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THE RECENT DEVELOPMENT OF THE PROBABILISTIC LINEAR MATCHING METHOD FRAMEWORK FOR RELIABILITY-BASED ASSESSMENT OF NUCLEAR COMPONENT

Haofeng Chen[1,2], Xiaoxiao Wang[3], Weiling Luan[1]

[1] Professor, School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai 200237, China (Haofeng.chen@ecust.edu.cn)
[2] Professor, Department of Mechanical & Aerospace Engineering, University of Strathclyde, James Weir Building, 75 Montrose Street, Glasgow G1 1XJ, UK
[3] Research Scientist, School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai 200237, China

ABSTRACT

The probabilistic Linear Matching Method (pLMM) framework is a physics-based reliability assessment program for high-temperature structures, covering shakedown, ratcheting, Low Cycle Fatigue (LCF) and creep-fatigue behaviours. Under pLMM, the failure information at the physical level is provided by the LMM procedures, and the data-driven model is constructed by artificial intelligence technology. To facilitate the computational efficiency of probabilistic analysis for nuclear components, the direct method-based artificial neural network is also proposed with high-fidelity numerical prediction capability. In this study, the recent development of the pLMM is introduced, where the probabilistic resistance boundary, distributions of damage and life, and reliability-based safety factor (RBSF) is elaborated, with the applications in nuclear engineering demonstrated.

1. INTRODUCTION

The nuclear energy industry depends on various high-temperature structures to achieve efficient energy conversion and utilization, which are frequently subjected to significant thermal-mechanical loading conditions, resulting in several high-temperature-related failure patterns due to low cycle fatigue (LCF) and creep-fatigue behaviour. To deal with the structural integrity assessment requirements of high-temperature components in nuclear infrastructures, the engineering design standards and codes provide applicable methodologies based on either simplified calculations or conservative evaluation schemes, such as the ASME BPVC Section III NH [1], EN-13445 [2] and RCC-MRx [3]. Aiming at performing the feasible creep-fatigue assessment, the ASME CodeCase 2843-2 [4] gives out three different analysis approaches to accommodate the strain limit evaluation for the cases with significant creep effects presumed, including the elastic analysis, simplified inelastic analysis and detailed inelastic analysis. Specifically, when operating in the creep regime, ASME CodeCase 2605-3 [5] and API 579-1/ASME FFS-1 [6] deliver a detailed numerical procedure of creep-fatigue interaction evaluation for pressurized components, with the Omega model-based constitutive relationship playing a key role in modelling the creep damage and creep strain. As a result, the creep-fatigue life is calculated according to the design fatigue life curves that are calibrated by the pure creep life and the cyclic equivalent stress amplitude [7].

The UK R5 procedure "Volume 2/3 Creep-Fatigue Crack Initiation Procedure for Crack-Free Structures" [8] adopts a more comprehensive assessment strategy to investigate the potential structural failure mechanisms under high-temperature conditions. Within this assessment framework, the structural saturated response of defect-free components at sensitive locations is calculated by means of the elastic follow-up factor, and, to account for the stress relaxation process arising out of the creep dwell effect, the associated creep damage is then predicted by the Ductility Exhaustion (DE) method [8]. In order to derive the necessary results during the evaluation process, Ponter and Chen [9, 10] proposed the Linear Matching Method (LMM) framework, which is a series of efficient direct methods relying on adjusting the modulus parameters at the material integral points. The core step of these approaches is to establish the proper linear matching conditions, and, hence, the nonlinear behaviour is able to be simulated by solving the iteration form of certain linear equations [11]. So far, the LMM framework has been inserted into the ABAQUS platform with the UMAT user subroutine and plugin function, covering the limit load analysis [12], shakedown analysis [13], ratcheting analysis [9], LCF analysis [14], creep rupture analysis [10] and creep-fatigue analysis [15] as displayed in Figure 1.

