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Operation-Adaptive Damage Assessment of Steam Turbines Using a Nonlinear Creep-Fatigue Interaction Model

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ABSTRACT For sustainable operation, power plants require accurate damage assessment of the steam turbines used for power generation. In the past few decades, steam turbine designs have considered only steady-state operation, without accounting for thermal cyclic loads. However, steam turbines designed for steady-state operation are often subjected to operation under cyclic and transient operation as well; this situation can cause both creep and fatigue damage. Creep and fatigue damage can interact with each other, thereby significantly impacting performance and leading to premature failure. Thus, this study proposes operation-adaptive damage assessment for steam turbines using a nonlinear creep-fatigue interaction model. The three-fold novel aspects of this study include methods to: 1) adaptively determine the hyper-parameters embedded in the nonlinear creep-fatigue interaction model depending on the operation mode (i.e., base-load and peak-load); 2) incorporate actual operation data acquired from field-deployed steam turbines; and 3) interpret the creep-fatigue damage interaction diagram with respect to the operation modes. It can be concluded from the results that the nonlinear creep and fatigue damage interaction is significantly affected by the operation mode as well as by the type of dominant damage mechanism.

INDEX TERMS Steam turbine, operation-adaptive damage assessment, cumulative damage rule, nonlinear creep-fatigue interaction model.

I. INTRODUCTION

Power generation companies have built supercritical steam turbine units with large capacity and high efficiency to reduce greenhouse gas (e.g., CO_2) emissions [1]. However, deterioration of steam turbine units can become accelerated as the operating time of the unit gets closer to reaching the end of its design life. Unplanned shutdown of a power plant due to accelerated degradation or unexpected failure can lead to considerable financial losses as well as potential widespread, even nationwide disaster [2]. Therefore, accurate damage assessment of critical components susceptible to failure is necessary for effective operation and maintenance of steam turbines [3]–[6].

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According to failure mode and effect analysis (FMEA) of steam turbines, a turbine's high-intermediate pressure (HIP) rotor is a critical component due to its high risk. Fig. 1 shows the schematic of a HIP rotor. It is known that 'creep' and 'low-cycle fatigue (LCF)' are major failure mechanisms of HIP rotors [7]–[9]. When the operating temperature is beyond 30% of the absolute melting temperature of metallic materials, creep damage can accumulate significantly. Creep damage can produce large deformations, stress relaxation, and crack initiation and growth [10]. On the other hand, during operation, fatigue damage can be caused by repeated stress beyond (low-cycle) or below (high-cycle) the yield strength of the material, especially at stress concentration configurations (e.g., holes, fillets, and notches). Fatigue damage results in localized plastic deformations at stress concentration configurations [11]. As shown in Fig. 1, creep damage, which

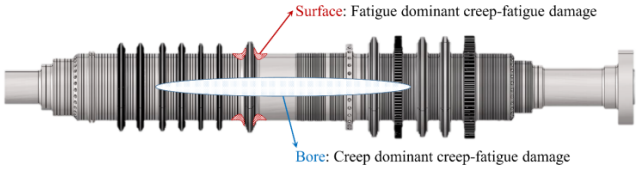

FIGURE 1. Schematic of a high-intermediate pressure (HIP) rotor and its damage mechanisms.

is dominant at the bore of the HIP rotor, is mainly caused by high temperature and centrifugal forces. Fatigue damage, which is dominant at the wheel root surface, is mainly caused by thermal cyclic loads due to frequent start-ups and shut-downs [12].

The operation modes of steam turbines can be categorized into the 'base-load mode' (steady-state operation) and the 'peak-load mode' (transient operation). In general, a base-load steam turbine in a coal-fired power plant runs continuously throughout a year. On the other hand, a peak-load steam turbine in a combined-cycle power plant runs only during the periods of peak demand for electricity; thereby, it experiences frequent start-ups and shut-downs [13]. This implies that creep damage is a primary concern for turbines under steady-state operation, while fatigue damage should be taken into consideration for turbines under transient operation. In the past few decades, when designing steam turbines, engineers have considered only steady-state operation, without accounting for thermal cyclic loads [14]. Recently, however, even steam turbines designed for steady-state operation are being asked to operate under cyclic and transient operation as well [15]; this situation can cause creep and fatigue damage in combination. Furthermore, increased operating temperatures are being proposed to improve the efficiency of combined-cycle power plants [1]; however, the durability of the main components against thermal fatigue must be ensured in these higher temperature settings [16], [17]. In other words, even though the dominant damage mechanisms might be different depending on the location (i.e., the bore and/or the wheel root surface), these mechanisms can interact with each other, thereby causing significant damage that can lead to premature failure.

