SEISMIC FRAGILITY EVALUATION OF A CONCRETE SHEAR WALL WITH AGE-RELATED DEGRADATION

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ABSTRACT

Age-related degradation is a common problem in concrete structures. Reinforced concrete (RC) structures particularly exposed to sea environments can suffer from corrosion of steel reinforcement due to the chloride penetration. Corrosion of steel reinforcement and spalling of concrete may lead to serious damage to a concrete structure member and to affect the durability of RC structures. Thus age-related degradation of safety-related concrete structures in nuclear power plants may significantly affect the serviceability of plants.

In this study, the RC shear wall which is often used in nuclear power plants was chosen as the analytical model. The time-dependent material property was investigated by using previous reports and papers to consider the degradation of RC shear wall. A seismic fragility evaluation was performed to evaluate the seismic capacity of the shear wall with aged-related degradation. A comparison study of a degraded model and an undegraded model was included. Besides a seismic fragility analysis considering different failure criteria was preformed to define dominant failure criteria over time. According to the analysis results, it was found that the median capacity changed over time because of degradation and concrete hardening effect. Besides, it was observed that the reduction ratio of HCLPF for degraded model was increased over time because of steel loss and concrete spalling.

INTRODUCTION

RC shear wall possess characteristics of stiffness, strength and ductility that are favorable for withstanding lateral seismic loads. For this reason, RC shear walls become imperative for civil structures from a deflection control point of view [1]. For example, RC shear walls are usually used to protect equipments and to resist seismic load for nuclear power plants (NPPs) such as containment buildings, diesel-generator buildings and auxiliary buildings.

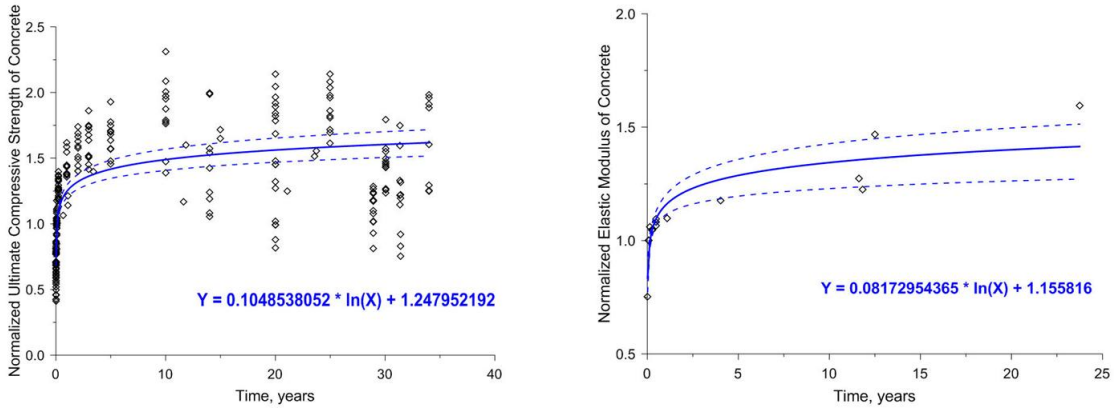
Before the occurring of degradation, the structural capacity withstanding lateral load is effective in the shear wall system. But RC shear wall structures were distressed after the occurring of degradation (e.g. alkali-aggregate reaction, sulfate attack, freezing and thawing, abrasion/erosion/cavitation, thermal exposure/thermal cycling, irradiation, etc.). The dynamic property of degraded structures had changed due to various degradation factors. Thus, to identify the performance of an aged structure, structural analysis considering degradation facts had been previously conducted. Sho et al. [2] pointed out the structural problems subjected to age-related structural degradation. Kassami et al. [3] demonstrated the relationship between the carbonation of concrete and the corrosion of reinforcements. Vidal et al. [4] introduced a set of relationships linking the distribution of reinforcement corrosion and the width of cover crack that results from such corrosion. According to the results, the degradation effects trigger each other. Chloride ions penetrate into a deactivated layer of steel bars. Subsequently, the corrosion of the steel bars begin, which results in concrete deterioration such as the declining of bond between steel and concrete, corroding expansion cracks along steel bars, loose and flake-off of concrete covering layer, and so on.

