

FE MODEL UPDATING OF A BASE-ISOLATED NUCLEAR POWER PLANT CONSIDERING AGING EFFECTS OF ISOLATORS

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ABSTRACT

Aging is defined as a continuing time-dependent degradation of material due to service conditions such as normal operation and transient conditions. It is expected that over long periods of time, there is gradual changes in the properties of structural materials. Since nuclear power plants (NPPs) are generally designed for a life cycle of 60 years, their stabilities and working capacity may be lost due to aging effects. The paper presents a new approach to update the finite element (FE) model of NPPs. FE Model updating based on iterative neural networks is proposed as a suitable and reliable tool to estimate the aging effects of NPPs. The method is applied to update the isolator model of a base-isolated NPP in order to validate the studies. Experiments and FE analyses have been also carried out to identify the aging effects of the isolators on the structural behavior. Parameters of which aging can significantly affect the isolator characteristics are identified by performing the sensitivity analysis. The obtained results indicate a great potential of the presented method for practical applications. Static and dynamic structural performances of the NPP are also observed and compared before and after aging. It reveals the considerable effects of aging on the NPP.

INTRODUCTION

Aging effect of NPPs is considered as one of the vital factors for safety and reliability of plant. Requirements and guidance related to degradation of structures and passive components, which include containments, water-control structures, and masonry walls, are available in international code and standards (e.g., ACI 318). Over the years, many researchers and engineers of the nuclear energy area have been developed studies to investigate and comprehend the performance of base-isolated nuclear power plant (base-isolated NPP) caused and affected by aging. They consist of age-related degradation of not only plant structures but also systems and components.

The aging process and aging assessment of containment cooling systems in NPPs were studied in Lofaro *et al.* (1994). The result shows that aging is a concern and should be addressed in the design of NPPs. A methodology was developed in Naus (1996) through a structural aging (SAG) programme, which addressed safety-related concrete structures and longevity considerations in nuclear power plants. Ellingwood (1998) proposed a mathematical formalism of a probabilistic risk assessment (PRA) for identifying aging structural components whose may play a significant role in NPPs due to aging effects. An assessment of age-related degradation of NPP structures and passive components were introduced in Braverman (2000). These studies emphasized that aging and its effects need to be defined and calibrated to account for the performance of NPPs.

Seismic isolation or base isolation systems are commonly used to ensure safety and reliability against earthquake of infrastructures: bridges, buildings and other mission critical structures like nuclear power plants. Since the 1980s, several pressurized water reactor units have been isolated successfully. Research about aging therefore needs to be done to investigate the performance of base-isolated nuclear power plant (base-isolated NPP). Model updating based on iterative neural networks is proposed in this paper in order to study the aging effects of base-isolated NPPs.

The model updating procedure has a natural logical flow: collect data, choose a model set, and then pick the “best” model in this set. It is quite likely, though, that the model first obtained will not pass the model validation tests (Ljung 1999). Neural networks (NNs) as the techniques that seek to build an intelligent program using models to mimic the function of human brain (Lippmann 1987). Adaptive NNs for model updating of structures introduced in Chang *et al.* (2000) open loop in nature and are capable of providing a confidence measure of the accuracy only during the training phase. Finite element (FE) model updating based NNs (Ramuhalli *et al.* 2005) has been developed for estimating the system parameters as well as structural damage detection related application (Kerschen *et al.* 2006, Zapico *et al.* 2008, Rouss *et al.* 2009).

A simplified approach has been adopted for FE model updating based on iterative NNs of a base-isolated NPP using the virtual static deflections of the lead rubber bearing (LRB). Thermal aging test has been performed on the LRB for the verification of the approach. The observed results indicate a great potential of proposed method to update the base-isolated NPP model accounting for aging effects. The static and dynamic analyses obtained estimated and initial parameters are performed and compared. The observed results show the considerable effects of aging on the behavior of the structure.