Based on Miner's rule, Lee *et al.* proposed a new life prediction method that considers fatigue and creep damage [18]. Miner's linear damage accumulation method can be used for creep and fatigue damage assessment of steam turbines, however, it is only applicable when damages are independent of each other and do not overlap [19]. For the nonlinear creep-fatigue interaction model proposed by Rusin [20], all the hyper-parameters are assumed to be fixed under conservative assumptions; thereby, the operation modes cannot be considered. These limitations of existing methods drive research interest in developing a methodology for damage assessment of steam turbines that considers the 'nonlinear creep-fatigue interaction', while accounting for the operation mode.

Thus, this study aims to develop a methodology for operation-adaptive damage assessment of steam turbines using a nonlinear creep-fatigue interaction model. The three-fold novel aspects of this study include: (1) adaptive determination of the hyper-parameters embedded in the nonlinear creep-fatigue interaction model depending on the operation mode; (2) incorporation of actual operation data acquired from field-deployed steam turbines into damage assessment of the HIP rotor; and (3) interpretation of the creep-fatigue damage interaction diagram with respect to the operation modes.

The remainder of this paper is organized as follows. Section II presents an operation-adaptive nonlinear creep-fatigue interaction model for damage assessment of steam turbines. Section III describes the actual operation and damage data acquired from field-deployed steam turbines. The performance of the proposed operation-adaptive nonlinear creep-fatigue interaction model is evaluated in Section IV. Finally, Section V outlines the conclusions of this study.

II. OPERATION-ADAPTIVE NONLINEAR CREEP-FATIGUE INTERACTION MODEL

This section proposes a nonlinear creep-fatigue interaction model for damage assessment of steam turbines. After briefly reviewing creep and fatigue damage models in Sections II.A and B, respectively, Section II.C describes the nonlinear creep-fatigue interaction model.

A. CREEP DAMAGE MODEL

1) STEADY-STATE STRESS FOR CREEP DAMAGE CALCULATION

When the HIP rotor rotates at a high speed, centrifugal forces are induced. Creep damage is mainly caused by the high temperature and centrifugal forces at the bore of the HIP rotor. It is well known that simplified methods can be used to calculate the stress with acceptable predictive capability, by replacing the complicated shape of the rotor with a hollow cylinder [21]–[24]. For a hollow cylinder, the radial and circumferential stresses, denoted by σ_r and σ_θ, are calculated by equations (1) and (2), respectively, as:

$$\sigma_r = \frac{(3+\nu)\,\rho\omega^2}{8}\left(r_i^2 + r_o^2 - r^2 - \frac{r_i^2 r_o^2}{r^2}\right) \tag{1}$$

$$\sigma_\theta = \frac{(3+\nu)\,\rho\omega^2}{8}\left\{r_i^2 + r_o^2 - \left(\frac{1+3\nu}{3+\nu}\right)r^2 + \frac{r_i^2 r_o^2}{r^2}\right\} \tag{2}$$

where r_i and r_o denote the inner (at the bore) and outer (at the surface) boundaries; ρ denotes the mass density; ω denotes the angular speed; and ν denotes the Poisson's ratio. The radial stress is zero at both the bore and surface. This implies that creep damage of the HIP rotor is mainly attributed to the circumferential stress.

The circumferential stresses at the bore and surface can be obtained, respectively, as:

$$\sigma_{\text{bore}} = \sigma_c|_{r=r_i} = \frac{\rho\omega^2}{4}\left\{(3+\nu)r_o^2 + (1-\nu)r_i^2\right\} \tag{3}$$

$$\sigma_{\text{surface}} = \sigma_c|_{r=r_o} = \frac{\rho\omega^2}{4}\left\{(3+\nu)r_i^2 + (1-\nu)r_o^2\right\} \quad (4)$$

Since the circumferential stress at the bore is larger than that at the surface, creep damage at the bore is more serious. The circumferential stresses obtained using equations (3) and (4) are used to estimate creep damage at the bore and surface, respectively, using the Larson-Miller parameter.

