THE EFFECT OF NUCLEAR RADIATION ON STRENGTH AND DUCTILITY OF REINFORCED CONCRETE ELEMENTS

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ABSTRACT

This paper investigates the effects of high levels of radiation on structural strength of reinforced concrete (RC) 2-D panels, which represent typical elements of Nuclear Power Plants (NPPs) structures. Reduction in concrete compressive and tensile strength due to radiation exposure was determines based on extensive literature review. Material properties, geometry, and load cases are selected based on the structural characteristics of the components in the existing nuclear power plants. A nonlinear analysis program, Membrane-2000, based on the Modified Compression Field Theory (MCFT) is used to compute the response of RC elements, which included ultimate strength capacity, and ductility index. The results show that ultimate shear capacity of highly reinforced elements subjected to combinations of shear and tension loading are reduced significantly in the highest radiation exposure category. RC panels under shear-biaxial and uniaxial compression show significant reduction in strength in high and moderate radiation levels. Failure modes of the elements change from yielding of steel to shear failure with increasing radiation exposure. Ductility of the RC panels is reduced below the acceptable level when they are exposed to the high levels of radiation.

INTRODUCTION

The nuclear power has played an important role in the energy supply worldwide. The contribution of nuclear power to energy mix varies across countries. Over 16 % of world's electricity, 20 % of US electricity, and 50% of electricity in Ontario (Canada) is generated by NPPs (World Nuclear Association, April 2009). In the North America life extension of plants that reach the end of first operating life is common through refurbishment of critical components, such as boilers and reactor piping system. There is always a concern about the reliability and remaining strength of concrete structures, since they are not easy to replace during the refurbishment. It is anticipated that refurbishment plants may undergo to the third round of refurbishment and operate up to 80-100 years. In this context, the fitness for service of concrete structures will be a deciding factor for life extension.

Although there are several mechanisms that can contribute to degradation of RC components [1], radiation induced deterioration is main topic of interest, since it is not well understood by structural engineers. Mechanical properties of concrete in RC structures that are close to radiation sources such as reactor core, and spent nuclear fuel storages are reduced significantly. Concrete strength reduction will adversely affect the ultimate strength capacity and structural ductility of these structures

Neutron radiation is produced as a result of a controlled reaction of nuclear fission during the transformation of a heavy nucleus into lighter nuclei. Neutron radiation is divided into three groups according to the level of kinetic energy. Thermal or slow neutron radiation has less than 0.5 electron volt (ev) energy. Epidermal or intermediate neutron particles have a level of energy around 5000 ev. Fast neutron radiation, which is the most important type for concrete deterioration, has the kinetic energy level higher than 500,000 ev [2]. Radiation can be described in terms of neutron flux or fluence. Neutron flux unit is n cm^{-2} s^{-1} and neutron fluence unit is n cm^{-2}. The important for age-related degradation is neutron fluence, which is calculated by multiplication of neutron flux and time. Thus the cumulative effect of flux over time produces high enough level of fluence to cause concrete deterioration. It should be noted that another type of radiation, Gamma radiation, also exist in NPP and it affects concrete properties significantly. This study, however, focuses on fast neutron radiation only [3].

The principal cause of concrete deterioration is aggregate expansion as a result of lattice movements due to fast neutron radiation. Radiation deterioration is however difficult to distinguish from temperature effect since both are affecting concrete at the same time. Experimental results suggest that effect of radiation on concrete without temperature is also significant for radiation levels beyond 5×10^{19} n cm^{-2} [4]. The authors could not find any previous research study on the effects of concrete strength reduction caused by fast neutron radiation on the structural response and structural capacity of the irradiated RC structures in NPPs.

ANALYTICAL PROCEDURE

Elements Analyzed

A RC membrane element is chosen for the study, since it represents RC wall elements commonly used in NPPs. The geometry, material properties and load cases are similar to that found in a typical NPP concrete structure. Six load cases and three radiation-induced degradation levels of concrete compressive and tensile strength are analyzed.

Concrete compressive strength f'_c is chosen as 27.6 MPa (4000 PSI) for all of the elements. The value of f'_c is selected based on the data available from shielding structures in existing NPPs. Reinforcing steel used for the RC panels is assumed to be the standard steel ASTM A-615 grade 60 with the yielding strength of the reinforcing steel is 414 MPa, which satisfy the maximum yielding strength of the code ACI-349 for safety-related RC structures in NPPs (415 MPa).