Most research on age-related degradation has been concentrated on the structural material (concrete and reinforcing steel) because there is a limit to structural analysis considering the material degradation. The research subjected to structural behavior with age-related degradation was recently performed supposing that concrete spalling and steel corrosion were quantitatively not related to degradation fact. Braverman et al. [5] evaluated seismic fragility of structural components with age-related degradation and collected data subjected to degradation at NPPs. They conducted fragility analysis with respect to shear wall having 20% loss of the steel area combined with the spalling of concrete. The research showed that the mean strength of the shear wall was reduced by degradation about 6%. Although previous research on degradation of RC shear walls has been conducted quantitatively, they do not consider the effect of concrete hardening over time. Therefore shear wall without concrete hardening effect can be underestimated.

The purpose of this study is (1) to investigate mechanism of concrete and reinforcing steel in the RC shear wall subjected to age-related degradation: (2) to evaluate the seismic fragility of a shear wall with age-related degradation using different failure criteria: (3) to evaluate the seismic fragility of a shear wall considering hardening and degradation of the RC.

TIME-DEPENDENT PROPERTIES OF MATERIALS

After the concrete is poured, the hardening of concrete which is affected by the strength and stiffness of the material is generally observed in RC structures. In this study, not only material degradation but also concrete hardening was applied to perform seismic analysis of an RC shear wall with age-related degradation. Because it is difficult to analytically define time-dependent material property, the material property over time is generally defined by a test. However, the test is impossible due to a limited time and specimens. In this study, a material DB of structural aging program (SAG) [6] was therefore used for defining the time-dependent material property. According to the SAG material DB on the power plants, a compressive strength and elastic modulus of concrete was measured at nuclear power and fossil power plants over a life-time and are expressed in figure 1. The solid line in figure 1 denotes mean of the concrete strength and elastic modulus. It was observed that the concrete strength and elastic modulus rose sharply from 0 to 5year and slowly after 5year. The regression equation was used to perform seismic analysis of the shear wall considering concrete hardening.



(a) Normalized compressive strength (b) Normalized elastic modulus

Fig. 1: Compressive strength and elastic modulus of concrete with time

The rebar corrosion by penetration of chloride may affect not only the reinforcing steel, but also the surrounding concrete through mutual interaction between the two materials by reducing bond strength. But the effect of steel corrosion on steel – concrete interaction is a long way from being completely solved because of its complexity, mainly due to the number of the parameters involved such as cover to bar diameter ratio, rebar position, confinement level, concrete quality, cover cracking, corrosion level, etc. Hence, it is difficult to generalize the test results and to develop simple numerical models which are able to simulate the real behavior of aged structures. Moreover, limited loss of bond has been detected for moderate levels of corrosive attack. For this reasons, in this study the effects of reinforcement corrosion on bond interaction is neglected. Consequently, the following aspects are considered: reduction of the reinforced steel section, reduction of reinforced steel yield strength and spalling of the concrete cover.

Steel corrosion due to a penetration of chloride may also affect the mechanical properties of steel. Test results which were performed by Rodriguez et al. [7] showed a significant reduction of steel elongation at maximum load, which is a loss of steel ductility. Such reductions reach values of 30% and 50% with losses to the steel section at 15% and 28%. Steel corrosion results in not only a decrease in the section and ductility but also an increase of internal stress. Furthermore, increased stress can result in concrete cracking. The propagation of a crack induces spalling of the cover concrete.

A steel cross-section reduces localized pitting corrosion or a uniformly distributed carbonation attack. In this study, general corrosion is assumed for analysis of the degraded shear wall. According to equation proposed by Choe et al. [8] the reduction of steel during life-long service is shown in figure 2. The chloride content was assumed to be 0.06%.

Spalling of the cover concrete which is induced by steel corrosion affects reduction of the concrete section. The cover concrete was cracked by steel corrosion while cracking in the core concrete which is confined by reinforcement will not occur as easily. For this reason, the loss of the concrete section was assumed to be 0.03in/year when considering spalling. When reduction of the wall thickness reaches the core concrete it was assumed that a crack does not propagate. Because a penetration of chloride occurs on the outside RC shear wall, it was assumed that spalling of the cover concrete will only occur on the outside of the wall. Figure 3 shows the thickness of wall over a period of time.