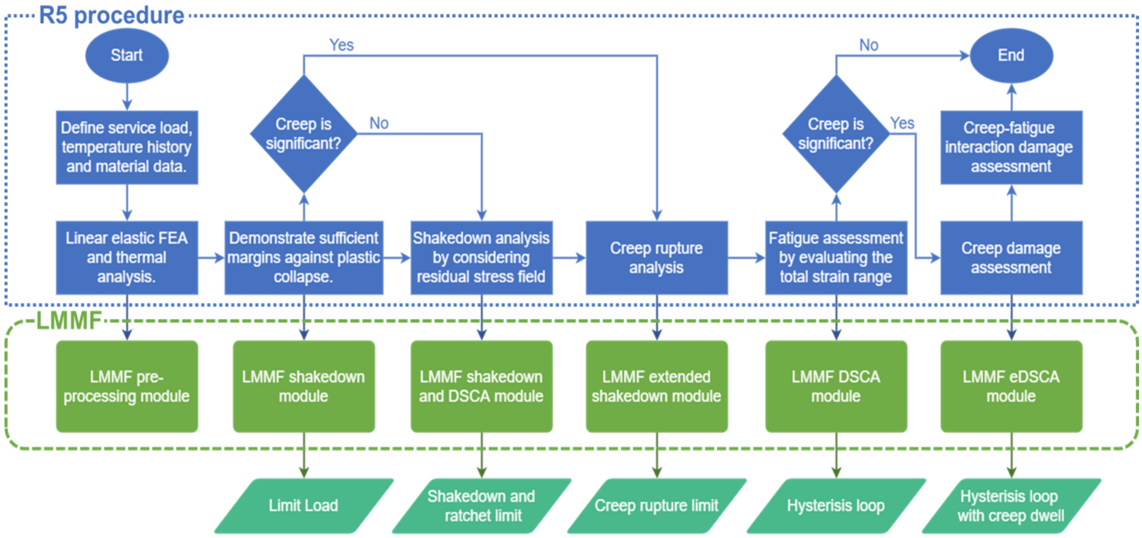

Figure 1. The analysis types of the LMM framework to support the structural integrity assessment procedure of R5.

Nowadays, extreme operation parameters are gradually being applied to the design scheme of the nuclear industry to alleviate the energy crisis all over the world, whereas, this poses a big challenge for the design and risk management of critical infrastructures. In addition, with the complexity of the working conditions rising, there are more uncertainties involved in the design considerations. Pessimistically, current design and assessment approaches mainly focus on deterministic method-based calculations, which, frequently, have to be dependent on pessimistic margin values and redundant safety factors to cope with the uncertain factors. Inevitably, this leads to the conservative analysis results and the underestimation of structural resistance against loading conditions under high-temperature environments. The recently issued R5 Volume 2/3 Appendix A15 “Advice on probabilistic assessments” [16] demonstrates complementary guidance regarding probabilistic analysis based on the previous deterministic analysis framework. The new technical instruction is intended to fully incorporate the fundamental uncertainties of design and operation conditions into the process of structural integrity assessment, including the material properties, geometry dimensions and loading conditions, and the structural failure probability concerning creep-fatigue crack initiation is able to be predicted by an adequate number of repeated Monte Carlo Simulations (MCS).

To make the probabilistic creep-fatigue analysis more applicable in the high-temperature industry, following the guidance of R5 Volume 2/3 Appendix A15, the probabilistic Linear Matching Method (pLMM) framework was proposed by Wang et al [17], which integrates the advantages of both direct method and probabilistic analysis approaches, forming a probabilistic structural integrity assessment framework [18], with an outstanding balance between the computational efficiency and accuracy. Under the developed pLMM framework, the physics-based LMM programs act as the predictor to generate the structural limit resistance against certain failure mechanisms, and the data-driven technology is also adopted to derive the high-fidelity surrogate model of structural responses subjected to high-temperature conditions. Furthermore, by providing the failure risk, the reliability-based assessment diagrams are built for different reliability requirements, which pave the way for replacing the conventional safety factor based on arbitrary experience and expert knowledge. In this study, the theoretical foundation of the pLMM is illustrated systematically, and, then, the recent research applications in nuclear engineering by means of the proposed pLMM methodology are introduced and discussed in depth.

2. THE OVERALL STRUCTURE OF THE PROBABILISTIC LINEAR MATCHING METHOD FRAMEWORK

The pLMM framework [19] includes three different levels to address the probabilistic structural integrity assessment. The first level is to capture failure mechanisms in terms of high-temperature circumstances with deterministic LMM programs, and, at the second level, the surrogate model is constructed by the artificial intelligence technique, aiming at implicitly expressing the complicated nonlinear relationship between the input and output, without depending on the detailed FEA program. The final level is to perform the probabilistic analysis which is able to provide statistical information on the key responses and the failure risk.