Four values of the reinforcement ratio 0.9, 1.35, 1.88, and 3 % are considered and designated as elements R1, R2, R3, and R4, respectively. Elements have same amounts of reinforcement ratio ρ in x and y direction. Reinforcement ratios are chosen from different locations of RC walls in NPPs, which are exposed to high levels of radiation [5].

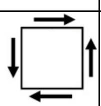
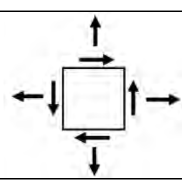
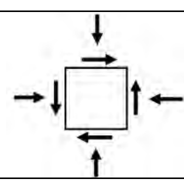
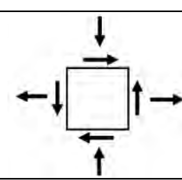
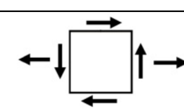
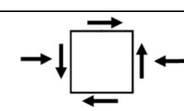
Loading Scenarios

Six different loading scenarios are considered for analysis (Table 1). These include:

1. pure shear (S)
2. shear-biaxial tension (STT)
3. shear-uniaxial tension (ST),
4. shear-biaxial tension-compression (STC)
5. shear-biaxial compression (SCC)
6. shear-uniaxial compression (SC).

Loading conditions are chosen based on the probable conditions panels in shell type structures of NPPs. Concrete compressive and tensile strength reductions affect shear capacity more than flexural capacity, which is dependent mainly in reinforcement properties. Hence, shear strength of the RC panels are analyzed for degradation levels U, D1, D2, and D3. The panels are analyzed under monotonically increasing loads (stresses) and the ratios of axial to shear stresses on a panel is always equal; same magnitude shear and axial stresses are applied and monotonically increased .

Table 1: Different loading patterns

Loading Category	S	STT	SCC	STC	ST	SC
Loading Pattern						

Degradation Factors

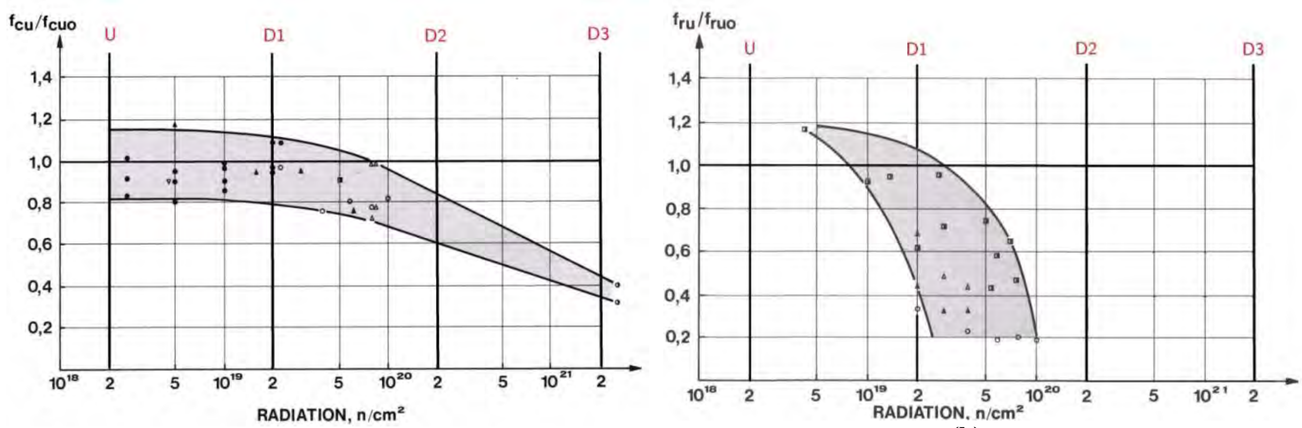
Very limited experimental data are available about the effects of fast neutron radiation on the reduction of concrete compressive and tensile strengths. Experimental results shown in Figures 1a and 1b provide data on radiation thresholds for NPP codes. Based on this information, compressive strength of concrete is reduced by the fast neutron fluence 2×10^{19} n cm^{-2}, 2×10^{20} n cm^{-2}, and 2×10^{21} n cm^{-2} by approximately 95%, 72%, and 40 %, respectively. Tensile strength of concrete is also reduced. Assumptions regarding compressive and tensile strength reductions and the three levels of radiation studied are shown in Table 2.

