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Study of Stress-Concentrated Areas in a 600 MW Corner-Fired Pulverized-Fuel Boiler under Flexible Operation: A Knowledge-Based Assessment Framework for Proactive Maintenance

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Abstract - Flexible operation of coal-fired units—frequent start-ups, rapid load ramps, prolonged part-load running and two-shifting—has become unavoidable as renewable energy penetration grows in India. Large pulverized-fuel (PF) boilers such as 600 MW corner-fired units were designed for steady base-load duty, so their pressure parts now experience thermal, mechanical and chemical cycling for which they were not originally optimised. This paper presents a structured, knowledge-based assessment (KBA) framework for identifying stress-concentrated areas and cracking potential in such a boiler so that maintenance can move from reactive repair to proactive prevention. Seven damage mechanisms (high- and low-temperature thermal fatigue, creep–fatigue interaction, corrosion fatigue, stress corrosion cracking, mechanical restraint and flow-induced vibration) are mapped to boiler components, and a five-phase method—data collection, expert knowledge elicitation, prioritisation of high-risk areas, inspection and monitoring strategy, and preventive and mitigation measures—is described. Pictorials, a mechanism–location matrix and a likelihood–consequence risk matrix are provided so that maintenance engineers can convert plant data into a ranked, targeted inspection plan during planned outages.

Keywords - boiler; stress concentration; thermal fatigue; flexible operation; corner-fired boiler; weld cracking; non-destructive testing; risk-based inspection; proactive maintenance

I. INTRODUCTION

The rapid addition of wind and solar capacity to the Indian grid has changed the role of coal-fired generation from steady base-load supply to flexible, load-following service [1]. Units that were designed, procured and commissioned for continuous operation near rated output are now asked to ramp quickly, run at part load for long periods and, in some cases, shut down and restart daily (two-shifting). Every one of these events imposes a thermal transient on boiler pressure parts, and the resulting cyclic stresses consume fatigue life much faster than steady running does [2].

A 600 MW corner-fired PF boiler contains a very large number of welds, tube bends and several thick-walled headers. A forced outage caused by a single through-wall crack costs generation, repair effort and—through the additional start-up cycles—further component life. Maintenance driven by failure history alone is therefore inadequate; a deliberate method is needed to identify, before failure, where cracks are most likely to start.

This paper presents such a method. A knowledge-based assessment (KBA) framework is described that (i) classifies the damage mechanisms active under flexible operation, (ii) maps them to boiler components, (iii) ranks locations by likelihood and consequence of cracking, and (iv) converts the ranking into a targeted inspection, monitoring and mitigation plan. Figures and tables are used throughout so that plant engineers can apply the approach directly during planned outages.

II. CRACKING MECHANISMS UNDER FLEXIBLE OPERATION

Before an assessment is made it is essential to understand why flexible operation produces cracks. Seven primary mechanisms are active; they are summarised in Table I and are explained below.

TABLE I
PRIMARY CRACKING MECHANISMS AND WHERE THEY OCCUR

Mechanism	Driver	Typical locations
High-temperature thermal fatigue	Repeated heating/cooling; differential expansion between parts at different temperatures	SH/RH, headers, drums, thick-walled parts
Low-temperature thermal fatigue	Rapid temperature swings during start-up; water chemistry upsets	Water walls, economizer
Creep–fatigue interaction	Time-dependent creep strain plus cyclic strain at high temperature	Older base-load-designed SH/RH sections
Corrosion fatigue	Cyclic stress with oxygen pitting, acid or caustic attack	Water-touched tubes, deaerator
Stress corrosion cracking (SCC)	Tensile stress + corrosive environment + susceptible material	Specific welds and materials
Mechanical restraint	Rigid attachments or improper supports resist thermal expansion	Buckstay, hanger, clip welds
Flow-induced vibration	Steam/water flow excitation	Small-bore or unsupported tube lengths