2.1 Physics-based Modelling Of Structural High-temperature Responses By Deterministic LMM Algorithms

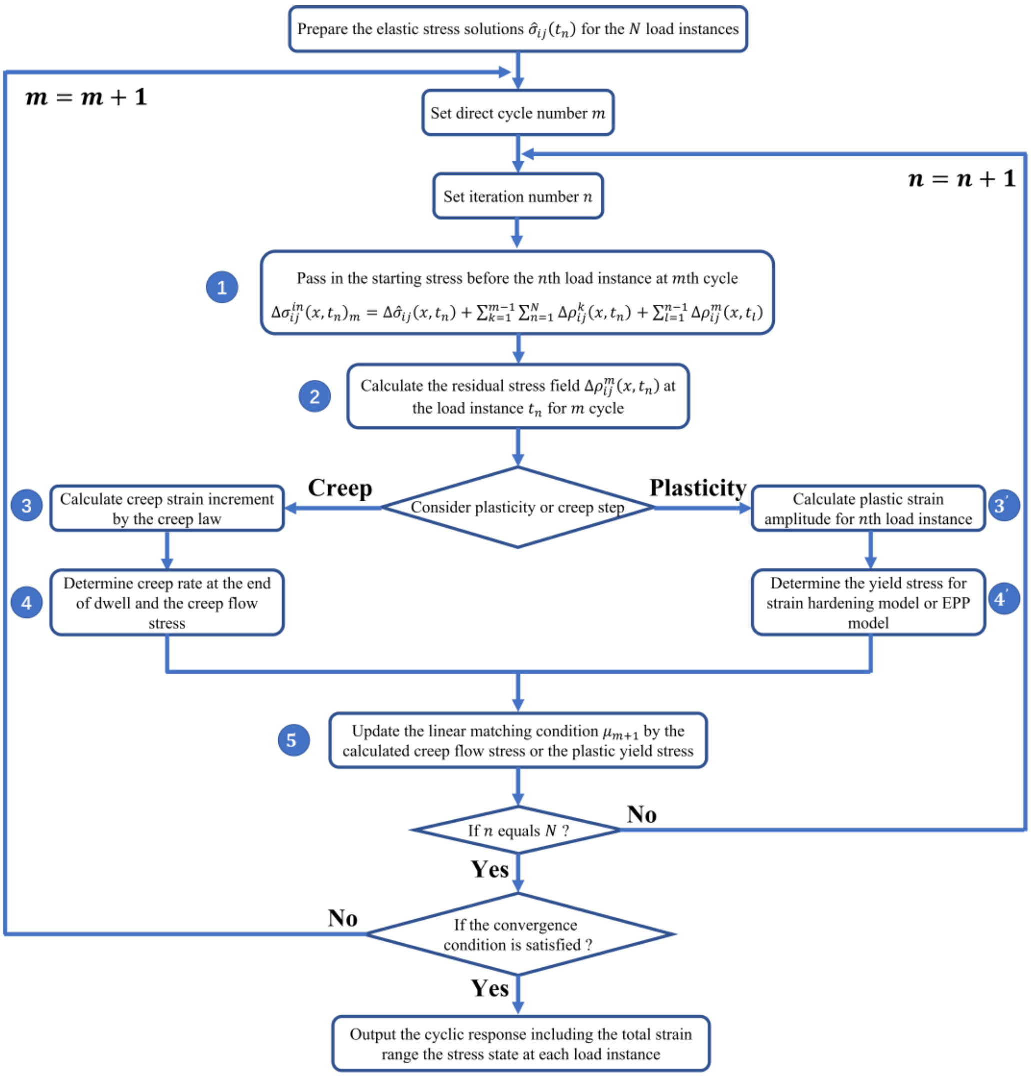

Figure 1. LMM eDSCA procedure for the evaluation of structural high-temperature responses, where the creep-induced residual stress is calculated iteratively according to the linear matching conditions.

The eDSCA procedure evaluates the structural steady cyclic response including plastic behaviour and creep effect by solving a series of linear equations, by which the cyclic plastic strain and creep strain increments are determined iteratively by means of the calculation process in Figure 2.

Given that under a certain iteration cycle $m = 1, 2, 3, \cdots, M$, lie several load time points t_n, where $n = 1, 2, 3, \cdots, N$. For the calculation of nth load time point under mth cycle, the iteration starts with constructing the input stress field $\Delta\sigma_{ij}^{in}$ at each material point by Equation 1, including the elastic solution of t_n and the accumulation of the previous residual stress. The accumulated residual stress $\rho_{ij}^{m}(x, t_n)$ until cyclic time t_n is determined by the summation of the previous history in Equation 2, and, hence, to further evaluate the inelastic strain increment, two different numerical schemes are constructed by LMM extended Direct Steady Cyclic Analysis (eDSCA) which are responsible for generating the corresponding plastic strain increment and creep increment, respectively.

$$\Delta\sigma_{ij}^{in}(x, t_n)_m = \Delta\hat{\sigma}_{ij}(x, t_n) + \sum_{k=1}^{m-1}\sum_{n=1}^{N}\Delta\rho_{ij}^{k}(x, t_n) + \sum_{l=1}^{n-1}\Delta\rho_{ij}^{m}(x, t_l) \tag{1}$$

$$\rho_{ij}^{m}(x, t_n) = \sum_{k=1}^{m-1}\sum_{n=1}^{N}\Delta\rho_{ij}^{k}(x, t_l) + \sum_{n=1}^{n}\Delta\rho_{ij}^{m}(x, t_l) \tag{2}$$

