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RESEARCH ARTICLE

Perceived effects of stress ratio and microstructural heterogeneity on fatigue life through damage accumulation and crack nucleation: A PLS-SEM study of practising engineers in Saudi Arabia

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ABSTRACT

Fatigue-related failures are an important limitation on the service life of metallic components subjected to cyclic loading in aerospace, defence, petroleum, and power-generation applications in Saudi Arabia. Guided by continuum damage mechanics, this research examined a mediated moderation model to determine how practising engineers perceive the effects of stress ratio (SR) and microstructural heterogeneity (MH) on fatigue life (FL). The study also examines how damage accumulation (DA) and crack nucleation (CN) mediate these relationships. In addition, the study tests for the moderating effect of operating temperature (TEMP) on each of the two sequential paths: DA → CN and CN → FL; TEMP is modelled as a moderator of these transitions, not as a stage within the serial pathway. A survey was conducted among 410 senior materials and mechanical engineers working for Saudi Arabian companies in the aerospace, defence, petroleum, power-generation, and heavy-industry sectors within the context of the Vision 2030 localisation strategy. Partial least squares structural equation modelling was used to analyse the data and to test for conditional indirect effects and the index of moderated mediation. All but one tested hypothesis was supported; the effects of SR and MH on FL via DA/CN were nearly four times larger across the temperature range examined. Additionally, the proposed model accounts for 35.4% of the variance in perceived FL. All six constructs are latent variables measured by seven-point Likert items capturing the judgements of experienced engineers; none is a physical quantity obtained from fatigue testing or material characterisation. The findings therefore describe perceived relationships among these constructs and constitute statistical evidence from expert judgement rather than experimental validation of the underlying fatigue mechanisms.

1. Introduction

Fatigue failure accounts for the majority of in-service failures of load-bearing metallic parts in aerospace, defence, oil and gas, power generation, and heavy industry.[1,2] Reliable fatigue-life prediction under service conditions is still considered one of the major challenges in mechanical and materials engineering since the path from the applied loads to the ultimate part failure includes a series of coupled micromechanisms—damage accumulation (DA) at the microstructural level, crack initiation at defects or grain boundaries, cracking propagation, and final fracture—and all these stages depend on the loading conditions, the metallurgical structure and the operational environment.[3,4] With respect to the Kingdom of Saudi Arabia, fatigue-life prediction will occupy an increasingly prominent place in the industrialisation strategy

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of Vision 2030 and in the National Industrial Development and Logistics Program whose objectives include producing fatigue-sensitive parts for the aerospace (by way of Saudi Arabian Military Industries [SAMI), the General Authority for Military Industries [GAMI], and Taqnia Aeronautics), defence (by way of SAMI Aerospace, SAMI Land, and the supply chain of the Saudi National Guard), oil and gas (by way of Saudi Arabian Oil Company's (Aramco) programmes on strategic materials and the manufacturing channels for offshore platforms of the Eastern Province), and electrical power generation (by way of the supply channel of the Saudi Electricity Company and the programme on readiness for nuclear operation of K.A.CARE). Although several individual components of the fatigue-life pathway were studied in detail in numerous programmes of aerospace research funded in the United States (US) and Europe, the whole chain connecting the input data of loading and metallurgy to life outputs was rarely modelled empirically at the scale at which practising engineers perceive it in their daily practice in high-performance manufacturing in Saudi Arabia—the scale at which fatigue-life predictions are made for day-to-day engineering decisions.

Stress ratio (SR)—the ratio of minimum to maximum cyclic stresses (in general denoted as $R = \sigma_{min}/\sigma_{max}$)—can characterise loading asymmetry but is not, by itself, a measure of loading seerity, influencing therefore the mean-stress effect on the rate of DA[1,5,6]; microstructural heterogeneity (MH)—the spatial variability in grain size, phase distribution, precipitates, porosity, and crystallographic texture—governs the number and localisation of preferred sites for initial damage.[4,7-9] The two inputs act through different but interconnected micromechanical pathways: SR primarily affects the rate of DA, whereas MH primarily determines where DA occurs and the conditions required for subsequent crack nucleation (CN). The service environments typical of the Kingdom compound both effects: sustained high-temperature operation at inland and Eastern Province installations, high-frequency vibratory loading in pumping equipment, gas turbines and rotating machinery, elevated thermomechanical loading in aerospace propulsion components, and chloride-bearing coastal atmospheres along the Gulf and Red Sea, in which corrosion–fatigue interaction shortens initiation life further still.[10]

Increasingly large bodies of computational and experimental work demonstrate that DA and CN generally constitute a serial pathway in most metallic alloys.[7,11,12] At first, damage accumulates through dislocation pile-up, grain-boundary sliding, slip-band formation, and void coalescence. Only when accumulated damage reaches a critical value at a preferred site does CN occur, marking a transition from a damage-dominated state to one increasingly governed by crack propagation. Finally, fatigue life (FL) is determined jointly by the rate at which this transition occurs and by the subsequent crack-growth kinetics.[2,5]

Temperature is a documented environmental factor that modifies this sequence. Increased temperature accelerates diffusion-controlled damage mechanisms (thermally activated dislocation mobility, diffusive transport along grain boundaries, oxidation-assisted damage), increasing the rate of DA and decreasing the activation energy required for CN.[13,14] Temperature also modifies the relationship between CN and life: at increased temperature after nucleation, cracks grow faster due to enhanced cracking velocity induced by environmental effects and creep–fatigue interactions.[14,15] This is not a marginal issue for operators in the Kingdom: gas-turbine power generation, aerospace propulsion components, oil-and-gas downhole equipment, and petrochemical pressure-vessel components all operate at temperatures where diffusion-controlled damage mechanisms become active, and at which life estimates derived from isothermal low-temperature data are known to be non-conservative.[14,15]

Although there is a well-established mechanistic description of this process, three empirical gaps remain. First, no empirical integrated model exists relating the entire pathway from loading and metallurgical inputs via damage and nucleation to life at the engineering practice scale. Most previous studies have investigated either the link between loading and damage or the link between crack growth and life separately. Second, although several studies investigated the influence of temperature on individual links, very few have accounted for the simultaneous modification of both the transition from damage to nucleation and from nucleation to life by temperature. Third, available evidence on high-performance manufacturing in Saudi Arabia remains sparse compared with the extensive evidence base generated by North American, European, and East Asian aerospace research programmes. This gap is increasingly relevant given the substantial expansion of Saudi Arabia's high-performance manufacturing sector under Vision 2030, including aerospace-grade, fatigue-critical component production by SAMI and Taqnia; expanded defence supply chains under GAMI's localised procurement programme; localised manufacture of oil and gas equipment under Saudi Aramco's In-Kingdom Total Value Add (IKTVA) programme; and the development of power-generation supply chains under the National Industrial Strategy.[15]

Based on continuum damage mechanics (CDM)[3], this study tests a moderated serial-mediation model in which SR and MH determine FL via sequential mediation of DA and CN, with TEMP being a moderator of both transitions. Data come from a survey conducted among 410 senior engineers involved in materials science and mechanical engineering at Saudi Arabian companies that use high-performance metallic alloys in the aerospace, defence, oil and gas, electric power generation, and heavy industries sectors. The analysis is organised around two questions. The first concerns the architecture of the pathway itself: whether the influence of perceived SR severity and perceived MH on perceived FL is transmitted serially, through DA and then CN, in the order that CDM would lead one to expect. The second concerns the role of the thermal environment: whether TEMP acts on both the damage-to-nucleation and the nucleation-to-life transition, so that the serial indirect effect is conditional on thermal severity rather than fixed. Taken together, these questions ask not merely whether the constructs are related, but whether experienced engineers organise them in the sequence and with the thermal conditioning described by the mechanistic literature.