2) CREEP DAMAGE CALCULATION

One of the most commonly used creep damage models is the Larson-Miller parameter, denoted by P, [21] as:

$$P = T(C + \log t_r) \quad (5)$$

where T denotes the temperature; t_r denotes the creep failure time. For 1Cr1Mo1/4V rotor steels, a plot of stress and Larson-Miller Parameter resulted in a single plot, within limits of scatter, regardless of the time-temperature combination employed to derive the parameter. C is a material specific constant, which is often approximated as 20 [22]. Since the creep strain is a temperature-related value, the Larson-Miller parameter considers the temperature T. Remember that the mean steam temperature (about 540 °C) during steady-state operation is used to calculate the creep damage. The Larson-Miller parameter can be used to estimate the creep failure time at a given temperature and stress level. The creep failure time can be estimated by rearranging equation (5) as:

$$t_r = 10^{\frac{P}{T}-20} \quad (6)$$

If the creep strain varies with the stress, the creep stress can be calculated by using the creep strain and tensile strength relations at room temperature. The creep life is then obtained from the creep stress. Steady-state stress is used in the case of creep damage.

After calculating the creep failure time t_r, the creep damage rate, denoted by D_{creep} can be obtained by using the operating time t as:

$$D_{\text{creep}} = \frac{t}{t_r} \quad (7)$$

B. FATIGUE DAMAGE MODEL

1) TRANSIENT PEAK STRAIN FOR FATIGUE DAMAGE CALCULATION

Fatigue damage, which is dominant at the wheel root surface, is mainly caused by thermal cyclic loads that arise due to frequent start-ups and shut-downs. Therefore, thermal strain under transient operation needs to be calculated to assess fatigue damage of the HIP rotor, while accounting for stress concentration factors at the critical regions [22].

During start-up or shut-down, the thermal stress or strain of the steam turbine can be calculated by finite element analysis. However, it is difficult to incorporate these complex turbine rotor components into the finite element code to simulate stress, strain, and temperature histories. To reduce the calculation costs, an approximation method was proposed to assess fatigue damage of the turbine rotor [9]. The thermal strains corresponding to the transient peak-load operation mode, as well as the stress and strain concentration factors at the critical regions, need to be calculated. Based on the approximate relationship between the thermal strain, geometric information, and material properties, the thermal strains at the surface and bore can be calculated. The dimensionless nominal thermal stress, denoted by $C_{\max}$, on the surface and bore of the HIP rotors can be expressed with the actual maximum thermal stress $\sigma_{\max}$ [22], [23] as:

$$C_{\max} = -\frac{(1-\nu)\sigma_{\max}}{E\alpha_{\text{T}}\Delta T} \quad (8)$$

where E denotes the Young's modulus; α_{T} denotes a thermal expansion coefficient (12.5 W/m°C at 500 °C); ΔT denotes the maximum temperature difference; and $\sigma_{\max}$ denotes the actual maximum thermal stress. The total (elastic-plastic) strain can be obtained by multiplying the dimensionless nominal thermal stress by the plastic strain concentration factor, denoted by K_ε, as:

$$\Delta\varepsilon_t = K_\varepsilon C_{\max} \quad (9)$$

The plastic strain concentration factor is a function of the thermal stress concentration factor; the detailed procedure used to calculate the plastic strain concentration factor can be found in [24]. The transient peak strain obtained in equation (9) is used to calculate fatigue damage by finding the Coffin-Manson relationship.