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Thermal fatigue arises when part of a component is forced to expand or contract differently from the rest. For a fully restrained element, or through the wall of a thick section, the thermal stress is

$$\sigma_{th} = E\,\alpha\,\Delta T / (1 - \nu) \qquad (1)$$

where E is Young's modulus, α the coefficient of thermal expansion, ΔT the temperature difference and ν Poisson's ratio. Repeated cycles of this stress produce a hysteresis loop (Fig. 1b); the plastic strain range governs the cycles to crack initiation, commonly expressed by the Coffin–Manson relation [5], [6]:

$$\Delta\varepsilon_p/2 = \varepsilon'_f\,(2N_f)^c \qquad (2)$$

Under base-load duty the metal temperature remains almost constant, whereas flexible duty superimposes large and frequent swings (Fig. 1a), so the number of damaging cycles N accumulates quickly. Where several cycle types occur, cumulative damage may be estimated by Miner's rule [13]:

$$D = \Sigma\,(n_i / N_i) \qquad (3)$$

At high temperature, creep adds time-dependent damage and the two mechanisms interact, accelerating crack growth [4]. *Corrosion fatigue* and *stress corrosion cracking* require a corrosive environment (oxygen, acids, caustic) in addition to stress, which is why feed-water and boiler-water chemistry is part of any cracking assessment. *Mechanical restraint* and *flow-induced vibration* act as stress raisers: a rigid attachment weld or a poorly supported tube can create a local stress far above the nominal value,

$$\sigma_{max} = K_t \cdot \sigma_{nom} \qquad (4)$$

where K_t is the stress concentration factor. Weld toes, stub-to-header junctions, header ligaments and openings all carry high K_t and are, therefore, the natural starting points for cracks.

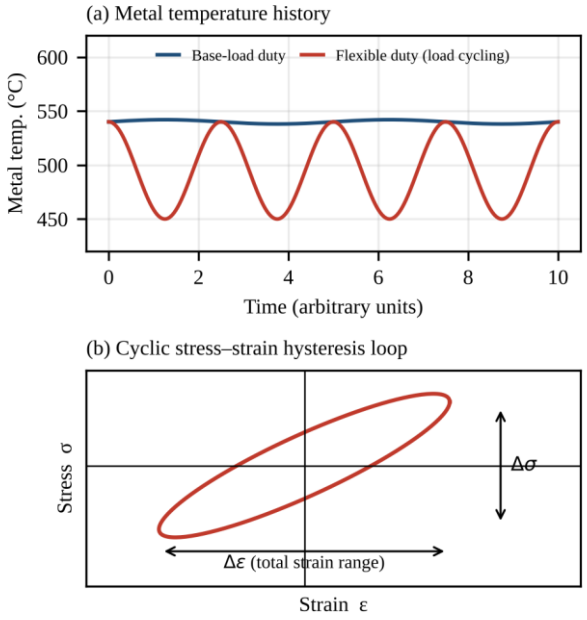


Fig. 1. (a) Metal temperature history under base-load and flexible duty; (b) resulting cyclic stress–strain hysteresis loop.

III. BOILER CONFIGURATION AND STRESS FEATURES OF CORNER FIRING

The boiler considered is a 600 MW corner-fired PF unit. Four windboxes, one in each furnace corner, fire fuel and air tangentially to an imaginary circle at the furnace centre, creating a rotating fireball (Fig. 2). This arrangement gives good mixing and flame stability, but it also has consequences for stress:

(a) heat flux to the water walls is non-uniform and highest near the burner elevations, with flame impingement and slag shedding on the wall zones shown in Fig. 2; (b) the corners contain tube bends and windbox openings with many welds; (c) residual swirl at the furnace exit produces gas-temperature imbalance across the width, so some superheater and reheater elements run hotter and see larger temperature swings during load changes; and (d) complex flow patterns in the superheater and reheater make stub-to-header welds particularly sensitive.

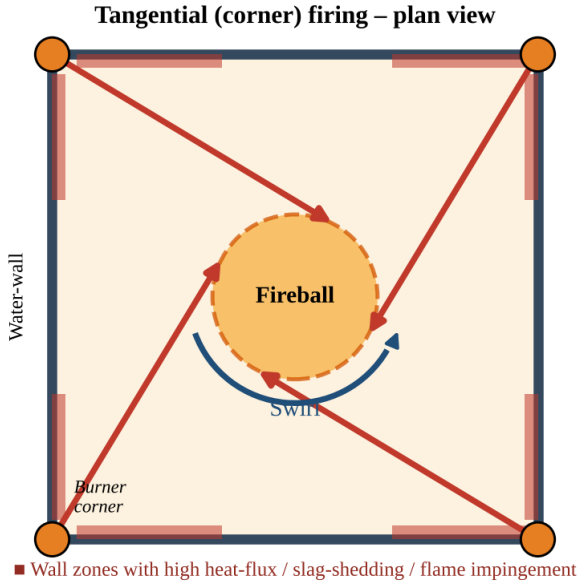


Fig. 2. Tangential (corner) firing, plan view, showing the fireball, swirl direction and wall zones of high heat flux and slag shedding.