This research makes four types of contributions: theoretical, methodological, contextual, and practical. It contributes theoretically to extending CDM to an integrated, mediated, serial-moderation model that is empirically consistent with the well-known micromechanical material response sequence. Contributions at the methodological level include the application of partial least squares structural equation modelling (PLS-SEM), conditional indirect effect testing, and the index of moderated mediation proposed by Hayes[16] to a practice-based data set in materials engineering. Contributions include providing evidence derived from engineers' perceptions based on 410 senior engineering professionals in aerospace, defence, oil and gas, power generation, and heavy industries across all five sectors of the Saudi Arabian economy operating as part of the Vision 2030 framework of industrial localisation. In practice, the study offers a structured account of how experienced engineers weigh these factors, which may help frame materials-selection discussions, thermomechanical design reviews, and service-life assessments across SAMI, Saudi Aramco, Saudi Basic Industries Corporation (SABIC), King Abdullah City for Atomic and Renewable Energy (K.A.CARE), GAMI's localised supplier chain, and the larger materials engineering ecosystem of the Saudi Council of Engineers.

2. Theoretical framework and hypothesis development

2.1. Continuum damage mechanics as the guiding framework

Continuum damage mechanics, which was first introduced by Kachanov[17] but then formally developed by Lemaitre and Chaboche[3], models progressive degradation of materials due to cyclic loading via a scalar or tensorial damage variable D whose evolution is defined by constitutive relations involving loading, microstructure, and environmental conditions. The widespread use of CDM as the primary method to predict the FL of metal components arises from its ability to model the three key characteristics of material degradation: the sequential progression of damage → nucleation → failure; the relationship between mechanical and metallurgical properties; and the effect of environmental factors, such as temperature, upon the rate at which damage occurs.[3,13,18]

The four attributes of CDM are particularly relevant to this study. First, CDM models the serial organisation of damage → nucleation → failure as specified empirically in the study. Second, CDM's constitutive equations include direct modelling of SR effects by incorporating them into the mean-stress-dependent terms describing the evolution of damage, and they also account for the variability associated with MH through the spatial-variability parameters of the damage field. Third, CDM is inherently thermomechanical in that temperature is included in the damage-evolution equations via thermally active constitutive parameters, thereby providing a mechanistic rationale for the moderation hypotheses examined here. Fourth, CDM has been successfully used to simulate behaviour across many engineering applications, including aerospace, automotive, and power generation. The alloy systems that dominate the present sample—Ti-6Al-4V, Inconel 718 and high-strength steels—are among the most extensively characterised in that literature[14,15], which provides a substantial body of established empirical experience against which perceptions elicited from practising engineers can be read.

2.2. Hypothesis development

2.2.1. Stress ratio and damage accumulation

The "stress ratio," or the amount of the applied cyclic load that is considered to be severe enough to cause the described damage mechanisms, i.e., the magnitude of the stress range plus the mean-stress component, is what causes the damage-producing "energy" to enter into the material. The higher the SR, the greater will be the damage-producing dislocations, grain boundary slips, and slip band formations, which will accumulate damage at a faster rate than at lower SRs. Across a broad range of metallic alloys, a monotonic increase in the rate of DA with increasing loading severity has been widely reported.[1-3,5,6]

First, the mechanical SR $R = \sigma_{min}/\sigma_{max}$ is not by itself a measure of loading severity, and its effect on damage cannot be signed without specifying what is held constant. At constant σ_{max}, an increase in R reduces the stress amplitude and generally lengthens life; at constant amplitude, an increase in R raises the mean stress and generally shortens life. Any statement that a higher SR accelerates damage is therefore conditional on the amplitude or mean-stress convention adopted.[2,5,6] Second, and consequently, the SR construct estimated in this study is not the mechanical ratio. It is a reflective latent variable capturing how severe and how asymmetric respondents judge the cyclic loading on their primary components to be, combining the perceived stress range, the perceived mean-stress component and the perceived asymmetry of the loading amplitude (**Appendix**). H1 is accordingly a hypothesis about perceived loading severity under the high-mean-stress conditions in which the respondents' primary components operate and should not be interpreted as a claim that increasing R in isolation increases damage.

H1. Because the perceived severity and asymmetry of the applied cyclic loading index the mechanical work available to drive dislocation activity, grain-boundary sliding, and slip-band formation, engineers who judge the loading on their primary components to be more severe are expected to also judge that damage accumulates more rapidly in those components. Perceived SR severity is therefore hypothesised to be positively associated with perceived DA.

2.2.2. Microstructural heterogeneity and damage accumulation

Microstructural heterogeneity, including variations in grain size, phase or precipitate distribution, the spatial distribution of pores and other defects, and texture, determines where damage initiates. Higher degrees of heterogeneity increase the concentration of damage in certain locations (large-grain areas, large-grain–small-grain interfaces, inclusion clusters, pore clusters), thereby increasing the local DA to a greater extent than if an average parameter were used.[4,7-9] Accordingly, greater perceived MH would be expected to correspond to greater perceived DA. This mechanistic relationship motivates the following hypothesis:

H2. Because spatial variability in grain size, phase and precipitate distribution, porosity, and crystallographic texture concentrates cyclic plastic strain at a limited number of favourably oriented or defective sites rather than distributing it uniformly, engineers who judge their primary alloy family to be more heterogeneous are also expected to judge damage to accumulate more rapidly. Perceived MH is therefore hypothesised to be positively associated with perceived DA.

2.2.3. Damage accumulation and crack nucleation

Crack nucleation will occur as soon as the DA at a given preferred site reaches a specific critical level, a phenomenon extensively studied using fatigue tests on metals and alloys in laboratory experiments and through modelling.[2,11,12] After this point, several mechanisms can produce a Stage I fatigue crack, such as the coalescence of microvoids, the coalescence of slip bands, or the loss of cohesion from grains and boundaries. These cracks may subsequently transition to Stage II propagation due to the applied cyclic loads. Therefore, higher levels of DA result in both an earlier onset of fatigue crack nucleation and an increase in the number of these events. This mechanistic relationship provides the basis for the following hypothesis:

H3. Because CN follows the attainment of a critical local damage state rather than occurring independently of the damage that precedes it, engineers who judge damage to accumulate rapidly are expected also to judge nucleation to occur earlier and at more sites. Perceived DA is therefore hypothesised to be positively associated with perceived CN.

2.2.4. Crack nucleation and fatigue life

Once a crack begins to grow, the time until it causes failure is directly related to how quickly it continues to grow and how much total length it has left before it reaches its critical length and fractures. Therefore higher intensities of CN lead to three effects which decrease FL: first, if there are many nucleating sites (cracks) then this creates additional potential crack fronts that compete with each other to see who grows faster; secondly, as the nucleation site occurs early on in the cycle there is less remaining time until the next cycle that would allow the existing crack(s) to grow further in length; thirdly, an increase in number of possible locations where a nucleation event may occur results in a greater likelihood of producing one or more "worst case" orientation(s) of the critical crack(s), which will result in a catastrophic failure sooner than later.[5,14] As a direct result of these factors, the relationship between FL and CN events is both monotonically decreasing and negatively correlated. For instance, the more CN events that occur within a given period, the shorter the FL will be. Accordingly, the expected inverse relationship between CN and FL motivates the following hypothesis:

H4. Because a larger and earlier population of nucleated cracks both consumes initiation life and raises the probability that at least one crack is critically oriented with respect to the applied stress, engineers who judge nucleation intensity to be high are expected to judge FL to be correspondingly shorter. Perceived CN is therefore hypothesised to be negatively associated with perceived FL.

2.2.5. Temperature moderation of damage–nucleation transition

Damage accumulation may lead to CN more rapidly due to thermally activated acceleration of grain-boundary diffusion, dislocation climb, and dynamic recovery, as Chaboche[13] and Pineau *et al.*[14] have previously documented. In addition to these mechanisms, oxidation-assisted damage occurs at higher temperatures, reducing the minimum level of damage required for CN. Thus, both effects are coupled and amplify the damage-to-nucleation (DA → CN) relationship originally proposed. The significance of these findings is most relevant in the context of Saudi Arabia's operations, including the eastern province refinery locations, empty quarter installations, and Red Sea coastal facilities. Due to the extreme heat experienced during the summer months, ambient temperatures of over 45°C, combined with elevated TEMP in gas turbines, aerospace engines, and downhole components for Saudi Aramco, result in extreme thermomechanical fatigue (TMF) conditions. These thermally activated mechanisms provide the basis for the following moderation hypothesis:

H5. Because grain-boundary diffusion, dislocation climb and dynamic recovery are all thermally activated, and because oxidation-assisted damage lowers the local damage state at which nucleation becomes possible, the coupling between DA and nucleation is expected to tighten as thermal severity rises. TEMP is therefore hypothesised to positively moderate the DA → CN relationship, such that the relationship is stronger at higher perceived temperatures.