2) FATIGUE DAMAGE CALCULATION

The relationship between the LCF life, denoted by N_t, and the total strain, denoted by $\Delta\varepsilon_t$, is proposed by Coffin [25], which is expressed as:

$$\Delta\varepsilon_t = \varepsilon_e + \varepsilon_p = Q_1 N_t^{h_e} + Q_2 N_t^{h_p} \quad (10)$$

where ε_e and ε_p are the elastic and plastic strains, respectively. And Q and h are parameters determined by materials for the elastic and plastic strain. After calculating the LCF life N_t, the fatigue damage rate, denoted by D_{fatigue} can be obtained by using the number of cycles N as:

$$D_{\text{fatigue}} = \frac{N}{N_t} \quad (11)$$

Since the LCF life is determined by using the total strain $\Delta\varepsilon_t$ under transient operation, it is necessary to consider the cold, warm, and hot start-up modes individually to calculate the LCF life. In other words, the dimensionless nominal thermal stress in equation (8) should be calculated according to each start-up mode; then, the corresponding actual strain and fatigue damage rate are determined. Finally, the total or cumulative fatigue damage rate can be obtained by summating the fatigue damage rates calculated for each start-up mode.

C. CREEP-FATIGUE INTERACTION MODEL

Due to its simplicity, Miner's linear damage accumulation method is a popular approach for creep and fatigue damage

assessment. Creep and fatigue damage can be evaluated by a linear summation rule as:

$$D = D_{\text{creep}} + D_{\text{fatigue}} \tag{12}$$

The linear cumulative damage rule is generally used to predict the lifetime of power plant components such as rotors, casings, and valves [26]–[29]; however, this approach is only applicable when the types of damage are independent of each other and do not overlap [19]. To overcome this limitation of linear damage models, this study implements a nonlinear continuum damage mechanics model to assess creep-fatigue damage of the HIP rotor [30]. The nonlinear creep-fatigue interaction model [20] for damage assessment can be expressed as:

$$D = aD_{\text{creep}} + bD_{\text{fatigue}} + \alpha \left(D_{\text{creep}} \cdot D_{\text{fatigue}}\right)^{\beta} \tag{13}$$

where a, b, α and β are the hyper-parameters related to creep-fatigue interactions. In the published literature [20], a and b are assumed to be fixed to 1 to have equal weights for creep and fatigue damages in linear creep-fatigue interaction models. The hyper-parameter α and β that determine the nonlinear interaction effects are assumed to be fixed to certain values under conservative assumptions; thereby, actual operation conditions cannot be considered. In this study, however, it is worth pointing out that the hyper-parameters α and β in equation (13) are determined adaptively, according to the operation mode (i.e., the base-load and peak-load). Thus, our approach enables operation-adaptive damage assessment of steam turbines that considers nonlinear creep-fatigue interactions. This feature is one novelty of our approach.

III. DESCRIPTION OF ACTUAL OPERATION AND DAMAGE DATA

This section describes the actual operation and damage data. To obtain the operating time t in equation (7) and the number of cycles N in equation (11), this study incorporates actual operation data acquired from field-deployed, large-scale steam turbines. Section III.A describes the actual operation data, while Section III.B describes the creep and fatigue damage data.

A. ACTUAL OPERATION DATA

Actual operation data contain a variety of information that cannot be easily collected in a testbed in a laboratory. Fig. 2 describes the typical real-time database (RTDB) obtained from a supercritical steam turbine, including the main steam temperature, the 1st-stage temperature, the power output, and the turbine speed under a typical in-service loading condition of a power plant. Here, the increasing rate of the main steam temperature is incorporated into calculating the fatigue damage during the start-up stage (transient), while the mean steam temperature (about 540 °C) during steady-state operation is used to calculate the creep damage. The start-up stage can be classified into cold, warm, and hot start-up modes. Furthermore, it is necessary to consider each start-up mode to calculate the LCF life; the stress is calculated in accordance with the start-up mode and fatigue damage is determined correspondingly. Then, the total fatigue damage can be obtained by accumulating the fatigue damage rate for each start-up mode.

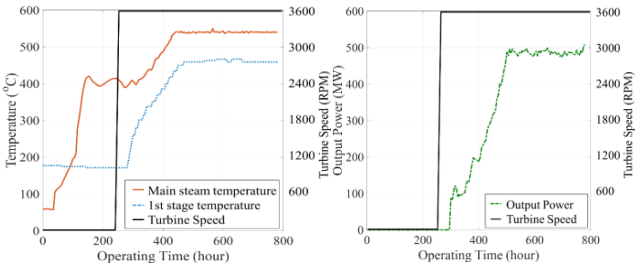

FIGURE 2. Typical real-time database (RTDB) obtained from a supercritical steam turbine: (a) main steam temperature, 1st-stage temperature, and (b) output power.