FE MODEL AND SENSITIVITY ANALYSIS

A FE model (Lee *et al.*, 1999) was developed in Opensees Software (McKenna and Fenves 2001) for an actual base-isolated NPP (Fig. 1). The containment building was modeled with 65.8-meter height using 13 elastic beam column elements. The element lengths were selected in accordance with the key levels of the NPP. The mass was distributed as concentrated loads at two nodes of each element. Diaphragm constrains are applied to connect the elements. The mechanical properties of frame elements were modeled with section properties selected based on sensitivity analysis, which has been done in (Lee *et al.*, 1999). A LRB with specifications described in Table 1 is considered for isolation devices. A bilinear model (Naeim *et al.*, 1999) with a zero length element (Ryan *et al.*, 2005) was built for numerical analysis as shown in Fig. 2 (a). Initially, the load-displacement hysteresis loop illustrated Fig. 2 (b) is observed from the equivalent properties of LRB calculated from the concept presented in Naeim *et al.* (1999).

Table 1 Specifications of laminated rubber bearings

Steel diameter D_s (mm)	Hole diameter D_h (mm)	Steel diameter D (mm)	Rubber thickness t_i (mm)	Number of Layer n	Steel thickness t_s (mm)	1 st shape factor S_1	2 nd shape factor S_2	Shear modulus G
259	56	279	3	29	3	21.6	2.98	0.4

where

$$S_1 = \left(\frac{D_s - D_h}{4t_i} \right) \quad (1)$$

$$S_2 = \left(\frac{D_s}{nt_i} \right) \quad (2)$$

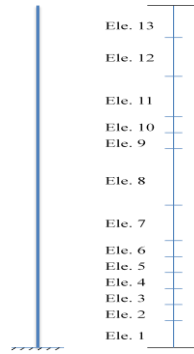
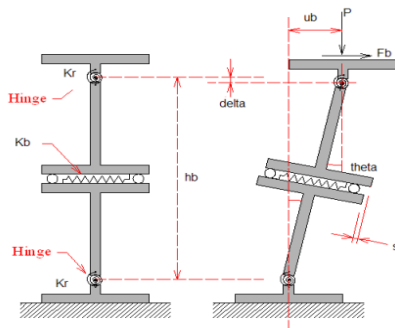
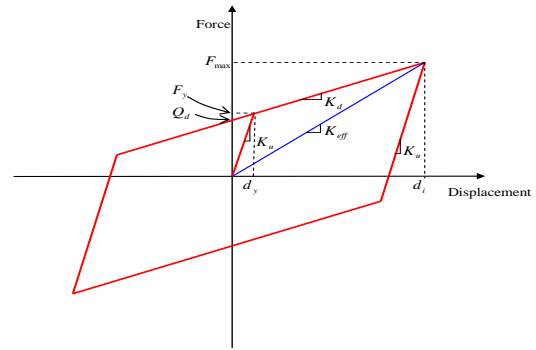


Fig. 1 Stick model of NPP containment building



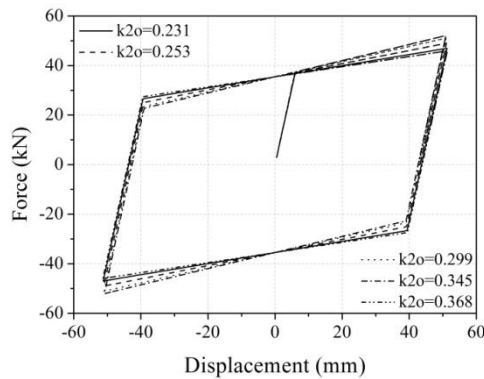
(a) Two-spring mechanical model



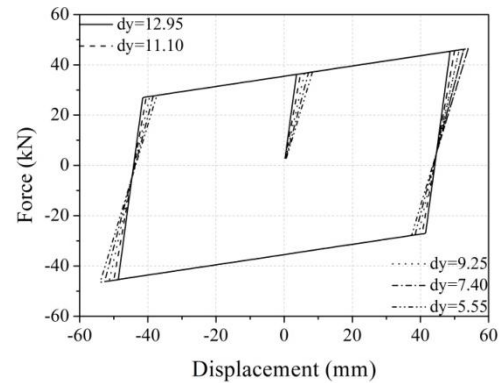
(b) Force-displacement hysteresis loop

Fig. 2 Isolation bearing model (Ryan *et al.*, 2005)