To predict the structural cyclic plastic behaviour, the plastic strain increment $\Delta\varepsilon_{ij}^{m}$ is given by Equation 3,

$$\left[\Delta\varepsilon_{ij}^{m}(x, t_n)\right]' = \frac{1}{2\bar{\mu}_m(x,t_n)}\left[\hat{\sigma}_{ij}(x, t_n)' + \rho_{ij}^{m}(x, t_n)'\right] \tag{3}$$

Here, $\bar{\mu}_m$ stands for the shear modulus that is read in at the start of this iteration procedure, and the mark $(')$ specifies the deviatoric component of each variable. For the purpose of considering the creep during the dwell period, the creep strain increment is addressed with Equation 4, by adopting the time-hardening constitutive law and the concept of elastic follow-up during stress relaxation, where the A, n^* and m^* are the creep parameters according to the creep rule $\dot{\bar{\varepsilon}}_c = A^*\bar{\sigma}^{n*}t^{m*}$. The creep flow stress is defined in Equation 5, by adding the creep effect-induced residual stress to the creep stress at the start of the dwell period.

$$\Delta\bar{\varepsilon}_c = \frac{A(n^*-1)\Delta t^{m^*+1}(\bar{\sigma}_s - \bar{\sigma}_c)}{\left(\frac{1}{\bar{\sigma}_c^{n^*-1}} - \frac{1}{\bar{\sigma}_s^{n^*-1}}\right)(m^*+1)} \tag{4}$$

$$\bar{\sigma}_c(x, t_n) = \bar{\sigma}\left[\left(\sigma_{sij}(x, t_n) + \Delta\rho_{cij}(x, t_n)\right)\right] \tag{5}$$

Before completing the iteration, a new linear matching condition $\bar{\mu}_{m+1}$ is also established by Equation 6, where the σ_0^m is either the plastic yield stress for plastic behaviour calculation or the creep flow stress with the creep effect involved, and $\bar{\dot{\varepsilon}}^F$ is the creep strain rate at the end of dwell.

$$\bar{\mu}_{m+1}(t_n) = \bar{\mu}_m(t_n)\frac{\sigma_0^m(t_n)}{\bar{\sigma}\left(\hat{\sigma}_{ij}(t_n) + \rho_{ij}^{m}(t_n)\right)} \tag{6}$$

2.2 Prediction Of Structural Lifetime in terms of Creep-fatigue Interaction

After the steady structural responses are identified by the eDSCA procedure, the subsequent evaluation of creep-fatigue damage and life contains four key steps which are illustrated by the flowchart in Figure 3. Firstly, according to the stress results from eDSCA (including the stress at the start of the dwell and the stress at the end of the creep dwell), the relationship between the changing stress and the time is given out by using the elastic follow-up factor. Secondly, with the mean stress during creep acquired, the creep damage rate is expressed in terms of the ratio of creep dwell time to creep rupture time by the Time Fraction Model. Then, as the eDSCA output of the total cyclic strain range is examined, the fatigue damage rate at the critical node is characterized based on linear damage summation assumption. Finally, the acceptable creep-fatigue life is calculated, where the maximum life should be inside the envelop of bi-linear interaction so that the summation of the creep damage and fatigue damage does not exceed 1.0