2.2.6. Temperature moderation of nucleation–life transition

Operating temperature influences the transition from nucleation to life. Higher TEMP increases crack velocity through environmentally assisted crack extension, creep–fatigue interactions, and decreased crack closure.[14,15,19] As a result, given a constant CN rate, higher TEMP reduces FL to a greater extent than lower TEMP. As such, it is anticipated that the interaction CN × TEMP will further intensify the existing negative CN → FL slope. Accordingly, temperature is expected to strengthen the adverse effect of crack nucleation on FL, leading to the following hypothesis:

H6. Because environmentally assisted crack extension, creep–fatigue interaction and reduced crack closure all accelerate growth once a crack exists, a given perceived nucleation intensity is expected to cost more life under high thermal severity than under low. TEMP is therefore hypothesised to negatively moderate the CN → FL relationship, such that the association becomes more strongly negative as perceived temperature rises.

2.2.7. Direct effects of loading and metallurgical inputs

The effects of the SR and MH are thought to be independent of the serially mediated pathway. The SR directly influences the crack growth rate by imposing mean stresses, thereby affecting it without going through the nucleation process.[5] Similarly, MH influences the number and size distribution of defects that cause fracture[4];

therefore, it affects the critical defect population that ultimately leads to failure. These mechanisms suggest that both loading severity and MH may also exert direct effects on FL beyond those transmitted through the serial DA → CN pathway. Accordingly, the following direct-effect hypotheses are proposed:

H7. Because mean-stress effects bear on crack-growth kinetics and on the closure behaviour of established cracks, and not only on the rate at which damage accumulates beforehand, perceived SR severity is hypothesised to retain a negative association with perceived FL once the serial pathway through DA and CN has been accounted for.

H8. Because microstructural variability governs the size distribution of the largest defect present as well as the rate at which damage accumulates, and because failure is governed by the extreme of that distribution rather than by its mean, perceived MH is hypothesised to retain a negative association with perceived FL once the serial pathway has been accounted for.

2.2.8. Serial mediation hypotheses

Bringing H1–H4 together, the combined serial-mediation architecture predicts that SR and MH influence FL through the coupled DA → CN pathway. Combined with H5 and H6, the serial indirect effects are conditioned by temperature, producing a moderated serial-mediation structure.

H9. Taking H1, H3, and H4 together, the association between perceived SR severity and perceived FL is hypothesised to be transmitted in part through the ordered sequence of DA followed by CN, yielding a negative and statistically significant serial indirect effect.

H10. Taking H2, H3, and H4 together, the association between perceived MH and perceived FL is hypothesised to be transmitted in part through the same ordered sequence, yielding a negative, statistically significant serial indirect effect.

The conceptual framework is shown in **Figure 1**.

3. Methodology

3.1. Research design and sampling

The study employed a two-wave time-lagged survey research design, as is typical in many previous studies that have used PLS-SEM to examine knowledge creation in engineering.[20,21] The total population consisted of all senior materials and mechanical engineers within high-performance manufacturing companies based in Saudi Arabia. These engineers were required to be directly responsible for making decisions relevant to fatigue in their work, including the selection of metallic alloys for components, and for implementing Saudi Arabia's Vision 2030 framework for industry localisation. Using four specific criteria: (i) at least five years of experience regarding fatigue-related engineering decisions; (ii) currently engaged with one or more high-performance metallic alloys (e.g., Ti-6Al-4V, Al 7075-T6, AISI 4340 steel, Inconel 718, or 300M steel); (iii) responsible for design, material selection, failure analysis or reliability engineering decisions; and (iv) worked within aerospace, defence, oil and gas, power generation, rail, shipbuilding or heavy industries sectors of Saudi industrial economy.

Senior-level respondents were recruited through six sources: (i) the professional membership registry maintained by the Saudi Council of Engineers; (ii) the registered suppliers/partners list held by SAMI; (iii) the registered supplier list of Saudi Aramco's Engineering and Project Management Services Division; (iv) network of advance materials engineers with SABIC; (v) register of locally sourced supply chain providers managed by GAMI; and (vi) alumni lists of leading Saudi engineering universities including King Fahd University of Petroleum and Minerals (KFUPM), King Abdullah University of Science and Technology (KAUST), King Saud University, and King Abdulaziz University.

The questionnaire was translated using the back-translation procedure described by Brislin.[22] Independent bilingual translators performed the forward and back translations, and discrepancies were reconciled by a senior bilingual materials engineer.[23] Pilot testing of the Arabic version was conducted with 22 senior engineers working for SAMI, Saudi Aramco, and SABIC to ensure the correct terminology was used in the fatigue mechanics technical vocabulary. The primary survey was conducted between March 2025 and March 2026 via Qualtrics (version 2025.1, Qualtrics LLC, United States of America). Access to the survey via a mobile-friendly interface was tested on a variety of devices running both Android and iOS, with locale settings set to Saudi Arabia. Data were collected over time using a two-wave design, with a 14-day gap between waves to help reduce common method bias.[24]

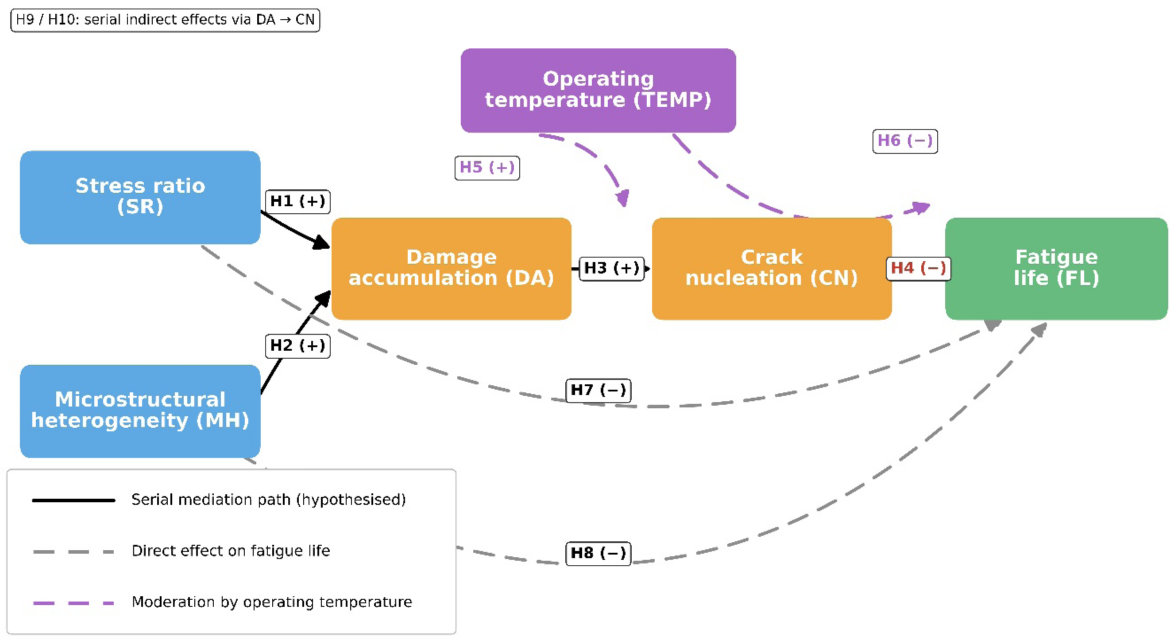

Figure 1. Conceptual framework with serial mediation (damage accumulation → crack nucleation) and dual-stage moderation by operating temperature

Of the 558 respondents who completed Wave 1, 410 completed Wave 2 and provided valid matched responses for analysis, corresponding to a retention rate of 73.5%. The number of respondents exceeded the ten times rule for PLS-SEM.[20,25]

3.2. Variable measurement

All measures for each construct were administered on a seven-point Likert scale (1 = "strongly disagree" and 7 = "strongly agree") and utilised items from validated engineering and industrial psychology assessments. The full wording of all items used is available in the **Appendix**.