Table 2: Degradation levels based on the critical levels of radiation.

Degradation Level	Neutron Flux n cm^{-2} s^{-1}	Time *year*	Neutron Fluence n cm^{-2}	Compressive Strength Reduction %	Tensile Strength Reduction%
U	0	40	0	0	0
D1	1.58×10^{10}	40	2×10^{19}	95	80
D2	1.58×10^{11}	40	2×10^{20}	72	50
D3	1.58×10^{12}	40	2×10^{21}	40	20

The level of radiation that structures are exposed to is related to the type of reactor and concrete mixture. According to the available data, primary shields may experience neutron radiation fluence beyond 5×10^{19} n cm^{-2} [4]. The tests from the BEPO reactor by United Kingdom Atomic Energy Authority (UKAEA) show a constant flux around 3×10^{11} n cm^{-2} s^{-1}, which is equivalent to the fluence 3.78×10^{20} n cm^{-2} after 40 years [6]. It is probable for the structures close to the reactor core to experience the critical fast neutron radiation levels at the end of their operating life time [7].

New generations of NPPs (1990s) have lower levels of radiation. The design of an ABWR, available in the public domain, shows that safety related structures may experience the neutron radiation fluence of the order of 10^{14} n cm^{-2} [8].



(a) (b)

Figure 1**:** Degradation levels 1, 2, and 3 are assumed for the analysis of RC panels, (a) f_{cu} is compressive strength of irradiated-unheated specimens and f_{cuo} is compressive strength of unirradiated-unheated specimens (b) f_{ru} is tensile strength of irradiated-unheated specimens and f_{ruo} is tensile strength of unirradiated-unheated specimens [4].

Numerical Solution

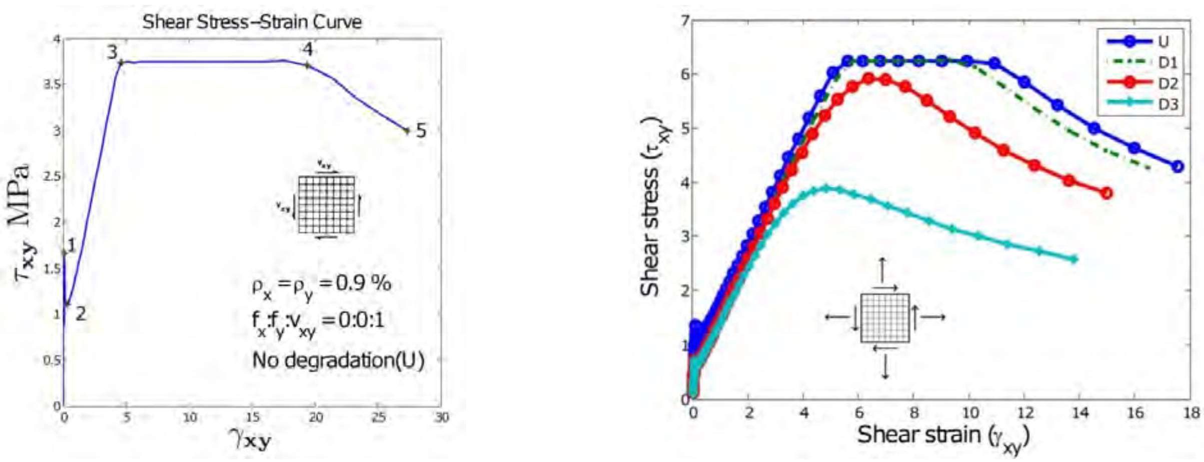
Reinforced concrete structures in NPP often take the form of shells, wall and plate structures. To represent the behaviour of different locations of such structures, under variety of loading conditions, a membrane element analysis program for reinforced concrete can be utilized. Membrane elements are analysed as scale models for RC walls in NPPs. The Modified Compression Field Theory (MCFT) is the long established nonlinear material behaviour theory that can be used to analyze behaviour of complex structures such as containments and their internal structures [9]. In this work we used a program *Membrane-2000* to analyse panels under inplane shear and shear plus axial loading conditions [10].