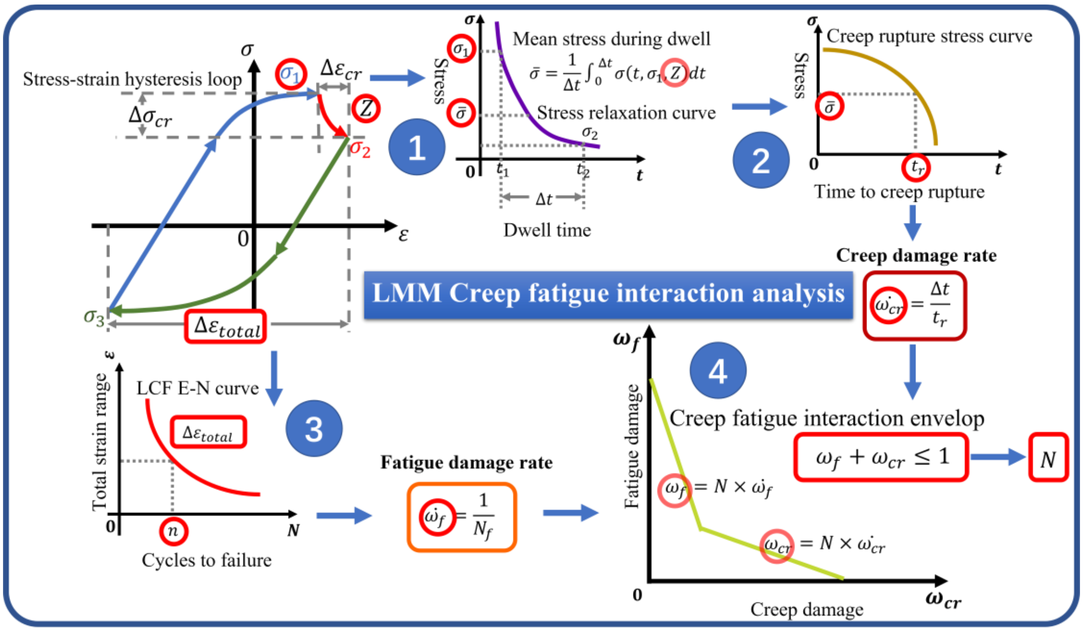

Figure 3. Assessment process of structural damage and lifetime in terms of creep-fatigue interaction.

2.3 Machin Learning-based Surrogate Modelling Of Structural Creep-fatigue Damage and Lifetime

The extended DSCA-driven neural network (EDDNN) [20] is constructed by the feedforward neural network functioning as the multi-layer perceptron (MLP) for approximation modelling and prediction. The commonly used neural network contains the input layer, the hidden layer and the output layer, as exhibited in Fig. 4. Initially, the weighted input vector was summed through the input layer and passed to the hidden layer. Then, the activation function existing in each neuron performs non-linear mapping which is dependent on the summation of input with weights and bias. Finally, the relationship between the input x and the output y is expressed implicitly.

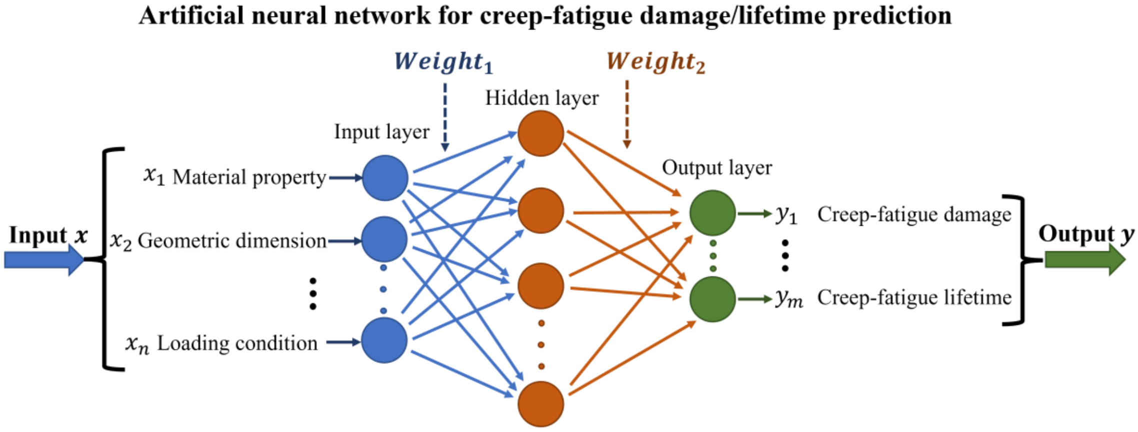

Figure 4. Three-layer neural network for structural response estimations of high-temperature conditions.

2.4 Probabilistic structural integrity assessment with surrogate model under pLMM framework

The probabilistic structural integrity assessment is implemented by using the conjunction of ABAQUS and Isight, and the core computational configuration of the extended DSCA-driven neural network (EDDNN) is formulated [20] in Figure. 5. To recognize the known data, firstly, the EDDNN is trained with a given database. It contains a series of random combinations of input data points produced in the design space by the Latin Hypercube Sampling (LHS) technique, which is then processed by the LMM Plugin program to derive the creep-fatigue damage and life accordingly. Hence, the prerequisites for building the EDDNN-based surrogate model, including the weight parameters and the bias term, can be calculated simultaneously by solving the combination of linear equations (see Equation 7).