Table 1 shows material property of a degraded model over time. It is observed that the area of steel (A), yield strength of steel (f_y), thickness of wall (T) and maximum displacement (D_{max}) decrease due to corrosion of steel, spalling concrete and reduction of ductility. While the compressive strength of concrete (f'_c) and the elastic modulus of concrete (E) increase because of concrete hardening. Furthermore it is observed that the change of variables is different due to various degradation levels over the years. The compressive strength of a 20 year model due to concrete hardening had increased about 36%, while the yield strength of steel due to degradation had decreased about 3.2%.

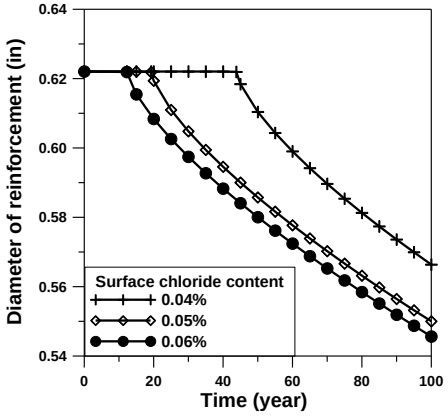


Fig. 2: Diameter of rebar with the chloride content

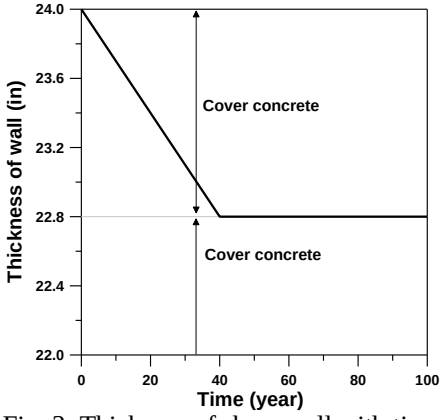


Fig. 3: Thickness of shear wall with time

Table 1: Time-dependent material property

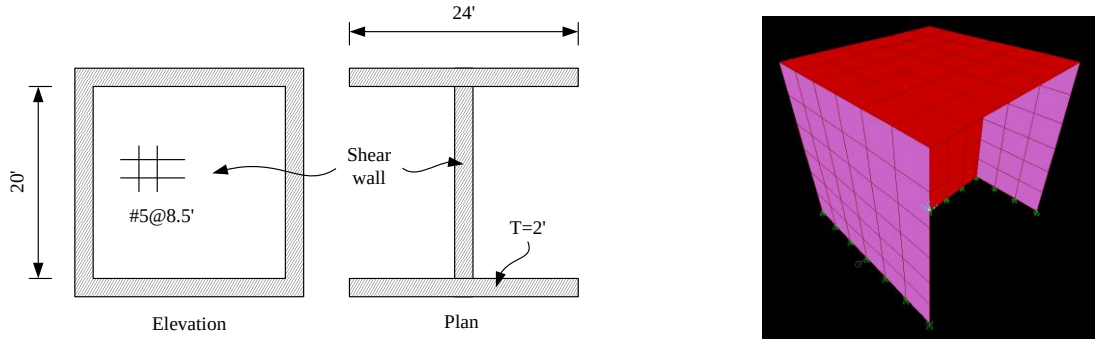
Time (year)	f'_c (ksi)	E (ksi)	A (in^2)	f_y (ksi)	T (in)	D_{max} (in)
0	4.40	3,834.00	0.30	71.00	24.00	0.30
10	6.55	5,152.92	0.30	71.00	23.70	0.30
20	6.87	5,370.11	0.29	68.68	23.40	0.28
40	7.19	5,587.31	0.27	65.24	22.80	0.24
60	7.38	5,714.37	0.25	62.53	22.80	0.21
100	7.62	5,874.43	0.23	57.94	22.80	0.16