The general arrangement of the boiler and the ten principal stress-concentrated locations identified in this study are shown in Fig. 3. The layout is generic; exact arrangements differ between designs, and the figure should be read together with the unit's own drawings.

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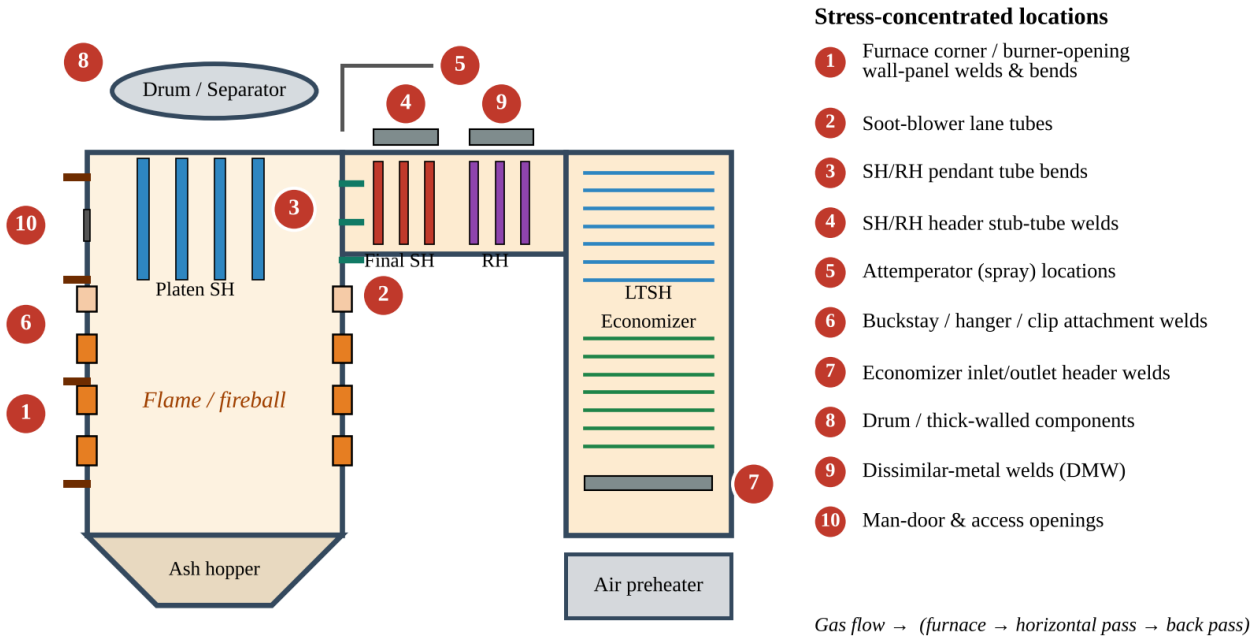


Fig. 3. General arrangement of a 600 MW corner-fired PF boiler (schematic, side elevation) showing the principal stress-concentrated locations (1–10).

IV. ASSESSMENT METHODOLOGY

The framework consists of five interconnected phases (Fig. 4). The output of each phase is the input to the next, and the last phase feeds back into the first so that the assessment remains current as operating experience grows.