All constructs in this study, including SR, MH, DA, CN and FL, are perceptual latent variables elicited from experienced engineers. None was obtained by fatigue testing, fractography, metallography or any other physical characterisation, and no specimen was tested. What the model estimates, therefore, is the structure of expert judgement about these mechanisms as encountered in service, not the mechanisms themselves. Two consequences follow and are carried through the whole of Sections 4 and 5. Relationships are reported as associations among perceptual constructs rather than as measured physical dependencies, and the coefficients quantify the consistency of engineering judgement rather than a calibrated material response. Shared professional training, common handbook conventions and the well-known qualitative expectations of fatigue theory may all contribute to the observed covariance, so convergence with established mechanistic understanding is corroborative rather than confirmatory.

Stress ratio was assessed using five items from Dowling[5] and Schijve[1], measuring the perceived severity of the cyclic-loading stress range, the magnitude of mean stress, the frequency at which loads are applied, the degree of symmetry in loading amplitude, and the total severity of loading as rated by respondents for their primary application(s).

Microstructural heterogeneity was assessed using five items from McDowell and Dunne[4] and Prithivirajan and Sangid[7], assessing respondents' perceptions regarding variation in grain size, uniformity of distribution of phases, variability in dispersion of precipitates, the degree of heterogeneity present in terms of porosity or inclusions, and the variability in crystallographic texture among respondents' primary alloy families.

Damage accumulation was assessed using six items adapted from Lemaitre and Chaboche[3] and

Chaboche[13], capturing respondents' perceptions of rates of DA including the rate at which dislocations accumulate, the rate at which grains slide along grain boundaries, the rate at which slip bands form, the rate at which microvoids coalesce, the severity of localised slip, and the overall rate at which damage accumulates.

Crack nucleation was assessed using six items from Sangid[11] and Suresh[2] assessing respondents' perception of both the location density of sites where cracks will first form and the time it takes before they form the first crack, the tendency of sites to cluster together in early stages of crack development, the population's growth during early stage crack populations, how frequently multiple nucleation sites occur simultaneously, and the overall level of intensity associated with nucleating new cracks.

Fatigue life was assessed using six items from Dowling[5] and Pineau *et al.*[14], assessing respondents' perception of life expectancy relative to design targets, performance over cycles until failure occurs, reliability of components being designed for fatigue, level of scatter in observed fatigue lives, frequency of failures experienced during in-service use, and overall life-expectancy ratings.

Operating temperature was assessed using five items from Pineau *et al.*[14] and Zhang *et al.*[15] assessing respondents' perception of the temperature in which equipment is operated under conditions of environmental exposure relative to the severity of those temperatures, levels of thermal gradient present during service, frequencies at which equipment experiences thermal cycling, risks associated with environmentally enhanced damage occurring due to thermal exposure, and overall ratings of thermal severity related to specific Saudi Arabian service locations including but not limited to: Eastern Province, Empty Quarter desert environment, Red Sea coastal regions and gas turbine services.

3.3. Data analysis

The data analysis was performed using PLS-SEM in SmartPLS version 4.0 (SmartPLS GmbH, Germany).[26] PLS-SEM was utilised as it provides an appropriate statistical framework for models containing multiple reflective latent constructs involved in a complex moderated serial-mediation relationship, given its efficiency within the partial least squares paradigm.[20,25] Moderation was defined using the product-indicator approach with orthogonalised interaction terms.[27] Bootstrapping using 5,000 subsamples of the coefficient products along the a × b × c path (SR, MH → DA → CN → FL) was conducted to test the effect of the serial mediation.[28] The index of moderated mediation, developed by Hayes[16], was adapted to evaluate the moderated serial mediation.

The measurement-model assessment followed Hair *et al.*[20,25] and Henseler *et al.*[29] Indicator loadings must be greater than or equal to 0.70. For each construct's internal consistency, Cronbach's alpha and composite reliability rho_c must both be greater than or equal to 0.70. To determine the average variance extracted (AVE) from each construct, the AVE must be greater than or equal to 0.50. Discriminant validity was assessed using the Fornell–Larcker criterion and the heterotrait–monotrait ratio of correlations (HTMT), with an HTMT value of < 0.85 indicating adequate discriminant validity.

The structural model was assessed using 5,000 bootstrap resamples. Explanatory power was evaluated using R^2, and predictor-specific effect sizes were assessed using f^2. Bootstrap standard errors and t statistics were used to characterise the uncertainty of each structural estimate (**Table 3**), while percentile bootstrap 95% confidence intervals were reported for the indirect and conditional effects (**Tables 4–6**). The potential impact of common-method bias was assessed using Harman's single-factor test and full-collinearity variance inflation factor (VIF).[24,30]

3.4. Ethical considerations

This study was conducted in accordance with the ethical principles and guidelines for research involving human participants, including the Declaration of Helsinki and its subsequent amendments, as well as the applicable research ethics guidelines of the University of Ha'il, Saudi Arabia. Before completing the questionnaire, all participants were informed of the purpose and procedures of the study, the voluntary nature of participation, and their right to withdraw at any time. Electronic informed consent was obtained from all participants before participation. No personally identifiable information was collected, and all responses were anonymized and kept confidential.

4. Results

4.1. Demographic profile

The sample comprised 410 engineers from the following Saudi industrial sectors: aerospace structures (16.1%) (predominantly SAMI Aerospace and Taqnia Aeronautics), defence/military industries (14.0%) (SAMI Land and GAMI Partners), aerospace propulsion/rotating machinery (12.3%), thermal power generation (12.0%) (Saudi Electricity Company Supply Chain), oil and gas equipment (12.2%) (Saudi Aramco Supply Network), rail/transportation infrastructure (12.0%) (Saudi Arabian Railways SAR), heavy industry pressure components (8.3%), petrochemical/SABIC affiliates (8.0%) (Jubail and Yanbu), nuclear readiness for power generation (5.1%) (K.A.CARE programme).

Respondents' demographic characteristics were as follows. Male respondents accounted for 77.8% of the sample, whereas female respondents accounted for 22.2%. Regarding age, 46.3% of respondents were aged 35–44 years and 27.6% were aged 45–54 years. In terms of educational attainment, 50.0% held master's degrees and 13.9% held doctoral degrees. By engineering discipline, 30.0% of respondents were in materials engineering, 28.0% in mechanical engineering, 18.0% in aerospace engineering, and 16.0% in metallurgy. Regarding position level, 23.7% were senior design engineers, 22.4% were research and development engineers, 18.5% were quality/reliability engineers, 13.9% were fatigue-testing leads, 13.9% were failure-analysis specialists, and 7.6% were chief engineers.

The principal alloy families reported by respondents were AISI 4340 steel (19.5%), Al7075-T6 (18%), Ti-6Al-4V (17.6%), Inconel 718 (14.1%), 300M steel (8%), Al–Li alloys (7.8%), Mg alloys (6.1%), mixed or multiple alloy families (8.8%).

Saudi nationals constituted 62% of the sample, expatriate engineers from Gulf Cooperation Council (GCC) countries accounted for 15.5%, and other expatriate engineers accounted for 22.5%. This respondent profile is broadly consistent with the wider emphasis on workforce localisation within Saudi Arabia's industrial sector, including localisation initiatives associated with GAMI and Saudi Aramco's IKTVA programme.