FRAGILITY ANALYSIS OF REINFORCED CONCRETE SHEAR WALLS

Analytical Model

The shear wall model of NUREG/CR-6715 [9] was selected to perform seismic fragility of analytical model. As shown in figure 4 (a), the analytical model is an H-shaped wall with two flange walls and one center wall. A total of 144 shell elements were used to model the shear wall. A four-point numerical integration formulation is used for the shell stiffness. Stresses and internal forces at moments, in the element local coordinate system, are evaluated at the 2-by-2 Gauss integration points and extrapolated to the joints of the element. The 3-D view of the RC shear wall meshing is shown in Figure 4 (b). The thickness of the wall is 2' throughout. The length of the center wall is 20', the length of the flange wall is 20', and the height of the wall is 24'. The reinforcement consist of #5

(diameter 0.622") bars spaced at 8.5' (21.6 cm) at each face in each direction resulting in a horizontal and vertical reinforcing ratio equal to 0.003. A vertical load was applied in the wall equal to 300 psi. The shell element was made up of many layers with different thickness as shown in figure 5. And different material properties were assigned to various layers. This means that the reinforced steel was smeared into one layer or more. During the finite element calculation, the axial strain and curvature of the middle layer was obtained in one element. Then according to the assumption that plane remains plane, the strains and the curvatures of the other layers were calculated. Finally, the corresponding stress was calculated through the constitutive relations of the material assigned to the layer.



(a) Shape of shear wall (b) Finite element model

Fig. 4: Analytical model

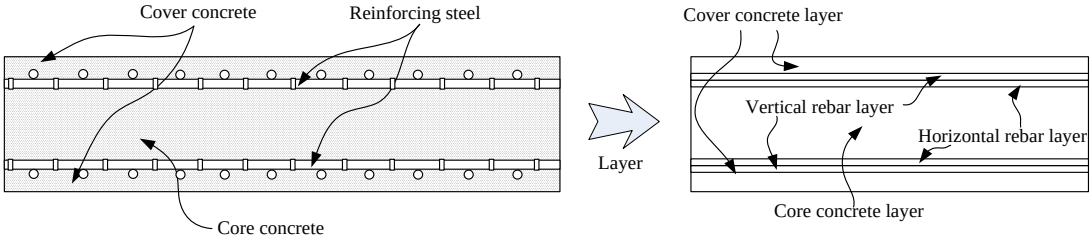


Fig. 5: Layered shell element of analytical model

Methodology for Time-Dependent Seismic Fragility Analysis

Seismic fragility parameters, the median capacity and uncertainties (e.g. aleatory, epistemic), are changed over time. In this study, therefore the seismic fragility of analytical model was calculated considering time function as shown in the following equation.

Seismic fragility was performed by increasing time (e.g. 10year, 20year, 40year, 60year, and 100year) to investigate the degradation effect of the RC shear wall over time. In each monitored year, the material property and degradation degree were calculated using SAG material DB and an equation proposed by several researchers [8, 9]. Concrete hardening and degradation effect was considered to realistically simulate seismic behavior of a degraded RC shear wall.

$$f'(t) = \Phi\left[\frac{\ln(S_m(a)(t)/C_m(t)) + \beta_U(t)\cdot\Phi^{-1}(Q)}{\beta_R(t)}\right]$$

Where, a and Φ^{-1} represents a peak ground acceleration as a ground motion parameter and the inverse of the standard Gaussian cumulative distribution function, t represents the age of the RC shear wall and $S_m(a)(t)$, $C_m(t)$, $\beta_R(t)$, and $\beta_U(t)$, represent the median seismic response at a given ground acceleration, median capacity, randomness and uncertainty at time, respectively.

According to the failure mode of the RC shear wall, the diagonal shear cracking, moment, shear friction, and top displacement of shear wall can be used as a limit state. Because diagonal shear cracking is the primary failure mode in low-rise RC shear walls, diagonal shear cracking force of the RC shear wall was calculated by using an equation proposed by Barda et al. [10]. The RC shear walls of NPPs are usually considered to have large capacity against seismic load because of their heavy construction. Therefore, in seismic probabilistic risk assessments, structural failure of the RC shear wall can be generally defined to occur when the deformations are sufficient to impair the functionality of attached equipment. The lognormal standard deviation on randomness and uncertainty was assumed to be 0.15.

