Irradiated Effect on Shear-Moment Interaction of Reinforced Concrete Slab

Tae-Hyun Kwon [a], HyungTae Kim [b], Kyoungsoo Park [b], Jun Yeon Kim [a], Sang-Ho Kim [c*]

[a]*Korea Atomic Energy Research Institute, Daedeok-daero 989-111 Yuseong-gu, Daejeon Korea*
[b]*Yonsei University, 50 Yonsei-ro Seodaemun-gu Seoul Korea*
[c]*Hyundai Engineering, Seoul Korea*
[*]*Corresponding author: skim21@live.com*

1. Introduction

Reinforced concrete (RC) structures in nuclear power plants (NPPs) include a containment, shielding walls, foundations, and supports. For the life extension of aging NPPs, it is essential to assess deleterious effects for such RC structures. Several deleterious mechanisms include chronic high-temperature exposure, freeze-thaw, and chemical attack and have been reviewed extensively in the literature [1]. On the other hand, the effect of irradiation on RC needs further investigations for the long-term operation of existing NPPs. In this regard, the RC biological shield structure is located in closest proximity to a reactor core and expected to see the highest levels of irradiation over the lifetime.

The biological shield structure may undergo a large lateral load from earthquake and become thicker for a suitable shielding. Although the bending strength is easily predictable with the altering steel properties, the more complete behaviors should be studied to see if the promised performance is achievable. Given this, in this study, the shear-moment (VM) interaction of a typical one-way slab representing the biological shield structure is investigated with incremental neutron irradiation.

2. Methods and Results

A nominal design lifetime of NPPs is 40 years and it is possible to extend its operation for an additional 20 years by the submission of a license renewal application. An estimate of the total neutron fluence for the biological shield structure can be inferred from the neutron flux field reported in the safety analysis report (SAR) of Shin-Kori NPP [2]. Table I shows the estimated total neutron fluence at 10, 40, and maximum years of operation, where 10 year is the first interval for the periodic safety review.

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}

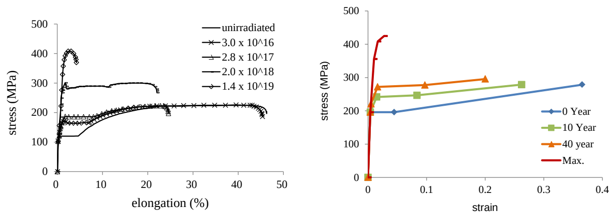
* A year that matches with available maximum neutron fluence in experimental data (Fig. 1).

2.1 Material Behavior of Irradiated Concrete

The most cited work for irradiation effects on the concrete strength is compiled by Hilsdorf et al. [3]. It shows that neutron fluence limit before a loss in the compressive strength is 1.0 x 10^{19}n/cm^2. The change in compressive strength is not significant for the neutron fluence below 1.0 x10^{19}n/cm^2. Therefore, a parabolic strain-stress relationship is fixed with incremental neutron irradiations. Note that the compressive strength (f_c') and its corresponding strain (ε_c') are 40MPa and 0.002, respectively.

2.2 Material Behavior of Irradiated Reinforcement

The effect of irradiation in RC also occurs in the reinforcement embedded in concrete. It is reasonable to assume that the reinforcement is exposed to environment due to long-term micro cracks around a concrete cover and affected by neutron irradiation. Reinforcement in RC is mostly mild steel and Murty et al. [4] reported strain-stress relationships of the mild steel with incremental irradiations as shown in Fig. 1. However, the results are obtained from a wire specimen atypical with a rebar specimen for RC. So strain-stress relationships with the wire are simplified with linear segmentations separated by yielding, stiffening, and ultimate points. Then, they are interpolated to result in the relationships matching with the target years listed in Table 1.



(a) (b)

Fig. 1. (a) strain-stress relationships with a wire specimen (b) modified strain-stress relationships matching with target years of NPP operation.

Lastly, they are consistently scaled such that the yield strength becomes 450MPa and the young modulus 183,000MPa (Fig. 2).