The design of LRB includes the post yield stiffness k_{2o} ; yield displacement d_y ; the ratios $PP_{cr} = P / P_{cr} = 1 / SF$ and $PP_o = P / P_o$. Sensitivity analysis was carried out to identify the parameters whose aging can significantly affect the performance of the LRB. Fig. 3 demonstrates variation of input parameters due to an equivalent lateral force cause the approximately the same displacement as design shear load and an axial load of 565 kN.



(a) Post-yield stiffness



(b) Yield displacement

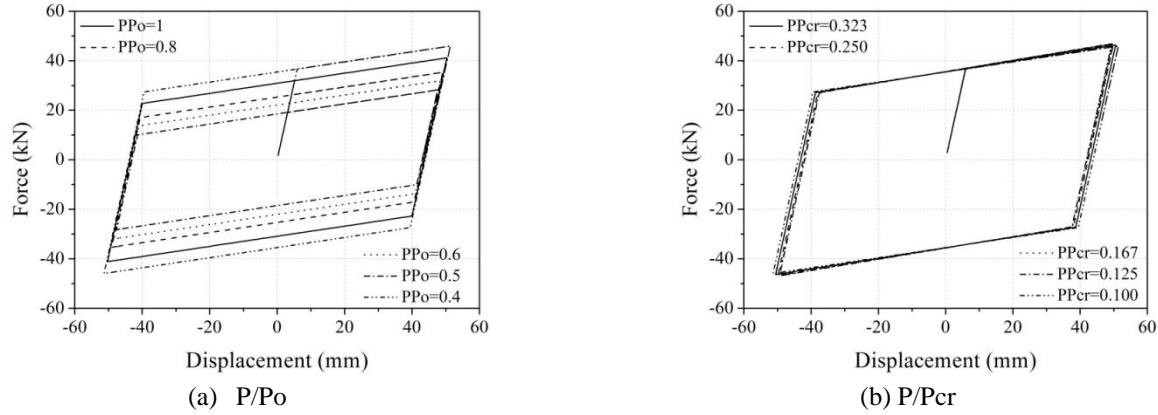


Fig. 3 Sensitivity Analysis

EXPERIMENT STUDY AND MODEL UPDATING

A LRB with the specimen geometry and specifications given in Table 1 and Fig. 4 was considered for experimental studies (Oh *et al.*, 2010). The bearing was a 275-millimeter diameter including a 10-millimeter thickness of outside surrounding rubber, 171-millimeter depth which consists of 29 layers with thickness of 3-millimeter laminated rubber and 3-millimeter steel plate.

The compressive-shear test was carried out to identify the variation of compressive and shear properties by comparing before and after thermal aging. The thermal aging experiments were performed in the accelerated exposure condition of 70°C for about 168 hours, which is equivalent to the estimated life of 60 years (ISO 11346). These thermally aged specimens were used for the compression-shear loading test in order to investigate the changes in the LRB parameters due to thermal aging. The vertical load of 565 kN was uniformly applied in order to maintain the designed in-plane pressure. The equivalent lateral load with a 5 Hz sinusoidal wave was employed to cause the approximately the same displacement as design shear load. The load was incurred and repeated 11 times. The obtained compression-shear loading curves for LRB before and after aging are shown in Fig. 5.

