Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 29-30, 2014

Effect of Neutron Radiation on Moment-Curvature Response of Reinforced Concrete Beam

Tae-Hyun Kwon [a*], Jun Yeon Kim [a], Man-Soon Cho [a], Sangik Wu [a], Kyoungsoo Park [b]
[a]*Korea Atomic Energy Research Institute, Daedeok-daero 989-111 Yuseong-gu, Daejeon Korea*
[b]*Yonsei University, 50 Yonsei-ro Seodaemun-gu Seoul Korea*
[*]*Corresponding author: taekwonkr@kaeri.re.kr*

1. 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 commonly used as a biological shield and as a load carrying support for a reactor vessel and, if any, changes in the mechanical properties can be particular significant for long-term irradiation. Fig. 1 shows an RC structure around a reactor vessel in a pressurized water reactor (PWR) system. The highlights can be considered as the most critical due to its load bearing in the RC design.

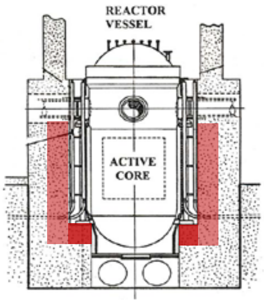


Fig. 1. RC as a biological shield and as load carrying support for the reactor vessel.

In this study, the response of a beam member in the RC design was investigated for long-term irradiation that RC supporting the reactor vessel may experience in aging nuclear power plants (NPPs).

2. Methods and Results

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 [1]. 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 was conservatively considered up to a neutron flux of $1.0\text{x}10^{19}$ n/cm^2.

2.1 Material Behavior of concrete

The stress-strain relationship for concrete can be assumed to be parabolic (ε_c', f_c') as shown in Fig. 2. Note that the compressive strength (f_c') and its corresponding strain (ε_c') are 40MPa and 0.002, respectively.

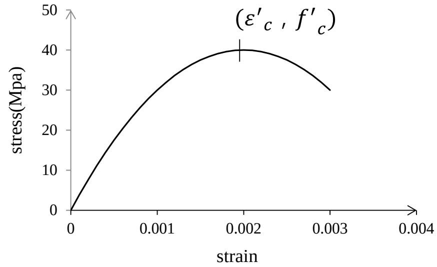


Fig. 2. Assumed parabolic strain-stress curve.

A general assessment is that the compressive strength of concrete decreases under neutron radiation exposure, and the neutron fluence on the order of $1\text{x}10^{19}$ n/cm^2 was reported to become critical for concrete strength [2, 3]. 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.

2.2 Material Behavior of Mild Steel

Irradiated metal and alloys show increased mechanical strength accompanied by a reduced ductility. In RC, reinforcement is mild steel bars and its strain stress relationship was once reported by Murty [4]. Fig. 3 shows digitized strain-stress relationships for incremental neutron radiation from Murty's study.

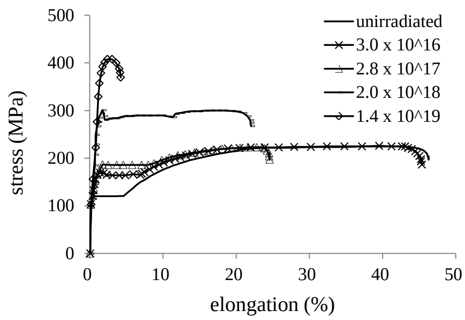


Fig. 3. Strain-stress curves of mile steel at room temperature with incremental neutron irradiation.

It shows that yield strength is increased 2.3 times and the ductility is 13-times less compared to the non-irradiated one. In RC, concrete can tolerate only a small tensile strain, and steel bars are assumed to be exposed to the environment due to long-term micro cracks around a concrete cover.

2.3 Response of RC beam

The response of the RC beam is typically described by the moment-curvature $(\mathrm{M}-\varphi)$. The RC beam is definitely non-linear and provides additional information which is overlooked in the design code where only ultimate strength matters. Here, a typical cross section is selected as an example (Fig. 4).