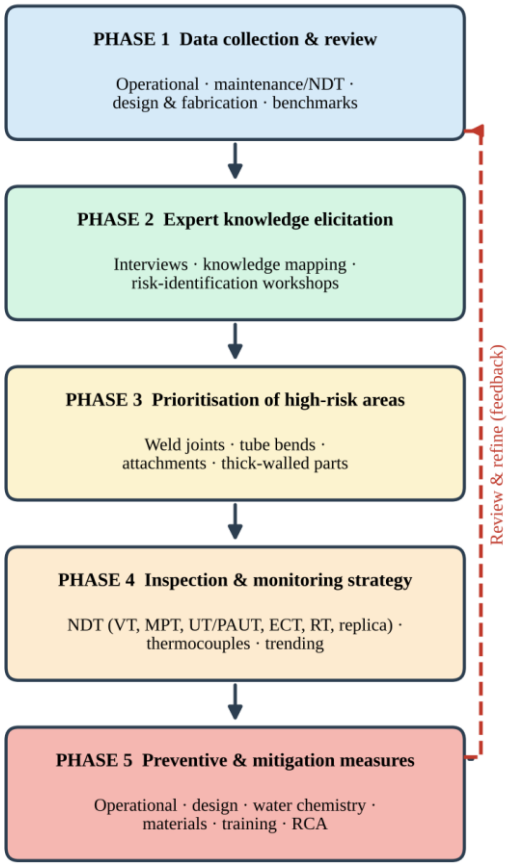


Fig. 4. Five-phase knowledge-based assessment (KBA) framework with feedback loop.

A. Phase 1 – Data collection and review

The foundation is all available historical and operational data that can shed light on past issues and current stress profiles (Table II). Load history—the number of starts and stops, load ramps, part-load operation and two-shifting—is paramount,

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followed by temperature trends, which must be examined for rapid fluctuations.

TABLE II
DATA REQUIRED FOR PHASE 1

Category	Required data
Operational	Load cycles (starts/stops, ramps, part load, two-shifting); trends of main/reheat steam, flue-gas, metal and feed-water temperatures; drum/steam pressures; burner and fuel-flow patterns; soot-blowing cycles; water chemistry (pH, conductivity, O_2, silica, chlorides, iron, copper)
Maintenance & inspection	Past failure-analysis reports with root causes and locations; earlier NDT results (UT, MPT, LPT, ECT, RT), including sub-critical indications; repair history and repeat failures; visual observations of bulging, distortion or surface irregularities
Design & fabrication	GA drawings, P&IDs and tube schematics; stress-analysis reports; WPS/PQR, welder qualification, heat-treatment and QC records
Benchmarking	Failure statistics and best practice from similar 600 MW corner-fired units; OEM and consultant advice

B. Phase 2 – Expert knowledge elicitation and analysis

Data alone does not reveal why a location fails. Operations engineers know the transients and the areas they perceive as highly stressed; maintenance engineers and technicians know where repairs repeat; metallurgists and failure-analysis specialists understand the degradation mechanisms. Their knowledge is gathered through structured interviews, and failure mechanisms (Table I) are systematically mapped to components and operating conditions. A cross-functional risk-identification workshop—operations, maintenance, engineering and C&I—then brainstorms candidate cracking locations based on historical failures, known stress-concentration points in the design and areas of high thermal gradient during flexible operation.

C. Phase 3 – Prioritisation of high-risk areas

Based on the data and expert input, the audit is focused on four groups of locations: weld joints, tube bends, attachment points and other high-risk areas. Table III lists the prioritised locations and the reason each is susceptible. The qualitative susceptibility of each location to each mechanism is shown in the matrix of Fig. 5, which also guides the choice of inspection method in Phase 4.

TABLE III
PRIORITISED HIGH-RISK LOCATIONS IN A 600 MW CORNER-FIRED BOILER

Zone	Location	Basis for priority
Weld joints	Furnace wall panel welds	Near burner openings, soot-blower lanes, and areas with flame impingement or slag shedding
	SH & RH header welds	Stub-to-header welds at inlet/outlet headers with large temperature swings; complex flow patterns in corner-fired boilers
	Economizer inlet/outlet header welds	Feed-water temperature fluctuations
	Attachment welds	Buckstay, hanger-rod and support-clip welds; highly fatigue-prone because thermal expansion is restrained
	Dissimilar metal welds (DMW)	Inherently high risk where ferritic and austenitic materials differ in thermal expansion
Tube bends	SH/RH pendant tube bends	High temperature and differential expansion within bundles; condensate pooling at start-up causes local overheating
	Water-wall tube bends	Furnace corners, near burners and high heat-flux areas; flow stratification or stagnation
	Economizer tube bends	Flow disturbances and thermal shock
Attachment points	Tube-to-header attachments	Stubs and ligaments where tubes enter or leave headers
	Soot-blower lane tubes	Thermal shock and erosion in the path of soot-blower jets, at attachments or bends
	Buckstay and hanger-rod attachments	Significant stress where thermal expansion is not accommodated
	Man-door / access openings	Localised stress concentration around openings
Other high-risk areas	Thick-walled components	Headers, drums and large-bore piping respond slowly to temperature change, so transient stresses are high; ligament cracking in headers
	Deaerator	Corrosion-fatigue cracking in welds if deoxygenation is poor
	Attemperator locations	Thermal shock where spray water is injected
	Flow disturbance / stratification areas	Localised hot and cold spots, causing thermal stress
	Areas with historical issues	Always prioritised: previous failures or frequent repairs