TABLE 1. Operation history of steam turbine.

Type	Coal-fired power plant				Combined power plant	
Mode	Base-load				Peak-load	
Steam turbine unit	B1	B2	B3	B4	P1	P2
Output power (MW)	500	500	500	500	182	200
Equivalent operating time (hour)	74,327	95,097	115,671	157,995	201,671	213,175
Number of cycles	39	58	122	134	556	582

Table 1 summarizes the operation histories of coal-fired and combined power plants. Base-load steam turbines in a coal power plant run continuously throughout a year, while peak-load steam turbines in a combined-cycle power plant run only during the periods of peak demand for electricity. This implies that steam turbine units operate with different fuel sources and power outputs, as shown in Table 1. To the best of the authors' knowledge, this is the first time a model has been devised that incorporates real operation data into creep-fatigue damage interaction assessment of steam turbines.

B. CREEP AND FATIGUE DAMAGE DATA

In this study, a test dataset from NIMS (the National Institute on Materials Science, Japan) was used for 1Cr1Mo1/4V rotor steel [31], [32]. It is well known that a laboratory specimen of 1Cr1Mo1/4V rotor steel at 565 °C is suitable to evaluate creep-fatigue damage of HIP rotors [33]. In the case of 1Cr1Mo1/4V rotor steel, the coarsening of carbides and the annihilation and rearrangement of dislocation tend to occur under long-term, high temperature operation, thereby resulting in softening.

Figure 3 (a) shows the creep rupture test data of a 1CrMo1/4V rotor steel specimen. These data contain

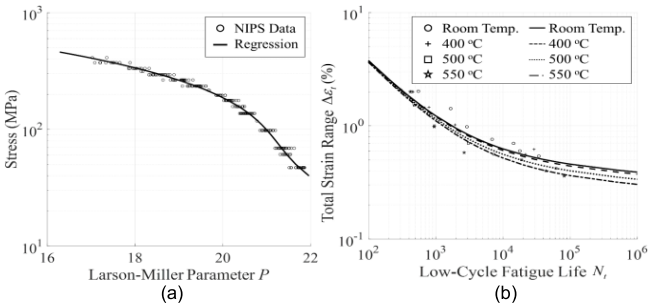

FIGURE 3. (a) Creep rupture test data (b) Low cycle fatigue test data of 1CrMo1/4V rotor steel.

information on the functional relation between the Larson-Miller parameter and stress; here, the stress and P relationship is normally described as a convex nonlinear curve. For a simple calculation, this functional relation can be expressed by using a multiple regression method as:

$$P(\sigma) \cong A_1 + A_2(\log\sigma) + A_3(\log\sigma)^2 + A_4(\log\sigma)^3 \quad (14)$$

where $A_1 = 11.483$, $A_2 = -24.204$, $A_3 = -21.394$, and $A_4 = -6.895$ for a 1Cr1Mo1/4V rotor steel. Note that the Larson-Miller parameter is expressed as a function of the stress. Then, using equation (6), the Larson-Miller parameter can be used to calculate the creep failure time. Fig. 3 (b) shows the LCF fatigue test data of a 1CrMo1/4V rotor steel at different temperatures; this contains information on the functional relation between the LCF life and total strain range. Here, both are described in a logarithmic scale. In equation (10), $Q_1 = 0.62994$, $Q_2 = 22$, $h_e = -0.04572$, and $h_p = -0.59$ for fatigue damage calculation of a 1Cr1Mo1/4V rotor steel. It can be observed from Fig. 4 that the LCF lives decrease as the temperature increases.

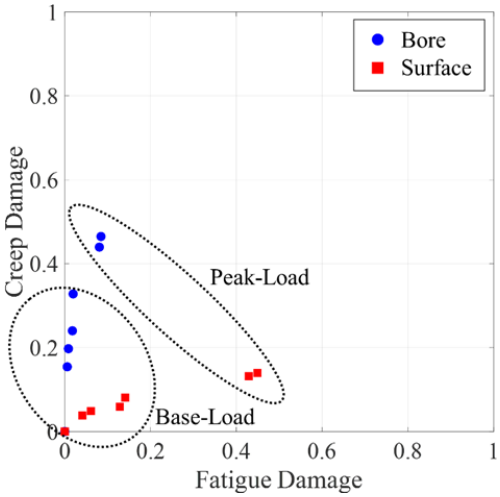

FIGURE 4. The trend of total damage with respect to the equivalent operating time.