4.2. Measurement model

All indicator loadings exceeded the 0.70 threshold (range, 0.812–0.874), supporting indicator reliability. Internal consistency reliability was also satisfactory, with Cronbach's alpha ranging from 0.894 to 0.914, Dijkstra–Henseler's rho from 0.912 to 0.932, and composite reliability from 0.922 to 0.933. Convergent validity was supported by AVE values ranging from 0.688 to 0.720 (**Table 1; Figure 2**). Construct means, standard deviations, interconstruct correlations, and the square roots of the AVE are reported in **Table 2**.

Discriminant validity was supported, as all HTMT values were below the 0.85 threshold, with the highest HTMT value observed between DA and CN (0.598). In addition, √AVE for each construct exceeded its correlations with all other constructs (**Table 2**), satisfying the Fornell–Larcker criterion. Regarding common-method bias, the first unrotated factor accounted for 30.87% of the total variance, below the 50% threshold, and all full-collinearity VIF values were below 2.6.

4.3. Structural model

The structural model was evaluated using 5,000-subsample bootstrapping (**Table 3; Figure 3**).

The model explained 26.3% of the variance in DA ($R^2 = 0.263$), 33.7% in CN ($R^2 = 0.337$), and 35.4% in FL ($R^2 = 0.354$). The DA → CN path

Table 1. Measurement model: Reliability and convergent validity

Construct	Cronbach's α	ρ_A	ρ_c	AVE
Stress ratio	0.901	0.919	0.927	0.717
Microstructural heterogeneity	0.903	0.921	0.928	0.720
Damage accumulation	0.914	0.932	0.933	0.700
Crack nucleation	0.910	0.928	0.930	0.689
Fatigue life	0.909	0.927	0.930	0.688
Operating temperature	0.894	0.912	0.922	0.703

Abbreviations: AVE: Average variance extracted; ρA: Dijkstra–Henseler's rho; ρc: Composite reliability.

had the strongest effect size ($f^2 = 0.315$, medium effect), while CN → FL also had a medium effect size ($f^2 = 0.200$). However, explained variance describes fit within the estimating sample and, by itself, does not establish out-of-sample predictive capability. Two qualifications govern any predictive claim made for this model. First, the quantity predicted is the perceptual fatigue-life construct, not a life in cycles: the analysis speaks to how consistently engineering judgement about FL can be reconstructed from judgements about loading, microstructure, damage, and thermal severity, and not to how accurately the model would reproduce a measured stress–life curve. A prediction error expressed in cycles, or a maximum error for a fatigue-life trend, is therefore undefined here—not large or small, but outside what the model estimates. Second, the seven-point response scale bounds indicator-level prediction error, so error magnitudes would not be commensurable with those reported for mechanistic or data-driven life-prediction models and should not be compared with them.

Within those limits, the uncertainty attaching to every estimate is reported in full. Each structural path carries a bootstrap standard error and t statistic from 5,000 subsamples, with effect sizes reported as f^2 (**Table 3**). The serial indirect effects carry percentile bootstrap 95% confidence intervals (**Table 4**), as do the conditional indirect effects at each of three temperature levels (**Table 5**) and the index of moderated serial mediation for both pathways (**Table 6**). All six conditional effects and both indices exclude zero. The interval widths in **Table 5** also make the precision of the temperature conditioning explicit: the conditional effect for the SR pathway is −0.031 (−0.055, −0.012) at low temperature and −0.121 (−0.167, −0.083) at high temperature. These intervals do not overlap, so the amplification is resolved by the data rather than merely suggested by the point estimates.

4.4. Serial mediation

Bootstrapping with 5,000 subsamples confirmed significant negative serial indirect effects of both

Figure 2. Measurement model: Reflective indicator loadings and reliability statistics for each construct ($N = 410$). Notes: All loadings exceed the 0.70 threshold; all α, ρA and ρc exceed 0.70; all AVE exceed 0.50. Structural relations among constructs are shown in **Figure 3**.

Abbreviations: α: Cronbach's alpha; AVE: Average variance extracted; ρA: Dijkstra–Henseler's rho; ρc: Composite reliability.

Table 2. Descriptive statistics, correlations, and discriminant validity (diagonal entries = $\sqrt{\text{AVE}}$)

Construct	Mean	SD	1	2	3	4	5	6
1. SR	4.02	0.96	0.847					
2. MH	4.04	0.97	0.249	0.849				
3. DA	3.99	0.98	0.413	0.371	0.836			
4. CN	4.02	0.97	0.261	0.240	0.546	0.830		
5. FL	4.00	0.98	−0.343	−0.248	−0.400	−0.528	0.829	
6. TEMP	4.00	0.96	0.157	0.201	0.232	0.225	−0.099	0.838

Abbreviations: AVE: Average variance extracted; CN: Crack nucleation; DA: Damage accumulation; FL: Fatigue life; MH: Microstructural heterogeneity; SD: Standard deviation; SR: Stress ratio; TEMP: Operating temperature.

Table 3. Structural path results

H	Path	β	SE	t	p	f^2	Decision
H1	SR → DA	0.328	0.044	7.403	<0.001	0.130	Supported
H2	MH → DA	0.264	0.045	5.914	<0.001	0.083	Supported
H3	DA → CN	0.510	0.047	10.783	<0.001	0.315	Supported
H4	CN → FL	−0.413	0.049	−8.479	<0.001	0.200	Supported
H5	DA × TEMP → CN	0.165	0.041	4.039	<0.001	0.039	Supported
H6	CN × TEMP → FL	−0.135	0.041	−3.278	0.001	0.023	Supported
H7	SR → FL (direct)	−0.174	0.045	−3.900	<0.001	0.031	Supported
H8	MH → FL (direct)	−0.078	0.044	−1.788	0.074	0.006	Not supported
—	TEMP → DA	0.128	0.044	2.916	0.004	0.020	Significant
—	TEMP → CN	0.108	0.042	2.563	0.010	0.016	Significant
—	TEMP → FL	0.059	0.042	1.418	0.156	0.005	Not significant.

Notes: $N = 410$; bootstrap sample size = 5,000. Abbreviations: CN: Crack nucleation; DA: Damage accumulation; FL: Fatigue life; MH: Microstructural heterogeneity; SE: Standard error; SR: Stress ratio; TEMP: Operating temperature.

Table 4. Serial indirect effects

Hypothesis	Path	Estimate	Boot SE	LL 95% CI	UL 95% CI	Significant?
H9	SR → DA → CN → FL	−0.069	0.013	−0.097	−0.044	Yes
H10	MH → DA → CN → FL	−0.055	0.012	−0.080	−0.034	Yes

Abbreviations: CI: Confidence interval; CN: Crack nucleation; DA: Damage accumulation; FL: Fatigue life; LL: Lower limit; MH: Microstructural heterogeneity; SE: Standard error; SR: Stress ratio; UL: Upper limit.

