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Effect of neutron irradiation on response of reinforced concrete members for nuclear power plants

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HIGHLIGHTS

- Effects of long-term irradiation on reinforced concrete (RC) structures were investigated.
- Responses of irradiated RC members were numerically investigated in terms of ductility.
- Results demonstrated that energy dissipation capacity decreased under radiation environment.
- Level of neutron radiation could be critical for RC structures during operation.

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ABSTRACT

In this study, the effects of long-term irradiation on the behaviors of reinforced concrete (RC) members were investigated to obtain a better understanding of the behaviors of RC structures under an irradiation environment, which include the biological shield walls and reactor vessel support structures of nuclear power plants (NPPs). The behaviors of three RC members were examined (a beam, beam-column section, and column under cyclic loading) by considering the changes in the constituent material properties due to neutron irradiation. The load capacity generally increases for a tension failure member with an increase in neutron irradiation because neutron irradiation increases the yield stress of reinforcing steel. However, the load capacity of a compression failure member decreases with a decrease in the compressive strength of concrete when the fluence of neutron radiation increases. Additionally, RC member analysis results demonstrate that the energy dissipation capacity, which is a critical factor in seismic design, decreases significantly when the fluence of neutron radiation is greater than 1.0×10^{17} n/cm^2. Therefore, the level of neutron irradiation could be critical for RC structures over the long-term operation of NPPs, and thus the effects of neutron irradiation on RC structures should be considered as age-related damage.

1. Introduction

Reinforced concrete (RC) structures constitute the main components of nuclear power plants (NPPs) and their reliable performance is essential for safe operation. The RC structures of NPPs are mainly used for the containment, biological shielding, support, and foundation of the reactor pressure vessel. Because their structural performance during their service life can be a critical factor, the guarantee of the long-term safe performance of RC structures in NPPs is highly desired.

Physical, chemical, and mechanical changes in the concrete and steel can contribute to the degradation of RC structures. These are common issues for infrastructures and include sulfate attack, corrosion, freeze–thaw cycles, and elevated temperature (Baroghel-Bouny et al., 2009; Mehta and Monteiro, 2006; Mindess et al., 2002). Such age-related degradation of NPPs has been identified and extensively reviewed in the literature (Graves et al., 2014; Naus, 2005). Braverman et al. (2004) evaluated the age-related degradation of structures and passive components, which could become significant contributors to risk during NPP operation. However, the radiation-induced degradation of RC has been the focus of research in recent decades from the perspective of the long-term operation of NPPs beyond the current 40-year limit. A general assessment is that the compressive and tensile strengths of concrete decrease under neutron radiation exposure. Experimental studies reported in the literature have focused on the strength reduction levels at specific radiation intensities (Hilsdorf

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et al., 1978). Kontani et al. (2010, 2013) noted that there is a pressing need to conduct new and more systematic tests to study the critical levels of neutron radiation because the sizes and sources of test specimens, as well as other experimental conditions, have been very different from each other.

Most of the RC structures in NPPs have been regarded as sound as long as the radiation does not exceed critical levels. In assessing the critical levels of radiation, Field et al. (2015) conducted radiation transport simulations and reported the distribution of the neutron flux through the reactor pressure vessel, cavity, and biological shield for different plant configurations. Based on a conservative estimation based on the maximum fast neutron flux reported at the outer radius of a reactor pressure vessel (RPV), they reported that the estimated neutron fluence exceeds 1.0×10^{19} n/cm^2 at 40 years and reaches up to 6.0×10^{19} n/cm^2 at 80 years on the surface of the biological shield when fast neutrons indicated a fluence of neutrons with energies greater than 0.1 MeV. This level of neutron irradiation may introduce deleterious effects on both the concrete and reinforcing steel. As a result, it was concluded that the loss of mechanical properties from radiation-induced expansion cannot be ignored for the biological shield during the long-term operation of NPPs (Field et al., 2015).

Based on the estimated levels of neutron irradiation, the RC structures around a reactor, such as the biological shield walls and reactor vessel support, were of utmost interest in this study. They are expected to see the highest levels of neutron irradiation over their lifetime because they have the closest proximity to the reactor. Fig. 1 shows an example of the RC structure of a reactor vessel in a pressurized water reactor (PWR) system.