ANALYSIS OF RESULTS

Load Deformation Information

A typical stress-strain curve for an element studies herein is shown in Figure 2a. Five important points on this curve are shown cracking point to crushing point. These points separate five parts of an element response that illustrate behaviour of the RC panels under monotonic loading. Point numbers 1, 3, and 4 are cracking, yielding and ultimate strength of the member, respectively. Displacement structural ductility μ_u is defined as ultimate strain over yielding strain of the element response ($\frac{\varepsilon_u}{\varepsilon_y}$).

Three most affected characteristic of the load-deformation curves, which are cracking shear stress v_{cr}, ultimate strength capacity v_u, and ductility index μ_u, are analyzed by comparing the results of the elements. Figure 2b is an example of the load-deflection response of element R3 (ρ =1.88) under shear-biaxial loading at different levels of degradation.



(a) **(b)**

Figure 2: (a) Typical load deformation diagram for a membrane element under in-plane stresses
(b) Comparison of the element R3 under shear-biaxial tension loading in different levels of degradation.

Ultimate Strength Capacity Reduction

Ultimate capacity of RC walls is affected by different variables; compressive strength, tensile strength, and reinforcement. The effect of degradation on shear capacity of the RC panels, for each of the four different reinforcement ratios are studied in this paper. Three variables: reinforcement ratio ρ, loading scenario ($\frac{v_{xy}}{f_x}$), and degradation levels (U, D1, D2, and D3) are considered.

Ultimate strength capacity of the elements under pure shear loading that is given in Table 3 show that radiation decrease strength capacity of the exposed RC panels. Similar behaviour can be observed under shear-biaxial tension, shear-biaxial tension-compression and shear-uniaxial tension loading conditions. The general trend observed from the elements under STT, STC, and ST loading show that by increasing radiation deterioration, the shear capacity of the elements for highly RC members, which have 3 % reinforcement ratio ρ, is decreased significantly. It also can be seen that low reinforced elements (ρ =0.9%) are not significantly affected by radiation. Degradation level 3 affects the elements with reinforcement ratio ρ greater than 1.88 %. The effect of the critical levels of radiation (between 2×10^{19} and $2 \times 10^{21}\ n/cm^2$) is not significant on the elements with the reinforcement ratio 0.9 %. Elements R2, R3, and R4 show different amounts of strength reduction for same levels of radiation. The element R4 with reinforcement ratio 3% is the most affected elements by high levels of radiation.

Elements under shear and compression also showed significant strength reduction with increasing level of radiation. Elements under shear-biaxial compression showed maximum reduction values of 39% and 71 % in degradation levels 2 and 3, respectively. RC panels under uniaxial compression loading conditions show the same pattern as the elements under shear-biaxial compression with the maximum reduction values of 45% and 82 % for the degradation levels 2 and 3, respectively.

For each specific loading scenario in different levels of degradation, ultimate shear strength v_u changes more significantly for elements with higher reinforcement ratio. This kind of behaviour can be explained by experimental relationship between ultimate strength capacity reduction and compressive strength[11]. Ultimate strength capacity becomes more dependent to concrete compressive strength f'_c when the reinforcement ratio increases. Significant reductions are for higher reinforcement ratios in all levels of degradation since they become more dependent on f'_c.

Table 3: Ultimate strength capacity reduction of elements R1, R2, R3, and R4 in different levels of degradation under various loading conditions

Loading Scenario	Degradation Level	Radiation n/cm^2	Element R1 $\rho = 0.9\ \%$	Element R2 $\rho = 1.35\ \%$	Element R3 $\rho = 1.88\ \%$	Element R4 $\rho = 3\ \%$
			$\frac{Strength\ of\ irradiated\ elements}{Strength\ of\ unirradiated\ elements}$ x [100%]			
S	D1	2×10^{19}	100	100	98	96
	D2	2×10^{20}	99	100	80	78
	D3	2×10^{21}	89	66	51	48
STT	D1	2×10^{19}	100	100	100	100
	D2	2×10^{20}	100	100	100	95
	D3	2×10^{21}	100	100	87	61
ST	D1	2×10^{19}	98	100	99	99
	D2	2×10^{20}	94	100	99	94
	D3	2×10^{21}	97	91	75	55
STC	D1	2×10^{19}	98	98	99	98
	D2	2×10^{20}	94	100	96	92
	D3	2×10^{21}	90	91	73	53
SCC	D1	2×10^{19}	94	94	94	94
	D2	2×10^{20}	71	71	71	71
	D3	2×10^{21}	38	38	38	39
SC	D1	2×10^{19}	99	98	96	95
	D2	2×10^{20}	94	88	83	82
	D3	2×10^{21}	64	51	47	45