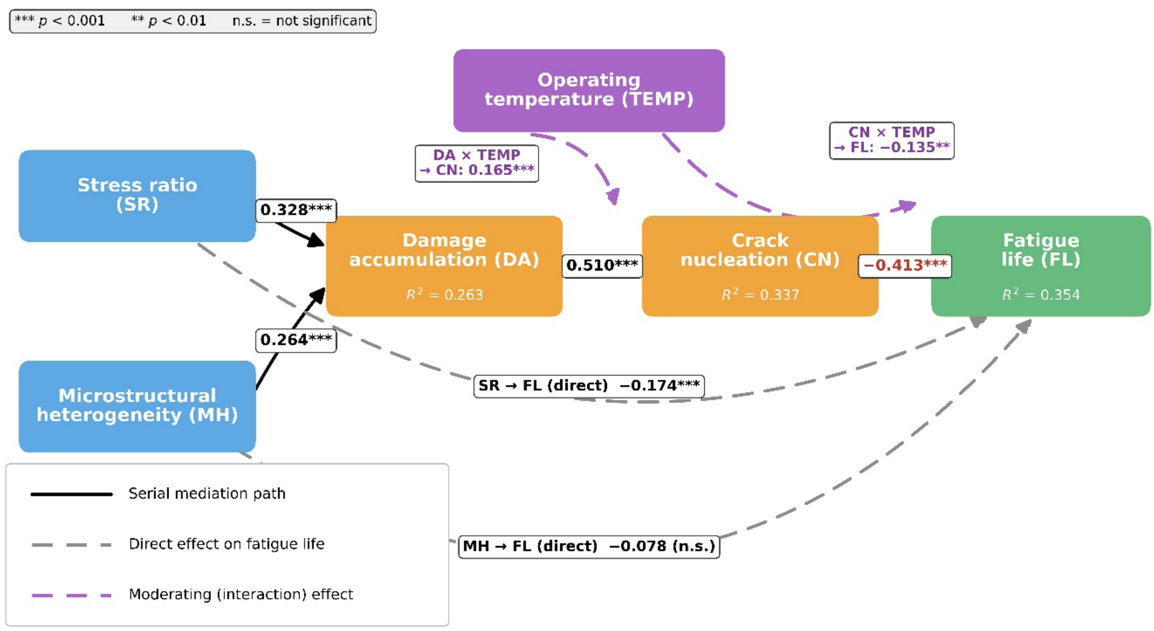

Figure 3. Structural model with standardised path coefficients. Notes: Solid arrows = serial mediation paths; grey dashed curves = direct effects on fatigue life; purple dashed arrows = moderating (interaction) effects. R^2 values are shown inside the endogenous constructs. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; n.s. = not significant. For visual clarity, the TEMP main effects included in the estimated model are omitted; these coefficients are reported in **Table 3**.

predictors on FL through DA and CN (**Table 4**).

Both serial indirect effects are negative and statistically significant. The total effect of SR on FL is −0.243 (direct −0.174 + serial −0.069), and the total effect of MH on FL is −0.133 (direct −0.078 + serial −0.055). For SR, the serial-mediated channel accounts for 28.5% of the total effect; for MH, 41.0% of the total effect is channelled through the DA → CN pathway, indicating that the serial pathway is quantitatively substantial for both predictors, and is proportionally larger for MH than for SR.

4.5. Moderated serial mediation

Conditional serial indirect effects at three levels of TEMP are reported in **Table 5** and visualised in **Figure 4**.

Both conditional serial indirect effects increase in magnitude monotonically with temperature: the SR path nearly quadruples in magnitude (from −0.031 to −0.121), and the MH path nearly quadruples (from −0.025 to −0.098), across the ±1 SD TEMP range. All six conditional effects are statistically significant.

Hayes's index of moderated serial mediation confirmed significant moderation of both serial pathways (**Table 6**).

4.6. Simple-slopes analysis

Figure 5 plots the slopes of DA → CN (**Figure 5A**) and CN → FL (**Figure 5B**) at three levels of TEMP. At low TEMP, the DA → CN slope is 0.345; at mean TEMP, 0.510; at high TEMP, 0.675—a 1.96-fold increase across the ±1 SD moderator range. The CN → FL slope moves from −0.278 at low TEMP to −0.548 at high TEMP, also nearly doubling in magnitude. The combined simple-slopes evidence confirms the amplifying role of temperature on both stages of the serial mechanism.

5. Discussion

The primary goal of this study was to test a moderated serial mediation model explaining how the SR and MH affect the FL of materials through sequential mechanisms (DA and CN) with TEMP moderating both processes, within the context of Saudi Arabia's high-performance manufacturing environment. A total of 10 hypotheses were tested; nine were

Table 5. Conditional serial indirect effects of SR and MH on FL through DA and CN

TEMP level	SR path CIE	SR 95% CI	MH path CIE	MH 95% CI
Low TEMP (−1 SD)	−0.031	−0.055, −0.012	−0.025	−0.046, −0.010
Mean TEMP (0)	−0.069	−0.098, −0.046	−0.056	−0.081, −0.034
High TEMP (+1 SD)	−0.121	−0.167, −0.083	−0.098	−0.138, −0.062

Abbreviations: CI: Confidence interval; CIE: Conditional indirect effect; CN: Crack nucleation; DA: Damage accumulation; FL: Fatigue life; MH: Microstructural heterogeneity; SD: Standard deviation; SR: Stress ratio; TEMP: Operating temperature.

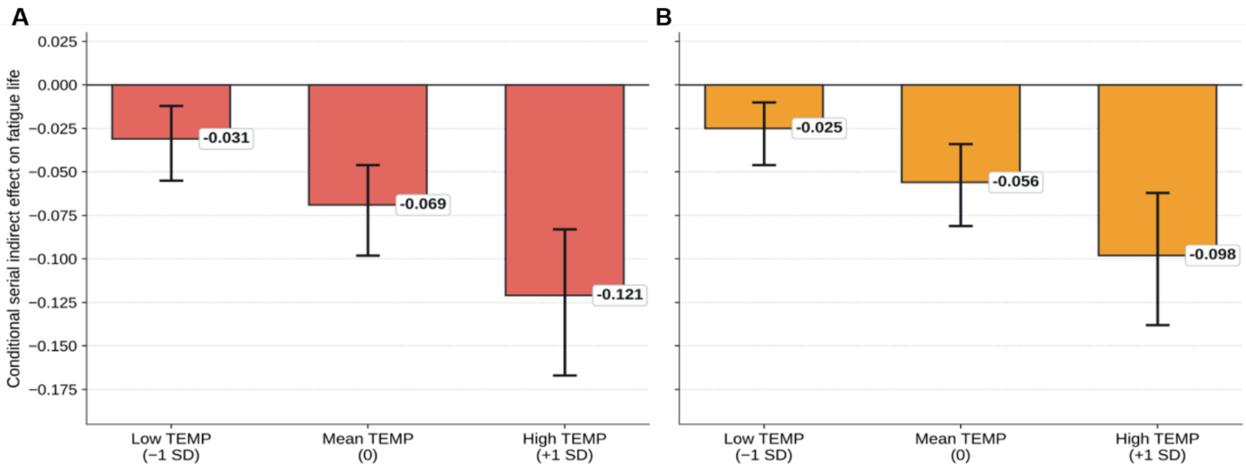

Figure 4. Conditional serial indirect effects of SR (left) and MH (right) on FL through DA and CN at low, mean, and high TEMP. (A) SR → DA → CN → FL. (B) MH → DA → CN → FL. Note: Error bars are 95% percentile bootstrap confidence intervals (5,000 subsamples, $N = 410$). All six conditional effects are significant. Abbreviations: CI: Confidence interval; CN: Crack nucleation; DA: Damage accumulation; FL: Fatigue life; MH: Microstructural heterogeneity; SD: Standard deviation; SR: Stress ratio; TEMP: Operating temperature.

Table 6. Index of moderated serial mediation

Path	IMM	Boot SE	LL 95% CI	UL 95% CI	Significant?
SR → DA → CN → FL	−0.045	0.011	−0.067	−0.026	Yes
MH → DA → CN → FL	−0.036	0.009	−0.054	−0.021	Yes

Abbreviations: Boot SE: Bootstrap standard error; CI: Confidence interval; CN: Crack nucleation; DA: Damage accumulation; FL: Fatigue life; IMM: Index of moderated mediation; LL: Lower limit; MH: Microstructural heterogeneity; SR: Stress ratio; UL: Upper limit.

fully supported, while H8, which examined the relationship between MH and FL directly (MH → FL) as opposed to indirectly via DA (MH → DA → CN → FL), was not supported ($p = 0.074$). Thus, it appears that the MH effect on FL is primarily routed through the sequentially mediated pathway and not directly from MH to FL. H5 and H6, which assessed whether TEMP moderates each of the two sequential relationships in the path sequence, also provided very strong evidence. In addition, H9 and H10, which evaluated each sequential mediation link in the path, also provided strong evidence. The index of moderated serial mediation indicated that both predictor variables had a statistically significant influence on the sequentially mediated pathways. Additionally, the conditional serial indirect effects measured across the full range of TEMP used in this experiment increased fourfold.