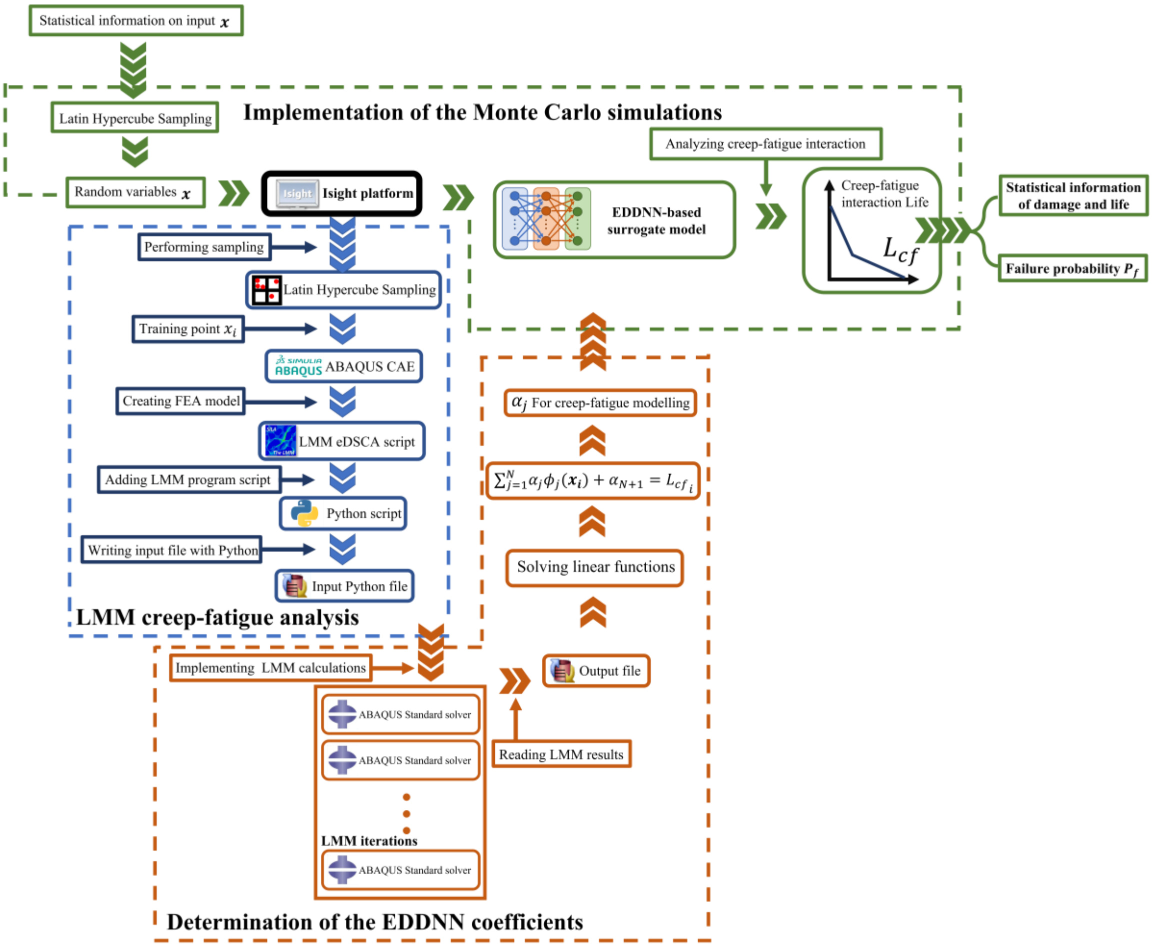

Figure 5. Numerical analysis procedure of probabilistic creep-fatigue assessment by pLMM.

$$\sum_{j=1}^{N} \alpha_j \phi_j(x_i) + \alpha_{N+1} = \begin{cases} D_i(x_i)\ for\ creep - fatigue\ damage\ evaluation \\ L_i(x_i)\ \ for\ creep - fatigue\ lifetime\ evaluation \end{cases} \tag{7}$$

3. THE RECENT APPLICATIONS OF PROBABILISTIC STRUCTURAL ASSESSMENT BY THE PLMM FRAMEWORK IN NUCLEAR ENGINEERING

To facilitate the reliability-based design and risk management, the probabilistic structural integrity assessment for the nuclear reactor pressure vessel is performed by the pLMM framework and the statistical distribution of the creep-fatigue lifetime is investigated quantitatively.

3.1 Model Description

The component of the nuclear reactor pressure vessel contains the outer insulation layer, the main vessel and the inlet nozzle of the cold hydrogen, as displayed in Figure. 6(a). Because of the symmetric attribution, a quarter model is created by the ABAQUS CAE for the LMM creep-fatigue analysis, with the 20-node quadratic brick element C3D20R utilized to discretize this geometry. Besides, around the transition region between the main vessel and the inlet nozzle lies the refined element zone, as pointed out by the red rectangle in Figure. 6(b), to depict the potential high-gradient effect (see Figure 6(c)) of the stress and strain within the structure. This reactor pressure vessel is manufactured by 2.25Cr1Mo steel, and to measure the yield resistance, the cyclic yield strength $R_{p0.2}(T)$ is adopted based on the 0.2% proof stress taken from the cyclic steady-state stress-strain curves. In addition, the classic Norton law is applied during the evaluation of creep strain, with the power law multiplier A^* and stress order n included.