Seismic Fragility of Shear Wall with age-related degradation

Nonlinear dynamic analyses of the analytical model were carried out using the program code SAP 2000. A crack caused by steel corrosion results in stiffness and strength reduction. Therefore considering a reduction model of stiffness and strength is essential to perform structural analysis with age-related degradation. The Takeda model [11] was used to consider stiffness reduction of the shear wall during seismic loading. A total of 20 different ground motions which were used on the SAC-steel project were selected for dynamic analysis of a shear wall. Figure 6 shows the spectral acceleration of the ground motion which was normalized at 0.2g. The amplification range of acceleration shows a range from 1Hz to 10Hz.

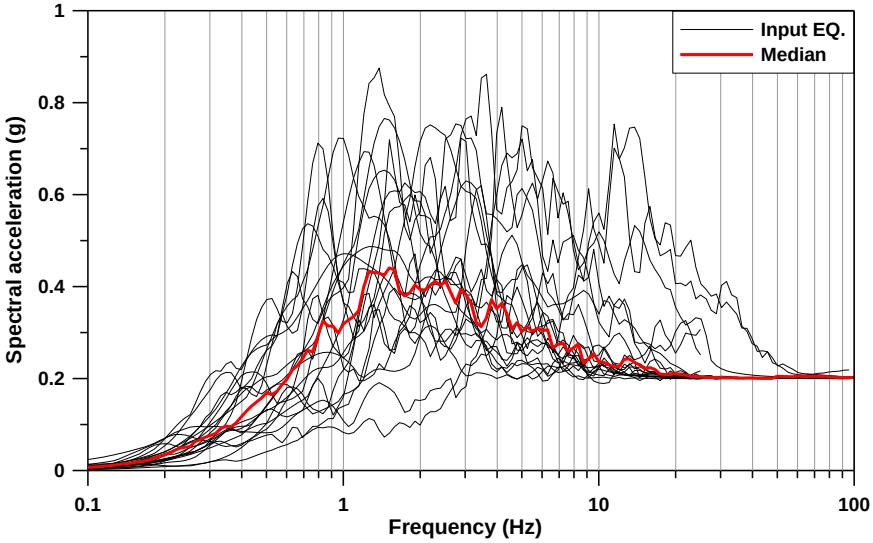


Fig. 6: Spectral acceleration of input ground motion

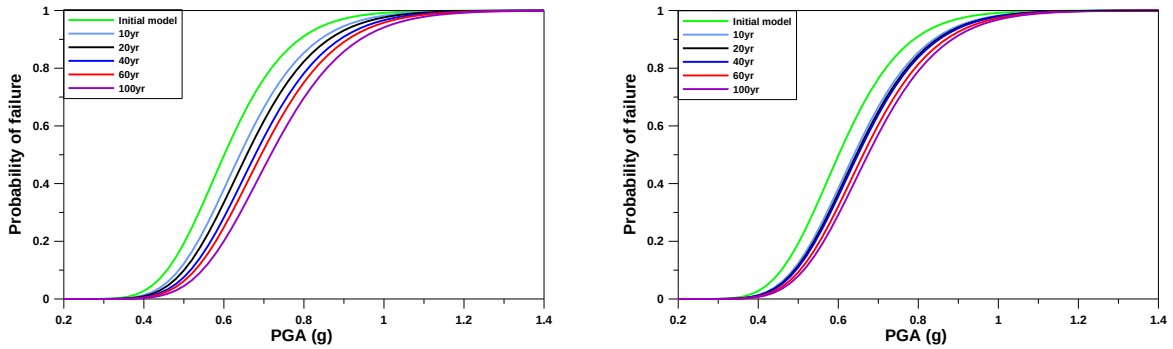
Table 2: Shear strength capacity and natural frequency

Time(year)	Shear strength capacity (kips)		Natural frequency (Hz)	
	Undegraded	Degraded	Undegraded	Degraded
0	3,344.46		10.67	
10	3,788.47	3,741.12	12.34	12.29
20	3,847.88	3,720.42	12.59	12.49
40	3,905.92	3,634.98	12.84	12.63
60	3,939.77	3,631.55	12.99	12.76
100	3,981.92	3,611.31	13.16	12.92