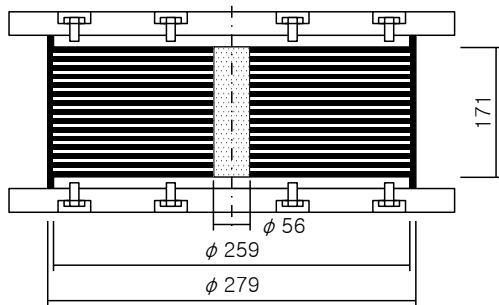


Fig. 4 Specimen geometry and specification

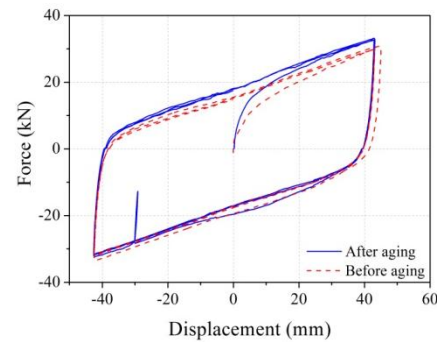


Fig. 5 Compression-shear loading curves

According to the sensitivity analysis represented by the objective function value (OFV), the ratio PP_o , k_{2o} and d_y are found to be largely affecting the LRB behavior while PP_{cr} , which is calculated according to the buckling load, is found to have small effect. It can therefore be concluded that the post yield stiffness (k_{2o}), yield displacement

(d_y), the ratio PP_o (between compressive and axial loads) are the key parameters in performance of LRB. Updating the model is therefore to estimate the representative stiffness, yield displacement and the ratio PP_o .

The optimization toolbox in MATLAB, which uses the objective function (Eq. 3) as the objective function, was employed to perform the model updating (an optimization process actually). The process of model updating method was a process of optimization as shown in Fig. 6.

$$OFV = \sum_{j=1}^6 \left(\left(\frac{d_j^{exp} - d_j^{num}}{d_j^{exp}} \right)^2 \right) \quad (3)$$

where OFV is the cost function, d_j^{exp} is the experimental displacement and d_j^{num} is the corresponding numerical displacement.

The optimization was converged at the end of about seven iterations. The value of the cost function is 1.636656 after the optimization process, which can conclude that the optimization process worked effectively. Fig. 7 shows the comparisons of the numerical compression-shear curve, after model updating, and the experimental curve. An agreement between the numerical and experimental results demonstrates that the presented method is effective and efficient to estimate the structural parameters considering aging effect.

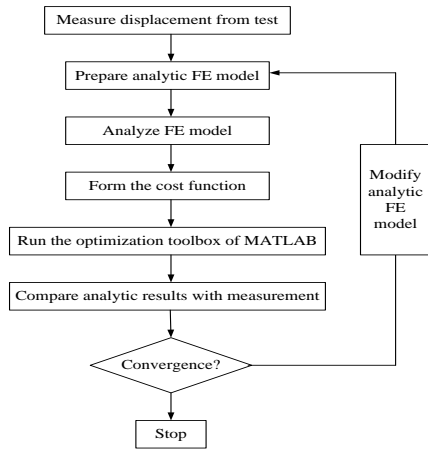


Fig. 6 Flowchart of the identification method

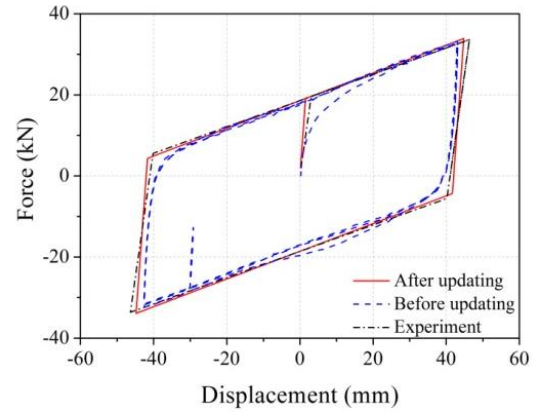


Fig. 7 Model updating

SEISMIC PERFORMANCE OF THE BASE-ISOLATED NPP

After model updating, dynamic and static behavior of the base-isolated NPP were performed in order to evaluate the aging effects on the structure. The observed results were compared before and after thermal aging of LRB. Table 2 shows the comparison of natural frequencies before and after aging. While Fig. 8 shows the comparison of seismic response under EI Centro earthquake.

