, 223-54.

Field, K.G., Remec, I. and Le Pape Y. (2015) “Radiation effects in concrete for nuclear power plants – Part I: Quantification of radiation exposure and radiation effects”, *Nuclear Engineering and Design*. 282, 126-43.

Park, K., Kim H.T., Kwon, T.H., and Choi, E. (2016) “Effect of neutron irradiation on response of reinforced concrete members for nuclear power plants”, *Nuclear Engineering and Design*, 310:15-26.

Shin-Kori Safety Analysis Report, Korea Hydro & Nuclear Power Co.

Kontani, O., Ichikawa, Y., Ishizawa, A., Takizawa, M. and Sato, O. (2010) “Irradiation effects on concrete structure”, *In International Symposium on the Ageing Management & Maintenance of Nuclear Power Plants*, 173-182.

William, K., Xi, Y. and Naus, D. (2013) “A review of the effects of radiation on microstructure and properties of concretes used in nuclear power plants”, *U.S. Nuclear Regulatory Commission*, Washington, DC.

Murty, K.L. (1984) “Is neutron radiation exposure always detrimental to metals (steels)?”, *Nature*, 308:51-52.

Bentz, E.C. (2000) “Sectional analysis of reinforced concrete members”, PhD Thesis, Department of Civil Engineering, University of Toronto, Canada.

ACI 318-11 (2011), American Concrete Institute.

AASHTO LRFD bridge design specification and commentary, American association of state highway transportation officials, Washingtons

Kang W.H., Kwon, T.H., Kim, H.T. and Park, K. (2016) "Design strength evaluation of RC beams under radiation environments for nuclear power plants", *Nuclear Engineering and Design*, 301:101-110.