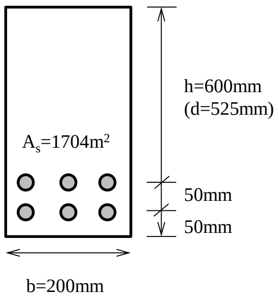
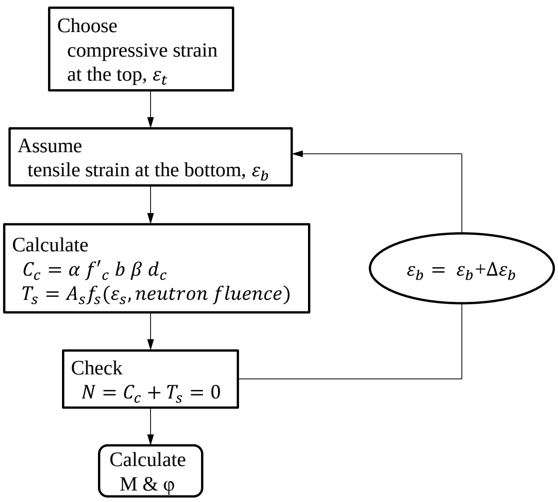


Fig. 4. Cross section for an example RC beam.

where $f_s = f(\varepsilon_s, neutron\,fluence)$, stress in reinforcement, is resulted from Fig. 3. The section satisfies the maximum reinforcement ratio, which limits the amount of reinforcing steel. It is a design code requirement to prevent brittle failure without warning signs.

The complete moment-curvature response is to determine the moments and curvatures corresponding to various values of top concrete strain. The solution procedure follows,



After computation, Fig. 5 shows the resulting moment-curvature curves with incremental neutron radiation.

The non-irradiated one shows a typical $\mathrm{M}-\varphi$ curve with ductile failure as designed, producing deformations that are large and serve as a warning. For the RC beam with the maximum neutron fluence, the ultimate moment capacity increases almost three times while its response demonstrates brittle failure, which may be sudden without warning signs. Table 1 shows the summarized results.

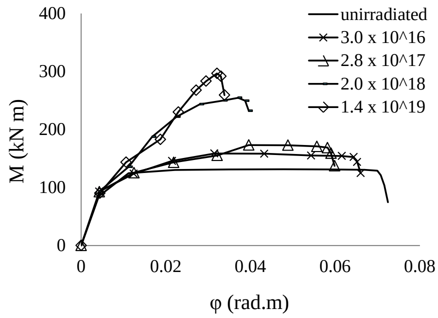


Fig. 5. Resulting moment-curvature curves with incremental neutron radiation.

Table I: Radiation, RC beam ultimate strength, ductility

Neutron fluence (n/cm^2)	Ultimate moment capacity (M_u, MPa)	Ductility ($q = \varphi_u/\varphi_y$)
Unirradiation	131.3	6.0
3.0×10^{16}	158.7	5.5
2.8×10^{17}	173.1	5.0
2.0×10^{18}	254.5	3.3
1.4×10^{19}	296.6	2.8

3. Conclusions

This study investigated the moment-curvature response of an RC beam with incremental neutron radiation. The RC structure close to the reactor vessel was 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 moment-curvature response of an RC beam was investigated with the maximum neutron fluence up to 10^{19} n/cm^2 and it shows twice the increase in ultimate strength, which is mainly contributed from the increased yield stress of mild steel. The RC beam response became so brittle that it may fail without large deformation as a warning. The same observation can be equally applied to other RC designs such as the column, slab, and foundation. Furthermore, the current investigation will be extended to a structural integrity evaluation of aging NPPs

REFERENCES

[1] Shin-Kori Safety Analysis Report, Korea Hydro & Nuclear Power Co.
[2] O. Kotani, Y. Ichikawa, A. Ishizawa, M. Takizawa, and O. Sato, Irradiated Effects on Concrete Structure", Proc. Of International Symposium on the Aging Managament & Maintenance of Nuclear Power Plants, pp173-182, 2010
[3] K. William, Y. Xi, and D. Naus, A Review of the Effects of Radiation on Microstructure and Properties of Concretes Used in Nuclear Power Plants, U.S.NRC, NUREG/CR-7171, 2013.
[4] K. L. Murty, Is Neutron Radiation Exposure Always Detrimental to Metals (steels), Nature, Vol. 308, pp.51-52, 1984