Table 2 Effects of aging

Parameters	Input parameters			Natural frequencies		
	k_{2o} kN/mm	d mm	PP_o	1 st mode Hz	2 nd mode Hz	3 rd mode Hz

Before updating	0.3291	9.25	0.45	0.5965	9.9436	25.0978
After updating	0.3465	4.63	0.40	0.6030	9.9436	25.0978

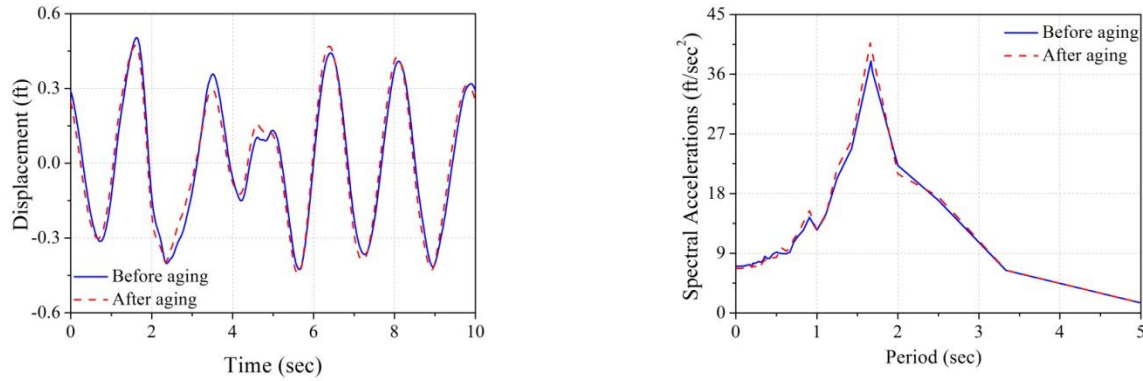


Fig. 8 Earthquake response

CONCLUSION

FE model updating based on neural networks is proposed in this paper in order to estimate the aging effects of the lead rubber bearings of the base-isolated nuclear power plants (base-isolated NPPs). The sensitivity analysis was performed in order to identify the parameters which may have critical effects on the LRB behavior in terms of aging. Numerical and experimental studies have been carried out in order to verify the effectiveness and accuracy of the presented method. The observed behaviors of the base-isolated NPP, both before and after model updating, were compared in order to indicate the aging effects on the structure. The main conclusions can be drawn from this study as follows:

1. Based on the sensitivity analysis presented by the objective function value (OFV), the ratio PP_o , k_{2o} and d_y are found to be largely affecting the LRB behavior while PP_{cr} , which is calculated according to the buckling load, is found to have a small effect. It can therefore be concluded that the post yield stiffness (k_{2o}), yield displacement (d_y), and the ratio PP_o (between compressive and axial loads) are the key parameters in the performance of the LRB.
2. It is observed that the post yield stiffness of the LRB is increased about 5% after optimization process, while observed value is about 3% from experiment. It indicates that FE model updating was successfully applied to estimate the effects of aging on the base-isolated NPP. It strengthens the suitability and efficiency of the proposed method in practice.
3. The static and dynamic behaviors of the base-isolated NPP were performed and compared before and after considering aging effects. The peak spectral acceleration at the top of the containment building was increased about 7.2 % due to aging. The displacement was also decreased remarkably. They show considerable effects of aging-related degradation on performances of the NPP. Aging effects are therefore required to be assessed and managed.

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APPENDIX

Q_d	: Characteristic strength
F_y	: Yield force
F_{max}	: Maximum force
k_d	: Post yield stiffness
k_u	: Elastic (unloading) stiffness
k_{eff}	: Effective stiffness
d_y	: Yield displacement
d_i	: Maximum bearing displacement
P	: Compressive load
P_o	: Axial load
P_{cr}	: Critical load
PP_{cr}	: Ratio between compressive load and critical load
SF	: Safety factor against buckling of LRB