Distribution types should be properly determined to statistically characterize the creep and fatigue damage data. Based on the chi-square (χ^2), Komogorov-Smirnov (K-S), and Anderson goodness-of-fit (GoF) tests, lognormal and Weibull distributions were selected to statistically characterize the creep and fatigue damage data of 1Cr1Mo1/4V rotor steel, respectively, as shown in Table 2. The statistical parameters were estimated using maximum likelihood estimation (MLE).

TABLE 2. The result of goodness-of-fit tests for the creep and fatigue data.

Damage mechanisms	Distribution type	p-value		
		Chi-Square	Kolmogorov-Smirnov	Anderson
Creep	Normal	0.1323	0.2643	0.1416
	Lognormal	0.4508	0.7663	0.9341
	Weibull	0.0699	0.2169	0.0809
Fatigue	Normal	0.4725	0.6871	0.6303
	Lognormal	0.2032	0.7219	0.9198
	Weibull	0.4648	0.8911	0.9432

IV. PERFORMANCE EVALUATOIN OF THE PROPOSED OPERATION-ADAPTIVE NONLINEAR CREEP-FATIGUE DAMAGE INTERACTION MODEL

This section is devoted to evaluating the performance of the proposed operation-adaptive nonlinear creep-fatigue damage interaction model. Section IV.A explains the estimation of the hyper parameters. After validating the proposed operation-adaptive creep-fatigue damage interaction model in Section IV.B, the effects of the operation mode on the nonlinear creep-fatigue interaction are discussed in Section IV.C.

A. ESTIMATION OF HYPER-PARAMETERS

In this study, the trust-region reflective least square method is implemented to estimate the unknown hyper-parameters α and β embedded in the nonlinear creep-fatigue interaction model in equation (13). The hyper-parameters are estimated in accordance with the operation mode (base-load and peak-load). The mean values of the estimated hyper-parameters are summarized in Table 3. Here, in order to investigate the nonlinear effects of the creep-fatigue damage interactions, a and b in equation (13) are set to be 1 under same conditions as [11]. The accuracy of the nonlinear creep-fatigue interaction model is evaluated by comparing the true data with the statistical distributions calculated by the damage model.

B. MODEL VALIDATION

The results obtained by the operation-adaptive creep-fatigue damage interaction model were compared with those derived from the two existing models (i.e., the linear model and the nonlinear interaction model with fixed hyper-parameters). In the comparison, material test data for turbine rotor steel during 157,995 hours and 213,175 hours of operation were used for the base-load (B4 Unit) and peak-load (P2 Unit) modes, respectively. The hyper-parameters embedded in the

TABLE 3. Mean values of the estimated interaction parameters.

Mode	Location (Dominant damage)	True damage	Linear model		Nonlinear model with the fixed hyper-parameters		Proposed nonlinear model	
			Est.	Error	Est.	Error	Est.	Error
Base-load	Surface (Fatigue)	0.6080	0.2217	63.6 %	0.3016	50.4 %	0.6218	11.8 %
	Bore (Creep)		0.3368	74.2 %	0.3769	74.2 %	0.6098	0.5 %
Peak-load	Surface (Fatigue)	0.8193	0.5886	28.2 %	0.7763	5.2 %	0.8209	0.2 %
	Bore (Creep)		0.5492	33.0 %	0.6977	14.8 %	0.8193	0.0 %

proposed nonlinear interaction model in equation (13) were estimated using nonlinear regression analysis.

TABLE 4. The results of damage assessment for each operation mode.