The base shear of the RC shear wall was calculated to evaluate the capacity of an RC shear wall. The median responses of the degraded RC shear wall were calculated by nonlinear dynamic analysis. According to the input ground acceleration spectrum, it was observed that the shear force responses of analytical model over time was

similar to initial model, since there was no difference between the acceleration of the degraded model and initial model at a field natural frequency. To compare seismic capacity of an undegraded shear wall with a degraded shear wall, the fragility curves of two models are represented together in the figure 7. Because the degradation was caused by the corrosion of steel and spalling of concrete, it was observed that the fragility curve of degraded RC shear wall is located on the left side of the undegraded RC shear wall. That is, the probability of failure was higher for the degraded model than for the undegraded model at a given peak ground acceleration. As shown in table 3, a reduction ratio of high confidence low probability failure (HCLPF) due to an increasing degradation level had increased over time. Where, $HCLPF_D$ and $HCLPF_U$ is HCLPF of degraded model and undegraded model, respectively.

When the seismic fragility was performed, it was also observed that the capacity of the undegraded model had increased by concrete hardening. According to SAG material DB, since the compressive strength at 10 years had reached 86% of the maximum hardening strength during the service life, the median capacity of the undegraded model increased rapidly to the 10 year and steadily after 10 year as shown in table 3.



(a) Undegraded model (b) Degraded model

Fig. 7: Fragility curve of analytical model with time

Table 3: Median capacity and HCLPF

Model		Am	HCLPF	$\frac{HCLPF_D}{HCLPF_U}$ (%)
Initial		0.601	0.367	-
10yr	Degraded	0.639	0.390	99.7
	Undegraded	0.640	0.391	
20yr	Degraded	0.645	0.394	98.3
	Undegraded	0.657	0.401	
40yr	Degraded	0.649	0.396	95.7
	Undegraded	0.678	0.414	
60yr	Degraded	0.662	0.404	95.5
	Undegraded	0.693	0.423	
100yr	Degraded	0.674	0.411	93.8
	Undegraded	0.717	0.438	

Comparison of Response According to the Failure Criteria

The limit state for NPPs was usually defined by strength and displacement as representative failure criteria. It is expected that the seismic capacity of degraded shear wall is change over time. Therefore, the force and displacement criteria in this study were used to define dominant failure criteria over time.

According to the NUREG/CR-6715 [12], the limit state of analytical model was defined as the drift ratio equal to 4 times yield displacement, a point where significant damage to attachments and penetrations may occur. The stiffness variation of the RC shear wall due to degradation and concrete hardening results in the displacement variation of the degraded model as shown in figure 8.

The top displacement of the shear wall over time had decreased as shown in figure 8 because a decreasing rate of time-dependent variables due to degradation was lower than an increasing rate of time-dependent variables due to concrete hardening. These results show that the behavior of a degraded model is mainly affected by concrete hardening. Although the displacement of the degraded RC shear wall decreased due to concrete hardening, the median seismic capacity of the degraded RC shear wall can decrease considering a decreased limited state under degradation. For this reason, the probability of failure for a degraded RC shear wall considering steel ductility reduction at a given peak ground acceleration decreased at 20years and increased after 20years as shown in figure 9.

The median capacity was lower for shear force criteria than for displacement criteria as shown in figure 10 because cracking for shear wall occurs and then failure of attached equipment occurs. But the displacement criteria will change according to the attachment state of equipment or a type of equipment, since it had been defined by the capacity of the attached equipment. Thus, the difference of median capacity considering the uncertainty of capacity for attached equipment will be lower than that of figure 10.

When the diagonal shear strength was used as the failure criteria, the HCLPF of RC shear wall with age-related degradation was decreased by the concrete spalling. But the steel corrosion did not have a significant effect on the decrease of the seismic capacity for degraded shear wall because of low steel ratio. On the other hand, when the displacement was used as the failure criteria, the steel section loss as well as the concrete spalling was important variables on the seismic capacity of RC shear wall with age-related degradation because the ductility of RC shear wall was generally governed by the steel. According to the table 1, the loss ratio of steel was higher than that related to concrete spalling. Therefore, the reduction ratio of $HCLPF_D$ to $HCLPF_U$ for RC shear wall based on displacement criteria was higher than that based on shear force criteria as shown in figure 11.