The results are consistent with expected positive associations for both SR → DA (β = 0.328) and MH → DA (β = 0.264), as reported in previous work in engineering mechanics and micromechanical modelling.[2,4,5] In particular, the results indicate that DA → CN (β = 0.510, f^2 = 0.315) has an especially large positive value, consistent with earlier predictions made by classical damage mechanics regarding the strength of this link in the overall path sequence.[3]

Finally, the negative coefficient associated with CN → FL (β = −0.413) is positioned toward the higher end of values identified previously in empirical studies focused on predictive health management[12,14], likely due to the highly sensitive nature of Saudi aerospace, defence and oil-and-gas engineers to nucleation events resulting from their use of high-performance materials in accelerated material-development programmes conducted within the Kingdom and the strict fatigue-qualification requirements established by SAMI and GAMI's local procurement programme for fatigue-qualified materials.

The observed moderation by TEMP at both stages of the sequentially linked mechanism in this investigation represents a theoretical extension of existing research on TMF[13,14], indicating that TEMP affects both stages of the sequentially linked mechanism similarly in terms of its quantitative effect on FL. Moreover, because of the approximately fourfold increase in the conditional serial indirect effects across the range of temperatures considered in this study, it indicates that applications involving elevated temperatures (commonly found in gas turbine power generation in Saudi Electricity Company's facilities, aerospace propulsion system components manufactured by SAMI Aerospace for commercial aviation platforms, oil-and-gas downhole drilling equipment manufactured by Saudi Aramco for deep drilling activities, and pressure vessel equipment manufactured by SABIC for petrochemical processing at Jubail and Yanbu) will require conservatively calculated life prediction factors that exceed those derived using simply linear correction for temperature.[14,15]

5.1. Relation to established fatigue-life prediction methods

It is important to be explicit about what the present approach does and does not offer relative to established fatigue-life prediction. Stress-life and strain-life formulations, linear damage summation, fracture-mechanics-based crack-growth integration and CDM all take physical inputs—stress amplitude, mean stress, strain range, defect size, and temperature—and return a life estimate in cycles for a specified material and geometry.[2,3,5] More recently, data-driven and machine-learning models trained on experimental fatigue databases have been shown to perform the same task with accuracy competitive with, and in some regimes superior to, closed-form formulations[31-36], and the same data-driven logic has been applied more broadly to quality outcomes in manufacturing.[37] All of these methods are calibrated against measured lives and can therefore be validated, in the ordinary sense of that word, against held-out experimental data.

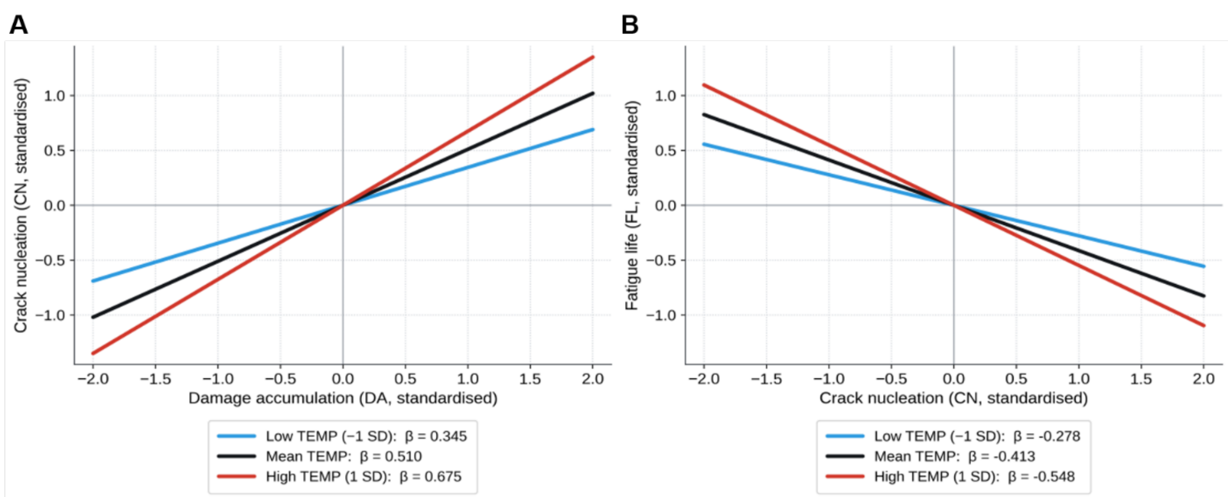

Figure 5. Simple slopes at low, mean, and high TEMP. (A) DA → CN. (B) CN → FL. Abbreviations: SD: Standard deviation; TEMP: Operating temperature.

The model estimated here does none of this, and is not offered as a competitor to those methods. Its inputs are Likert judgements rather than physical quantities, and its output is a set of standardised associations among latent perceptual constructs rather than a life in cycles. It cannot be validated against fatigue test data, because it does not predict fatigue test data. The appropriate comparison is therefore not one of predictive accuracy but one of object: mechanistic and data-driven models describe how materials behave, whereas the present model describes how experienced engineers represent that behaviour when they make design, material-selection and inspection decisions. A claim of superiority in either direction would be a category error.

That distinction also answers why a latent-variable statistical approach is appropriate to the question actually asked. Perceived loading severity and perceived MH are not directly observable, and cannot be captured by a single indicator without confounding the construct with that indicator's measurement error. PLS-SEM was selected because it estimates such constructs from multiple reflective indicators while simultaneously estimating a structural model containing two mediators in series and two interaction terms, and because it remains serviceable at the sample sizes attainable from a specialist professional population.[20,25] Its use here is a claim about the measurement of judgement, not a claim about the mechanics of metal.

The practical value of the exercise lies in the gap it can reveal. Where the structure of expert judgement matches the mechanistic literature, that convergence supports the continued use of established engineering heuristics in early-stage design. Where it diverges—if practitioners were found to weight heavily a factor that fatigue theory treats as secondary, or to discount one it treats as governing—the divergence identifies a specific target for training, for revised design guidance, or for experimental work. Neither use requires the model to predict life, and neither is served by treating it as though it did.

5.2. Theoretical implications

This paper provides three theoretical contributions. Firstly, this paper operationalises the entire CDM serial-mediation architecture (microstructural/damage loading→ damage → nucleation → life) into an empirical model, thus allowing for quantifying the constitutive equation framework which has historically been evaluated using individual linkages. Secondly, this study shows that TEMP consistently amplifies both the damage-to-nucleation transition and the nucleation-to-life transition, thereby supporting a multiplicative TMF interaction rather than a simple additive model. Lastly, the utilisation of engineer perception data provides complementary evidence to experimental micromechanical testing and computational modelling; specifically, this allows for a mechanistic aggregation at the scale of engineering practice, especially important given the rapid growth of high-performance manufacturing in Saudi Arabia as part of Vision 2030.

5.3. Practical implications for the Saudi industry

To assist materials selection and design engineers at Saudi Aramco, SAMI Aerospace, SAMI Land, SABIC, K.A.CARE and defence suppliers in Saudi Arabia to be able to understand how the DA can be controlled by MH, the DA → CN coupling factor ($f^2 = 0.315$) indicates that control of the rate of DA will provide the most effective means of increasing the low-cycle fatigue lives of structural components. Thus for applications involving high temperature such as gas turbine components in the power generation facilities of the Saudi Electricity Company; aerospace components being used in SAMI Aerospace; downhole equipment being used in Saudi Aramco's upstream petroleum operations; and components undergoing evaluation for nuclear readiness through K.A.CARE, the respondents' judgements place thermal severity alongside mechanical design as a factor deserving explicit attention in life assessment, although the relative weight of the two can only be established by testing. A similar microstructural improvement would result in significantly larger increases in FL at lower temperatures than at elevated temperatures.