Ductility Index Reduction

Ductility is a factor that shows the capability of a material, section, structural element, or structural system to have large deformation before failure happens. Ductility in this study is computed by dividing the ultimate strain by the yield strain ($\mu_u = \frac{\varepsilon_u}{\varepsilon_y}$). Members with low ductility index have brittle failure; so it is always desirable for designer, to control this factor by an appropriate limit. For example, values between 1.5 and 2.5 are suggested by Newmark [12]. Since the range suggested by Newmark is not conservative enough for NPPs codes, Applied Technology Council (ATC) recommends a ductility factor between 3 and 4 [13].

Effects of radiation on ductility index for elements with different reinforcement ratios when shear loading increases is studied in this section. Yielding and ultimate points of the analysis results are retrieved from the stress-strain curves to compute ductility index of the elements.

Ductility indices of elements R1, R2, R3, and R4 in different levels of degradation are given in Table 4. The ductility indices of elements decrease to the values below ATC range when degradation increases. Ductility index values that are below allowable values are highlighted in Table 4. The results coincide with the fact that there is no yielding of steel before failure for highly reinforced elements, so ductility index of the elements is actually the ultimate strain over a point close to ultimate. It makes the value of ductility index of these elements around 1.

Table 4: Ductility index of elements R1, R2, R3, and R4 under different loading condition in different levels of degradation.

Loading Scenario	Degradation Level	Radiation n/cm^2	Element R1 $\rho = 0.9$ %	Element R2 $\rho = 1.35$ %	Element R3 $\rho = 1.88$ %	Element R4 $\rho = 3$ %
			μ_u			
S	U	0	4.2	2.1	1.2	**1.1**
	D1	2×10^{19}	4.2	1.9	**1.1**	**1.1**
	D2	2×10^{20}	2.8	**1.1**	**1.1**	**1.1**
	D3	2×10^{21}	**1.1**	**1.1**	**1.1**	**1.1**
STT	U	0	11	6.4	3.8	**1.8**
	D1	2×10^{19}	10.7	5.9	3.8	**1.5**
	D2	2×10^{20}	8.2	4.2	**2.6**	**1.1**
	D3	2×10^{21}	5.0	**1.6**	**1.1**	**1.1**
ST	U	0	8.6	4.2	**2.1**	**1.3**
	D1	2×10^{19}	8.6	3.4	**1.8**	**1.2**
	D2	2×10^{20}	7.7	**2.6**	**1.5**	**1.1**
	D3	2×10^{21}	**2.59**	**1.5**	**1.2**	**1.1**
STC	U	0	8.0	4.6	**2.6**	**1.3**
	D1	2×10^{19}	8.0	3.8	**2.4**	**1.3**
	D2	2×10^{20}	7.4	3.1	**2.1**	**1.1**
	D3	2×10^{21}	3.1	**1.3**	**1.2**	**1.2**
SCC	U	0	2.6	3.4	4.2	5.6
	D1	2×10^{19}	3.4	4.2	5	6.7
	D2	2×10^{20}	4.6	6.1	7.4	10
	D3	2×10^{21}	9	12	16	21.2
SC	U	0	**1.6**	**1.2**	**1.1**	**1.1**
	D1	2×10^{19}	**1.3**	**1.1**	**1.1**	**1.1**
	D2	2×10^{20}	**1.2**	**1.1**	**1.1**	**1.1**
	D3	2×10^{21}	**1.1**	**1.1**	**1.1**	**1.1**

Failure Mode

Failure mode of RC panels subjected to pure shear loading can be divided into three areas based on reinforcement ratio[9] . First area is related to the elements with very low amount of reinforcement in which cracking load is responsible for failure. The second area covers a large interval of reinforcing steel ratio where yielding of steel governs the failure. The third area is for highly reinforced members that experience concrete crushing because of shear.