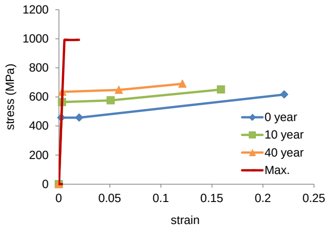


Fig. 2. Modified strain-stress relationships for reinforcement with years of NPP operation.

2.3 Shear and Moment Interaction

The section of a typical one-way slab is defined by unit length in Fig. 3. This figure shows the comparison of VM interactions in terms of irradiation time, which is obtained based on AASHTO LRFD [5].

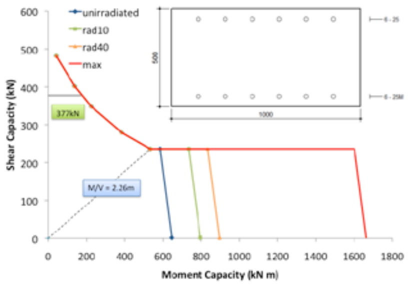


Fig. 3. VM strength interaction diagram (w/o shear reinforcement, unit for the section is in mm).

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.

3. Discussion

As presented in the earlier study [6, 7, 8], the bending behavior of a RC member becomes more brittle as it is exposed to neutron radiation. ACI318-11 [9] 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 II. The ductility is defined as the ultimate strain divided by the yield strain, referring to Fig. 2. The relative ductility of the steels is normalized and linearly interpolated between 0.75 and 1.0.

Table II: Strength Reduction Factor

	yield strain	ult. strain	Ductility		Factor
	a	b	b/a	norm'ed	(-)
rad0	0.0025	0.2210	88.4	1.00	1.00
rad10	0.0031	0.1589	51.5	0.58	0.90
rad40	0.0035	0.1212	34.9	0.40	0.85
ultimate	0.0054	0.0167	3.1	0.03	0.76
ref. point	-	-	0.0	0.00	0.75

The VM diagram (Fig. 3) is reproduced in Fig. 4 by applying the strength reduction factors calculated in Table 2.

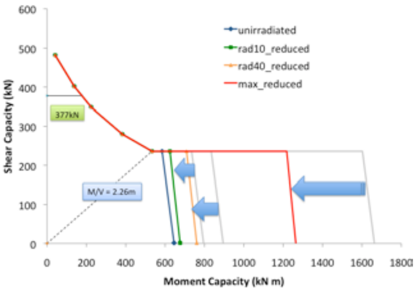


Fig. 4. Modified VM strength interaction diagram modified by the strength reduction factors.

3. Conclusions

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.

REFERENCES

[1] Primer on Durability of Nuclear Power Plant Reinforced Concrete Structures – A Review of Pertinent Factors, NUREG/CR-6927, 2007.
[2] Shin-Kori Safety Analysis Report, Korea Hydro & Nuclear Power Co.
[3] H. K. Hilsdorf et al., The Effects of Nuclear Radiation on the Mechanical Properties of Concrete, ACI SP-55, 1978.

[4] K. L. Murty, Is Neutron Radiation Exposure Always Detrimental to Metals (steels), Nature, Vol. 308, pp.51-52, 1984.
[5] AASHTO LRFD Bridge Design Specifications and Commentary, American Association of State Highway Transportation Officials, Washington .
[6] T.H. Kwon et al., Effect of Neutron Radiation on Moment-Curvature Response of Reinforced Concrete Beam, Trans. Of the Korean Nuclear Society Spring Meeting, 2014.
[7] W. H. Kang et al. Design Strength Evaluation of RC Beams under Radiation Environments for Nuclear Power Plants, Nuclear Engineering and Design, 2015(under review).
[8] K. Park et al., Effect of Neutron Irradiation on Response of Reinforce Concrete Members for Nuclear Power Plants, Nuclear Engineering and Design, 2015 (in preparation).
[9] ACI 318-11, American Concrete Institute, 2011