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Fig. 5. Mechanism–location susceptibility matrix (qualitative, based on service experience and literature; to be validated with plant-specific data).

Each location is then scored for the likelihood (L, 1–5) of cracking and the consequence (C, 1–5) of a crack in terms of safety, forced outage duration and repair cost. The product L × C places the location in a risk band (Fig. 6, Table IV). The scores shown are indicative, assigned by engineering judgement for the purpose of illustration; each plant should replace them with its own data from Phases 1 and 2. The identification numbers follow the row order of Fig. 5.

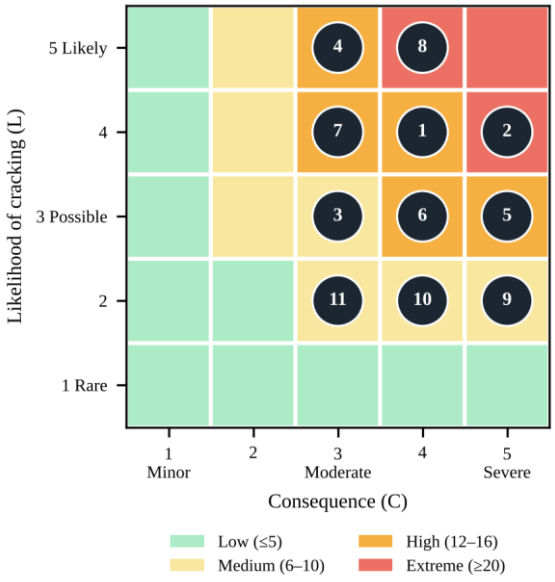


Fig. 6. Likelihood–consequence risk matrix (indicative). Numbers refer to the rows of Fig. 5.

TABLE IV
INDICATIVE RISK RANKING (L × C)

ID	Location	L	C	L×C	Band
2	SH/RH header stub-tube welds	4	5	20	Extreme
8	Soot-blower lane tubes	5	4	20	Extreme
1	Furnace wall burner/soot-blower zone welds	4	4	16	High
5	Dissimilar-metal welds	3	5	15	High
4	Attachment welds	5	3	15	High
6	SH/RH pendant tube bends	3	4	12	High
7	Water-wall corner tube bends	4	3	12	High
9	Thick-walled headers / drum ligaments	2	5	10	Medium
3	Economizer header welds	3	3	9	Medium
10	Attemperator locations	2	4	8	Medium
11	Deaerator welds	2	3	6	Medium

D. Phase 4 – Inspection and monitoring strategy

Once the high-risk areas are known, a targeted plan is formulated. Off-line non-destructive testing is selected according to the mechanism and location (Table V) [8]. For instance, surface-breaking fatigue cracks at attachment welds in ferritic steel are best found by MPT, whereas cracks initiating from the inside diameter of thick headers need UT or phased-array UT.

TABLE V
NDT AND MONITORING METHODS

Method	Application
Visual (VT)	Scale exfoliation, bulging, discolouration and surface cracks, during every outage
Magnetic particle (MPT)	Surface and near-surface cracks in ferritic materials at welds and attachments
Liquid penetrant (LPT)	Surface cracks, including non-ferrous materials, on accessible surfaces
Ultrasonic / phased-array UT	Internal flaws, crack sizing and weld integrity in thick sections and inaccessible areas; ID-initiated cracks
Eddy current (ECT)	Surface and near-surface cracks in tubes; internal bore inspection

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Method	Application
Radiography (RT)	Volumetric flaws and cracks in welds; limited by access and radiation safety
Replica metallography	Microstructural damage such as creep damage and fatigue striations
Thermocouples (on-line)	Metal temperature gradients and rate of change at headers, SH outlets, furnace walls and attachments during transients
Acoustic emission / strain gauges	Real-time crack propagation and local strain during critical events; implementation is complex in a boiler environment
Operational data trending	Continuous trending of temperatures, pressures and load changes against historical data and design limits

Cycle data should be counted (for example by rainflow counting of the load and temperature records, separating hot, warm and cold starts from load ramps) and converted to a usage factor using Eq. (3). Together with thermocouple data, this tells maintenance how much of the fatigue life of each ranked location has already been consumed.