Failure mode of RC panels are changed from yielding of steel to concrete crushing when they are exposed to high levels of radiation. In order to study the failure mode of undegraded and degraded elements, the elements under pure shear loading are compared in Figure 3. The figure shows two sets of lines: cracking loads (normalized) versus normalized reinforcement ratio, and ultimate load versus reinforcement ratios. The slopes of the ultimate load curves decrease when level of degradation increases. Yielding of steel governs failure of the elements as long as slope is equal to one. Degradation level D3 changes failure mode of all elements with reinforcement ratios between 0.9 and 3% considerably. Degradation level D2 affects significantly failure mode of elements with reinforcement ratios between 1.35 and 3 % significantly. It can be concluded that failure mode of elements with high reinforcement ratios (ρ=3%) are more affected by degradation than elements with lower reinforcement ratios.

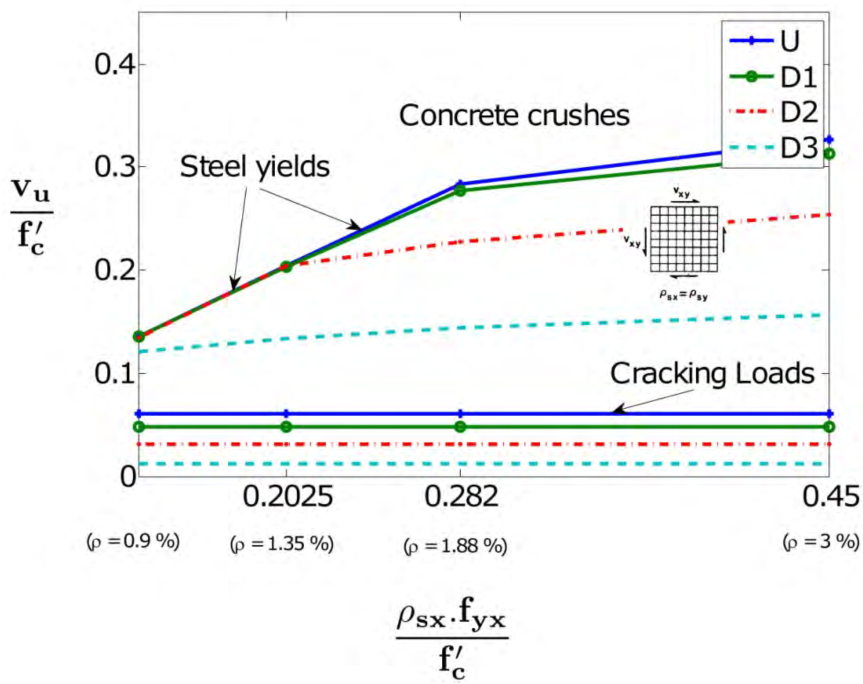


Figure 3: Failure mode changes when reinforcement ratio increases in different levels of degradation.

CONCLUSIONS

The behaviour of reinforced concrete structures exposed to the intense levels of radiation in NPPs is investigated in the paper. An RC panel with in-plane stresses was used as a representative scale element of typical shell type structures in a nuclear plant. Geometrical details, material properties, and loading cases were similar to those used in the plant design. The elements were analyzed with a nonlinear program, *Membrane-2000*, developed at the University of Toronto, which is based on the Modified Compression Field Theory.

Three effects of radiation on RC panels in this study: ultimate strength capacity reduction ductility reduction and failure modes were considered. The elements were subjected to shear and shear plus axial loading (tension and compression). Four different reinforcement ratios were considered. Based on the presented analyses the following conclusions can be offered:

- Ultimate strength capacity for the elements subjected to shear and tension was more affected by irradiation for high reinforcement ratios.
- Ultimate strength capacity was significantly reduced for highly reinforced elements (ρ =1.88% and 3%) when radiation was equal to 2×10^{21} n cm^{-2} (D3)
- Ultimate strength capacity reduction for the elements subjected to shear and shear and inplane compression was significantly reduced for all reinforcement ratios and for radiation level two (2×10^{20} n cm^{-2}) and three (2×10^{21} n cm^{-2}).
- Ductility was significantly reduced for elements subjected to shear and tension and with higher reinforcement ratios
- By increasing the level of radiation, ductility of the RC panels reduced to the values bellow the allowable ductility of RC structures in NPPs, which was equal to 3 based on Applied Technology Council criteria.
- Increased level of radiations can change the mode of failure of the reinforced concrete panels from ductile steel yielding to brittle concrete crushing.

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