The shaded region in Fig. 1 can be considered to be the most critical because of the irradiation and its load-bearing role in the RC design. It is a typical safety-related structure that is essential to the function of the safety class system. However, radiation and radioactive contamination limits the accessibility to such structures for periodic inspections. Any changes in their mechanical properties can be particularly significant in assessing risk.

Some of the previous studies on the radiation damage to concrete structures have focused on the changes in the microstructure and properties of concrete (Willam et al., 2013). Because the deterioration of concrete has primarily been related to concrete volume changes, Kelly et al. (1969) and Gray (1971) investigated the volume expansion of aggregate. Hilsdorf et al. (1978) reported that the compressive and tensile strengths of concrete decreased according to an increase in the fluence of neutron radiation. Decreases in the compressive strength and tensile strength were also observed with an increase in the level of γ-irradiation (Vodák et al., 2005). Fujiwara et al. (2009) emphasized the separation of high-temperature-induced damage from radiation-induced damage. Recently, Le Pape et al. (2015) used micromechanical modeling and reported that the damage to cement paste was mainly associated with neutron-induced damage and the swelling of aggregate.

However, the literature shows that there have been a limited number of studies involving RC structural analysis under a radiation environment. For example, Pomaro et al. (2011a) used a hygro-thermo-mechanical analysis to demonstrate a decrease in the concrete stiffness of a biological shield under long-term neutron radiation exposure. Mirhosseini et al. (2014) investigated the effects of neutron radiation on RC panels but only considered the concrete damage. Salomoni et al. (2014) analyzed biological shields in conjunction with the thermo–hygro-mechanical damage behavior of concrete. Le Pape (2015) developed a one-dimensional cylindrical model of an unreinforced concrete biological shield that accounted for temperature and irradiation effects. Based on the strength changes in concrete and steel, Kang et al. (2016) showed that the current design codes need to further consider non-conservative design possibilities under radiation environments.

A further in-depth investigation of the behaviors of RC structural members is needed in conjunction with the changes in material properties, including the strength of concrete and ductility of steel. This is because RC is a composite member, in which the concrete resists compression and the steel bars used as reinforcement are generally embedded in tensile regions to counteract the relatively low tensile strength and ductility of the concrete. The radiation degradation of RC may affect both the concrete and reinforcing steel.

Therefore, this study conducted a numerical evaluation of the response of RC members to neutron irradiation. It should be noted that RC structures such as a biological shield and reactor vessel support are designed based on the response of RC members. The results of the numerical evaluation demonstrated that the energy dissipation capacity, which is a critical factor in seismic design, decreased with an increase in the neutron radiation fluence as a result of changes in the material properties of the RC members.

The remainder of this paper is organized as follows. First, the stress–strain relationships of concrete and steel with incremental increases in neutron irradiation are determined based on a literature review. Neutron irradiation may reduce the ductility of the

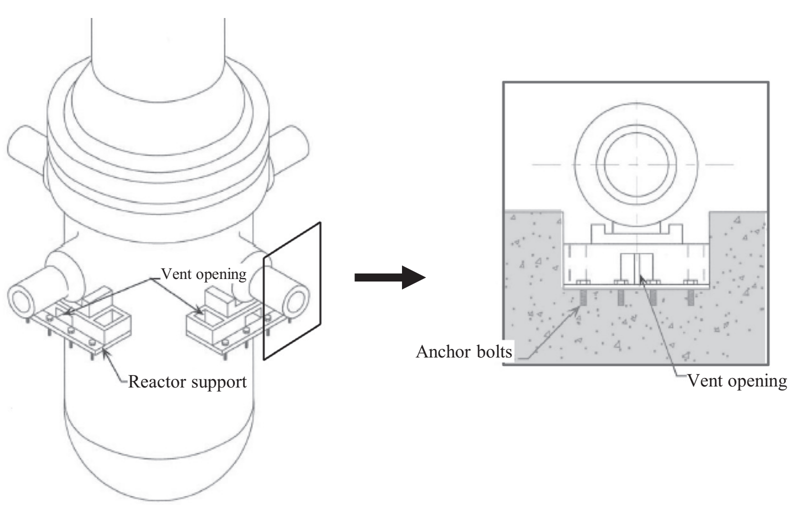

Fig. 1. Example of RC support for reactor vessel in PWR (USNRC, 2009).