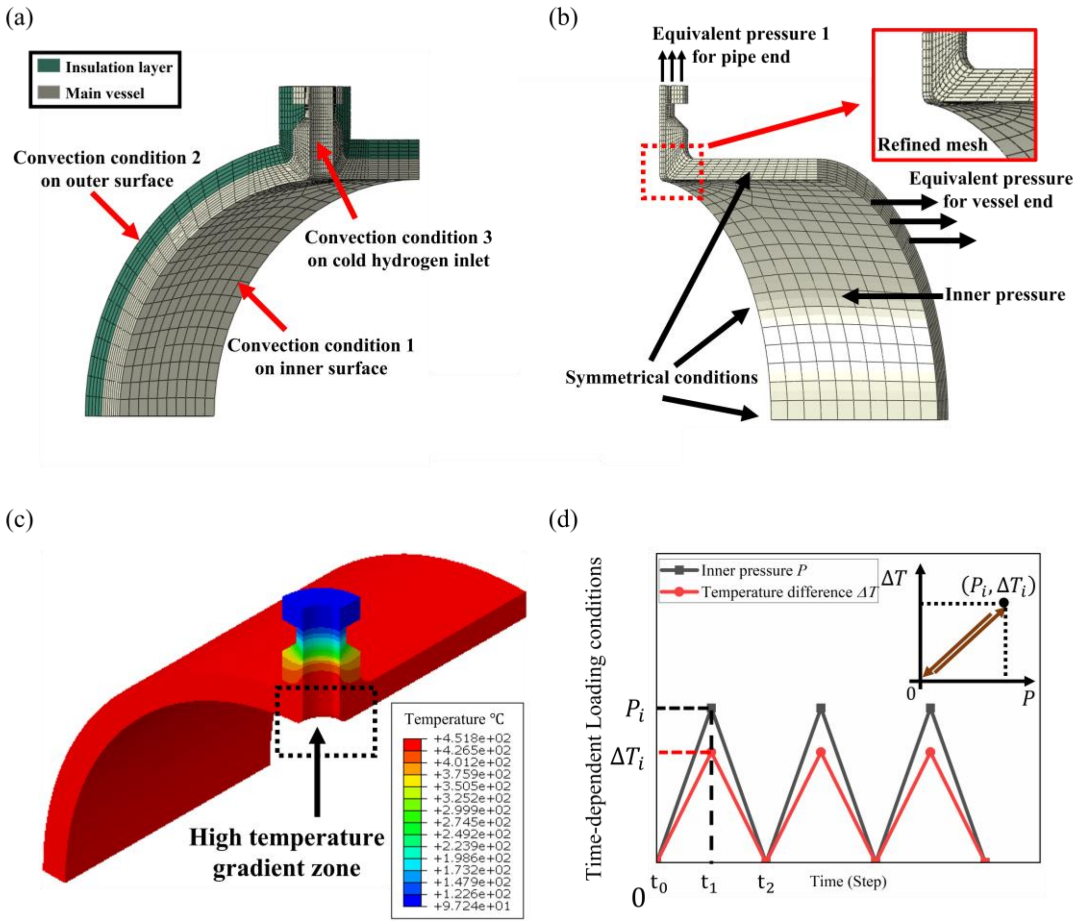

Figure 6. FEA model of the nuclear reactor pressure vessel: (a) FEA model for the thermal analysis; (b) FEA model for the creep-fatigue analysis; (c) temperature field for the creep dwell consideration; (d) time-dependent loading conditions for the creep-fatigue analysis.

When implementing the creep-fatigue analysis, the inner pressure and the associated equivalent pressures are defined on the inner surface and two ends as well, with the symmetric conditions exerted on the symmetric surfaces in Figure. 6(b). Given the operating requirement of the hydrogenation process, both the mechanical loads and the thermal load are assumed to be cyclic conditions, following the time-dependent load histories described in Figure. 6(d). Detailed information on the loading parameters for the probabilistic creep-fatigue analysis is listed in Table 1, which covers the mean value, statistical distribution and coefficient of variation.

Table 1: Applied loading conditions for the probabilistic creep-fatigue analysis.

	Mean value	Distribution	Coefficient of variation
Maximum cyclic inner pressure P [MPa]	10	Normal	0.05
Maximum cyclic temperature differenceΔT [°C]	454		
Creep dwell time t [hours]	400		0.1

3.2 Probabilistic Cree-fatigue Assessment Of Reactor Pressure Vessel

Under the pLMM framework, the statistical distribution of structural creep-fatigue lifetime is obtained by the MCS with the EDDNN surrogate model, considering the statistical features of the design parameters. During this process, the total number of random simulations meets the requirements in Equation 8 to guarantee the results of the MCS-derived probabilistic analysis are converged. As plotted in Figure. 7, the distribution of creep-fatigue life, probability density function and cumulative probability curve are displayed, and it can be seen that in this case, the creep-dominated lifetime of the reactor pressure vessel tends to follow the lognormal distribution, by which the mean value and the standard deviation are fitted as well.