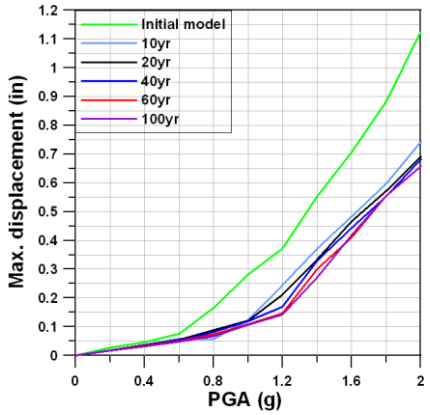


Fig. 8: Median response of degraded shear wall

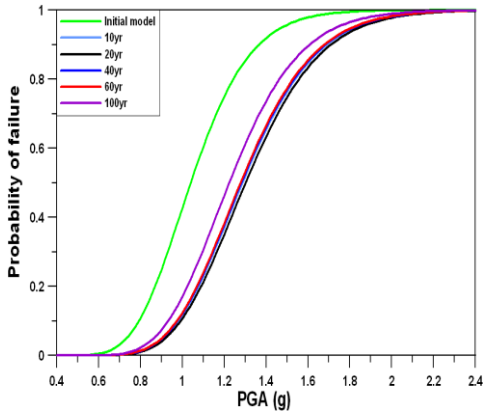


Fig. 9: Fragility curve of degraded shear wall

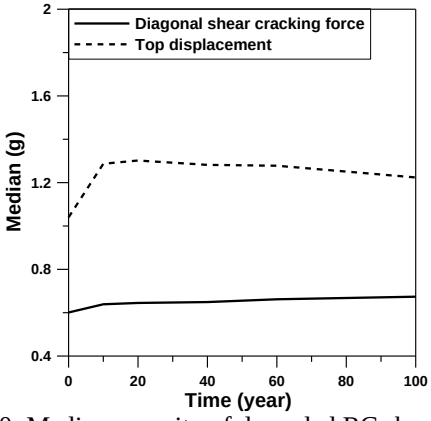


Fig. 10: Median capacity of degraded RC shear wall

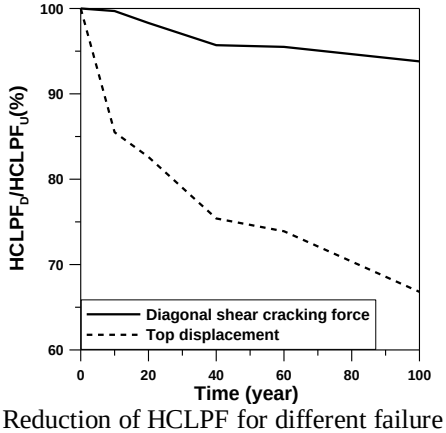


Fig. 11: Reduction of HCLPF for different failure criteria

CONCLUSION

The seismic capacity of a concrete shear wall with age-related degradation was investigated by finite element method. The natural frequency is lower for degraded shear wall than for undegraded shear wall because the stiffness of degraded shear wall is reduced due to steel corrosion and concrete spalling. Especially the dynamic property of RC shear wall with low steel ratio and thick core concrete is mainly affected by concrete hardening. Therefore concrete hardening effect should be considered in evaluating the seismic capacity of aged shear wall.

It was found that the variable reducing the seismic capacity of shear wall with age-related degradation is different according to the failure criteria. Thus it is recommended that dominant failure criteria and the seismic capacity of degraded structures are defined by the degradation level of materials.

According to the seismic fragility analysis of degraded shear wall, the median capacities of degraded shear wall at initiation of degradation was increased by concrete hardening, the median capacities over time was decreased with progression of degradation. Besides a tendency of seismic capacities for degraded shear wall can be changed by the degradation level. Therefore it can be concluded that the degradation level of materials and structure should be considered in realistically evaluating seismic fragility for the structures with a long service life and more data related to degradation should be collected in updating degradation model of material.

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