Mode	Location	Damage	Hyper-parameters		
			α	β	RMS
Base-load	Surface	Fatigue	1.213	0.279	0.974
	Bore	Creep	2.038	0.356	0.994
Peak-load	Surface	Fatigue	0.431	0.223	0.995
	Bore	Creep	0.312	0.044	0.994

Table 4 summarizes the results of damage assessment for the base-load and peak-load operation modes. The results of each damage rate according to the operation mode were compared with the true damage rates obtained from previous studies [7]. Note that creep damage is dominant at the bore of the HIP rotor, while fatigue damage is dominant at the surface. For the base-load mode, the creep and fatigue damage at the surface estimated using the existing linear model and nonlinear interaction model are 0.2217 and 0.3016, respectively; the errors are 63.6 % and 50.4 %, respectively. For the peak-load mode, the estimated results are in a good agreement with the observed results, compared to the base-load operation mode. On the other hand, it is worth pointing out that the mean values calculated by the proposed operation-adaptive creep-fatigue damage interaction model are in a very good agreement with the observed results regardless of the operation mode and the dominant damage mechanism. Thus, it can be concluded from the results that the proposed nonlinear creep-fatigue damage interaction model outperforms the existing models.

C. THE EFFECT OF THE OPERATION MODE ON THE NONLINEAR CREEP-INTERACTION

Figure 4 shows the trends of the mean values of total damage with respect to the equivalent operating time; the blue circle and red rectangular dots indicate the mean values of total damage at the bore and surface, respectively. The mean values of creep and fatigue damage are calculated using equations (7) and (11), respectively. Each dot corresponds to the equivalent operating time in Table 1, in chronological order. At the beginning of operation, there is almost no damage; however, damage gradually increases with the equivalent operating time. As can be seen in Fig. 4, even though creep and fatigue damage occur simultaneously and interact each other, creep damage is relatively larger than fatigue damage at the bore over the entire equivalent operating time. Fatigue damage is relatively larger than creep damage at the surface over the entire equivalent operating time. As the damage rate tends to increase over time, in addition, the fatigue damage increase rate on the surface of turbine decreases as the operating time elapses. On the other hand, the creep damage increase rate at the bore which is the main damage mechanism is seen to increase over the equivalent operating time. This underscores the necessity of operation-adaptive damage assessment of steam turbines.

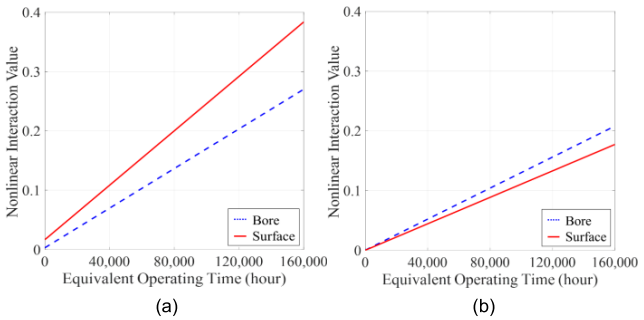

FIGURE 5. Nonlinear interaction value with the equivalent operating time: (a) base-load and (b) peak-load.

Figure 5 shows the nonlinear interaction value of creep and fatigue damage, which is calculated by the third term on the right-hand side in equation (13), with the equivalent operating time. The red solid line indicates the nonlinear interaction value at the surface, where fatigue damage is dominant; the blue dotted line represents the nonlinear interaction value at the bore, where creep damage is significant. Please note that the hyper-parameters in equation (13) are calculated adaptively according to the operation mode. Overall, the nonlinear interaction value under base-load operation (Fig. 5 (a)) is larger than that under peak-load operation (Fig. 5 (b)). It is worth pointing out that the nonlinear interaction value at the surface is larger than that at the bore under base-load operation, while it is smaller under peak-load operation. Thus, it can be concluded that the operation mode significantly affects the nonlinear creep and fatigue damage interaction. Fig. 5 ascertains the importance of considering the operation mode for accurate damage assessment of steam turbines.

Figure 6 shows the creep and fatigue damage interaction diagram under the base-load and peak-load modes. The linear model (black solid line) is only applicable when the damages are independent of each other. Furthermore, the nonlinear creep-fatigue damage interaction model with fixed hyper-parameters (gray dashed line) cannot account for the effect of the operation mode on the creep and fatigue damage interaction diagram. However, it is worth pointing out that the proposed nonlinear creep-fatigue damage interaction model