$$N_{MCS} > \frac{100}{P_f} \tag{8}$$

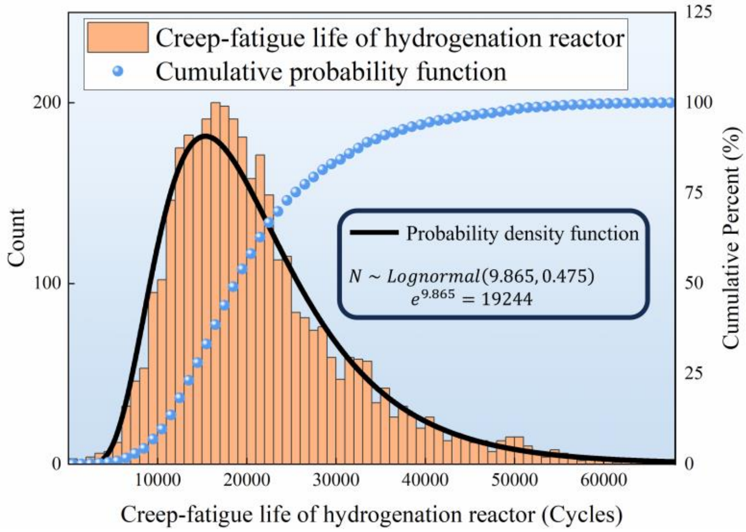

Figure 7. Distribution of the predicted creep-fatigue life under uncertain design conditions.

3.3 Reliability-based Assessment Curve And Safety Factor Of Reactor Pressure Vessel

Based on the results of the probabilistic creep-fatigue analysis, the reliability-based creep-fatigue assessment curve of the reactor pressure vessel by the critical location is proposed in Figure. 8, with three different safety requirements formulated.

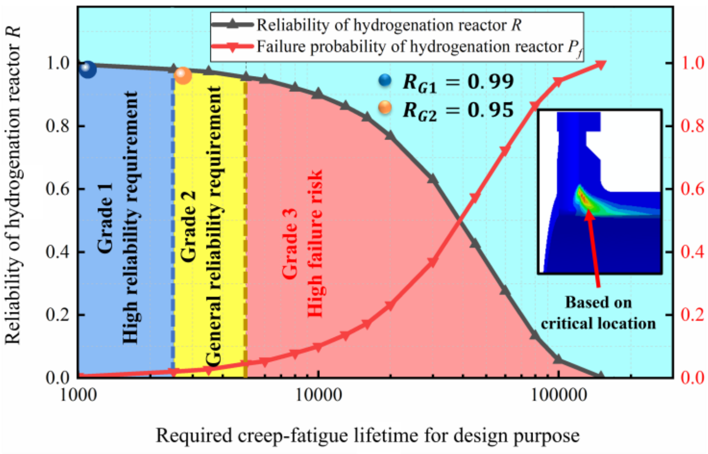

Figure 8. Reliability-based creep-fatigue assessment curve of the reactor pressure vessel by the critical location with different safety requirements.

According to the deterministic analysis, the average of the structural creep-fatigue lifetime, N_m =2,769 Cycles, is calculated by the LMM eDSCA with the mean value of each design parameter. To reflect the potential design conservativeness and take the reliability level into account for the decision on structural creep-fatigue life, the RBSF for this pressure vessel is derived given this creep-fatigue assessment curve. Here, two RBSFs are suggested corresponding to the classification of reliability grades by Equations 9 and 10:

Grade 1:

$$n_{G1} = \frac{N_m}{N_{G1}} = \frac{2769}{1000} = 2.769 \tag{9}$$

Grade 2:

$$n_{G2} = \frac{N_m}{N_{G2}} = \frac{2769}{2500} = 1.108 \tag{10}$$

CONCLUSION

The pLMM framework is developed for the probabilistic structural integrity assessment facing inevitable uncertain design conditions. By means of the direct method-based procedure, the high-fidelity training dataset is generated to reflect the creep-fatigue failure mechanism, and with the data-driven ANN technology utilized, the EDDNN-based surrogate model is proposed to predict the creep-fatigue lifetime, where the complicated creep-fatigue interaction behaviour is involved. Besides, the statistical distribution of the creep-fatigue lifetime of the reactor pressure vessel is investigated by the probabilistic creep-fatigue analysis, and the failure probability regarding the specified design lifetime is able to be estimated with a good balance between computational efficiency and accuracy. In addition, to further express the relationship between the required design life and the failure probability, the reliability-based evaluation diagram is constructed, which divides the potential design lifespan into three regions according to different reliability grades. Finally, the RBSF is derived from the built safety assessment curves, which is conducive to quantitatively characterising the conservativeness of the design scheme with uncertainty.

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