To support fatigue-testing laboratories and reliability engineers throughout Saudi Arabia, particularly those working with the imaging and characterisation capabilities of KAUST's Imaging and Characterization Core Laboratories, the corrosion-testing capabilities of KFUPM's Center of Research Excellence in Corrosion, Saudi Aramco's R&D center, and SABIC's technology innovation center, the statistically significant conditional associations indicate that test protocols should cover the full service-temperature range since life prediction models developed from single-temperature testing will underestimate the degree of FL degradation occurring due to operation at elevated temperatures. The significant MH → DA path relationship (β = 0.264) indicates that practitioners regard microstructural consistency as relevant to fatigue performance, which supports examining the case for tighter microstructural specifications at supplier qualification where fatigue-critical aerospace, defence, or oil and gas components are destined for inclusion in the industrial localisation efforts outlined by the Vision 2030 initiative. Furthermore, the results of this investigation have direct relevance to K.A.CARE's nuclear readiness programme. The consistency with which respondents associate thermal severity with fatigue degradation suggests that temperature dependence warrants explicit treatment when life-prediction factors are set for nuclear-grade components. However, the factors themselves must be derived from qualification testing rather than from perceptual data.

5.4. Limitations and future research

The present study has several limitations that should be acknowledged. First, because this study is based on a two-wave time-lagged survey design, which restricts what we can say about causality, longitudinal designs that track components throughout their entire service life will improve our ability to show that what comes first affects what follows. Second, since the manufacturing focus of Saudi Arabia's high-performance manufacturing industry may limit how well we can generalise these findings from one country to another, if we were to replicate these results in US aerospace manufacturing, European aerospace manufacturing, or East Asian aerospace manufacturing, this would improve the extent to which we can generalise these results to other countries. Similarly, replicating these results across all other GCC industrial economies (such as the UAE, Qatar, and Kuwait) would help us determine how well these results apply regionally.

Third, the perceptual data collected from engineers regarding their primary components and applications could be complemented with direct experimental fatigue testing and computational micromechanical modelling to validate the serial mediation structure depicted above; this validation could occur using several research facilities including but not limited to KAUST's Imaging and Characterization Core Laboratories, KFUPM's mechanical testing laboratory, and the Saudi Standards, Metrology and Quality Organization laboratory that provides materials testing services. A complementary direction is to couple the present perception-based model with data-driven life-prediction approaches, which have advanced rapidly for both conventionally processed and additively manufactured alloys.[31-36] Fourth, although the six-construct model utilised in this study provides an excellent foundation for understanding the effects of various factors related to the degradation of turbine engine components during operation, future studies could extend it by incorporating additional constructs that have been shown to affect the degradation of turbine engine components during operation specifically in the service environment of Saudi Arabia (e.g., residual stresses, surface roughness, corrosion caused by exposure to the marine environment of the Arabian Gulf and/or the Red Sea coastline, effects of varying loading frequencies).

Fifth, the model pools respondents working with alloy families whose fatigue behaviour differs substantially. Ti-6Al-4V, Al 7075-T6, AISI 4340, Inconel 718 and 300M steel differ in slip character, phase stability, environmental sensitivity and temperature capability, and the sample additionally includes respondents working with aluminium-lithium and magnesium systems, whose creep and fatigue responses differ again from that of the five principal families[38]; a single set of structural coefficients estimated across them assumes at least metric measurement invariance, which was not established here. The reported coefficients are therefore averages over heterogeneous mechanisms and should not be read as applying uniformly within any one alloy family; this materially limits the generality of the conclusions. Multi-group analysis across specific alloys (Ti-6Al-4V, Al 7075-T6, AISI 4340, Inconel 718, 300M steel) will provide information on whether there are significant differences in the magnitudes of the coefficients in the serial mediation structure among different alloy families. These comparisons will also enable researchers to determine whether the relationships observed in this study are consistent across various alloy families.

Sixth, no out-of-sample predictive assessment of the perceptual fatigue-life construct was undertaken. Cross-validated indicator-level criteria such as Q^2predict could be computed for the measurement model, and indicate how well one engineer's judgements are reconstructed from those of others; they would not, however, speak to the accuracy of any fatigue-life estimate in cycles, which this design cannot address at all. Establishing predictive accuracy in the sense that matters to a designer requires instrumented testing against measured lives, and is properly the task of the experimental programme that this study is intended to help prioritise rather than to replace.

6. Conclusion

Experienced engineers in Saudi high-performance manufacturing consistently judge SR severity and MH to bear on FL through a serial pathway running from DA to CN, and they judge that pathway to be amplified at both stages by thermal severity. A moderated serial-mediation model accounts for approximately 35.4% of the variance in perceived FL. Because all constructs are perceptual, this is statistical evidence about the structure of expert judgement, not an experimentally validated description of fatigue mechanisms; its value lies in complementing and helping to prioritise experimental and simulation work rather than in standing alongside it as independent mechanistic evidence. Subject to these limitations, the findings may help frame materials-selection discussions, life-assessment practices, and thermomechanical design reviews within organisations such as SAMI, Saudi Aramco, SABIC, K.A.CARE, and GAMI-associated supply chains, as well as within the broader Saudi materials-engineering community supporting aerospace, defence, oil and gas, power-generation, and heavy-industry localisation under Vision 2030.

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Conflict of interest

The authors declare no conflict of interest.

Author contributions

Conceptualization: Shaher Alshammrei
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Methodology: Shaher Alshammrei
Writing – original draft: Sidra Ghulam
Writing – review & editing: All authors

Availability of data

The data are not publicly available due to confidentiality. The survey responses were collected from practising engineers under assurances of confidentiality and cannot be shared. However, Its available from the authors on reasonable request.

AI tools statement

No generative AI tools were used in the preparation of this manuscript.

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Appendix

A. Measurement items

All items were rated on a seven-point Likert scale (1 = strongly disagree, 7 = strongly agree) with reference to the respondent's primary alloy family and primary application. The questionnaire was administered in parallel Arabic and English versions produced by back-translation.

Stress ratio (SR)

SR1. The cyclic stress range applied to my primary components is severe.

SR2. The mean-stress component of the loading on these components is high.

SR3. These components are subjected to a high frequency of load application.

SR4. The loading amplitude on these components is markedly asymmetric.

SR5. Overall, the severity of cyclic loading on these components is high.

Microstructural heterogeneity (MH)

MH1. Grain size varies appreciably within my primary alloy family.

MH2. The distribution of phases in this alloy family is non-uniform.

MH3. Precipitate dispersion in this alloy family varies appreciably.

MH4. Porosity and inclusion content in this alloy family are heterogeneous.

MH5. Crystallographic texture in this alloy family varies appreciably.

Damage accumulation (DA)

DA1. Dislocations accumulate rapidly in these components under service loading.

DA2. Grain-boundary sliding proceeds rapidly in these components.

DA3. Slip bands form rapidly in these components.

DA4. Microvoids coalesce rapidly in these components.

DA5. Slip localisation in these components is severe.

DA6. Overall, damage accumulates rapidly in these components.

Crack nucleation (CN)

CN1. The density of sites at which cracks first form in these components is high.

CN2. The time to formation of the first crack in these components is short.

CN3. Early-stage crack initiation sites in these components tend to cluster.

CN4. The population of early-stage cracks in these components grows quickly.

CN5. Multiple nucleation sites frequently occur simultaneously in these components.

CN6. Overall, the intensity of crack nucleation in these components is high.

Fatigue life (FL)

FL1. These components achieve their design-target fatigue life.

FL2. The number of cycles to failure achieved by these components is satisfactory.

FL3. The fatigue reliability of these components as designed is high.

FL4. Scatter in the observed fatigue lives of these components is low.

FL5. In-service fatigue failures of these components are infrequent.

FL6. Overall, the fatigue life of these components is satisfactory.

Operating temperature (TEMP)

TEMP1. The service temperature of these components is high.

TEMP2. Thermal gradients across these components in service are severe.

TEMP3. These components undergo frequent thermal cycling in service.

TEMP4. The risk of environmentally assisted damage from thermal exposure is high.

TEMP5. Overall, the thermal severity of the service location of these components (Eastern Province, Empty Quarter, Red Sea coast or gas-turbine service) is high.