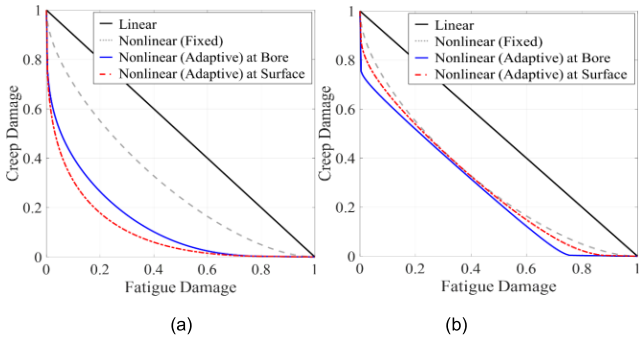

FIGURE 6. Creep and fatigue damage interaction diagram under: (a) base-load operation and (b) peak-load operation.

with the adaptive hyper-parameters clearly shows that the creep and fatigue damage interaction diagram is affected significantly by the operation mode as well as the type of dominant damage mechanism. In general, creep damage, which is dominant at the bore, is a primary concern under the base-load operation mode; creep damage is mainly caused by high temperature and centrifugal forces. Fatigue damage, which is dominant at the surface, should be taken into consideration under the peak-load operation mode; fatigue damage is mainly caused by thermal cyclic loads that are due to frequent start-ups and shut-downs. If a steam turbine designed for the base-load mode operates under the peak-load mode, the reduction of its lifetime is accelerated due to the nonlinear interaction at the bore, where fatigue damage is a concern.

Please note again that the hyper-parameters embedded in the proposed nonlinear creep-fatigue damage interaction model were determined adaptively in accordance with the operation mode (base-load or peak-load). In Fig. 6, the hyper-parameters for the base-load and peak-load modes were estimated using the operating history of steam turbine units of coal fired power plants (B1 to B4) and combined power plants (P1 and P2), respectively. The equivalent operating times of units B1 to B4 are shorter than those of units P1 and P2. This implies that the creep and fatigue damage interaction diagram under base-load operation is valid below a damage level of 0.4∼0.6, while the diagram under peak-load operation is valid above that level.

V. CONCLUSION

Base-load steam turbines in a coal-fired power plant run continuously throughout a year, while peak-load steam turbines in a combined-cycle power plant run only during periods of peak demand for electricity. However, steam turbines designed for a base-load (steady-state) operation mode are often subjected to operation under a peak-load (cyclic and transient) operation mode as well. In other words, even though dominant damage mechanisms might be different depending on the location (i.e., the bore and the wheel root surface), these damage types can interact with each other, thereby causing significant damage that leads to premature failure. Thus, this study proposed a methodology for operation-adaptive damage assessment of steam turbines using a nonlinear creep-fatigue interaction model. The three-fold novel aspects of this study include: 1) adaptive determination of the hyper-parameters embedded in the nonlinear creep-fatigue interaction model depending on the operation mode; 2) incorporation of actual operation data acquired from field-deployed steam turbines into damage assessment of the HIP rotor; and 3) interpretation of the creep-fatigue damage interaction diagram with respect to the operation mode.

Our research shows that the rate of increase of fatigue damage is slightly higher under peak-load operation (transient), while the rate of increase of creep damage is slightly higher under base-load operation. Furthermore, the nonlinear interaction value at the surface is larger than that at the bore under base-load operation, while the nonlinear interaction value is smaller under peak-load operation. From the results obtained by the proposed operation-adaptive, creep-fatigue damage interaction model, we identified three key findings: 1) for accurate damage assessment of steam turbines in which creep and fatigue damage occur simultaneously, their nonlinear interaction effects have to be taken into consideration; 2) the creep and fatigue damage interaction diagram is significantly affected by the operation mode as well as by the type of dominant damage mechanism; and 3) if a steam turbine designed for the base-load mode operates under the peak-load mode, its lifetime is reduced at an accelerated rate due to the nonlinear interaction at the bore, where fatigue damage occurs. Thus, it can be concluded that the proposed operation-adaptive, creep-fatigue damage interaction model can contribute to accurate damage assessment of steam turbines. Since accurate life prediction of aging steam turbines is becoming more important as the globally friendly energy policy requires operating a steam turbine designed as a base load at peak load, the results of this study can be useful for actual plant operation and maintenance.

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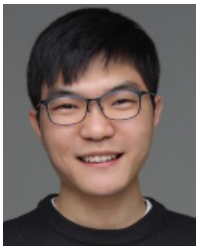

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