E. Phase 5 – Preventive and mitigation measures

The ultimate goal is to translate the assessment into action. Measures fall into operational, design, water-chemistry, materials and human/digital categories (Table VI), and are most effective when applied together.

TABLE VI
PREVENTIVE AND MITIGATION MEASURES

Category	Measures
Operational adjustments	Adhere to OEM start-up/shutdown ramp rates for temperature and pressure; optimised load following that smooths load changes; avoid prolonged operation below minimum stable load (flow instability, localised overheating/cooling); optimise soot-blower frequency and duration to limit thermal shock
Design modifications	Improve circulation in critical areas; modify supports to permit greater expansion; upgrade materials in high-stress zones; fit internal sleeves or thermal liners where thermal shock occurs; weld overlay/cladding in corrosion-fatigue areas; redesign attachments to reduce stress concentration
Water chemistry	Strict adherence to boiler-water parameters (pH, oxygen, impurities); effective deaeration; regular, properly executed chemical cleaning to remove internal deposits
Material selection	At repair or replacement, use material with better thermal-fatigue resistance where the existing material is prone to it
People & digital	Operator training on the effects of rapid load changes; digital twins and predictive analytics to simulate stress under operating scenarios; RCA of every failure, however small

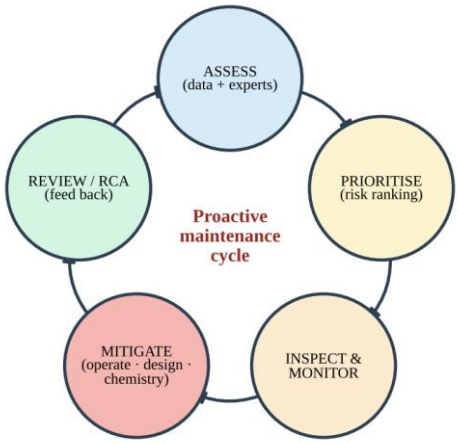


Fig. 7. Closed-loop proactive maintenance cycle: assess, prioritise, inspect and monitor, mitigate, review.

V. DISCUSSION AND APPLICATION

Reading the matrix. Fig. 5 shows that the damage mechanism differs by region. High-temperature locations—SH/RH header stubs, DMWs and pendant bends—are dominated by high-temperature thermal fatigue and creep–fatigue interaction, whereas furnace and economizer locations are dominated by low-temperature thermal fatigue and corrosion fatigue. Attachment welds are controlled mainly by mechanical restraint. Because the mechanisms differ, a single inspection technique is not adequate for all locations, and the matrix is used to match method to mechanism.

Using the ranking. In the indicative ranking of Table IV, SH/RH stub-tube welds and soot-blower lane tubes occupy the extreme band because both their likelihood and their consequence are high. A suggested philosophy is to inspect extreme- and high-band locations at every planned outage, medium-band locations on a rolling programme, and to keep the whole scheme within the statutory inspection regime of the Indian Boiler Regulations [12] and the applicable ASME and EN codes [7]–[9]. Where a crack indication is found, its significance should be judged by fitness-for-service assessment [10] rather than by detection alone.

Plant implementation. The framework is best applied as a living crack-risk register: one line per location, with its mechanism, score, last inspection result, cycle-based usage factor and the next planned action. Every failure or indication is fed back through root cause analysis, and the L and C scores are revised. In this way the assessment becomes more accurate with each outage.

Limitations. The framework is qualitative and depends on the quality of plant data and expert judgement. The susceptibility and risk scores presented here are indicative and are not a substitute for unit-specific stress analysis, remaining-life assessment or OEM recommendations. They should be calibrated against actual failure history and inspection findings before being used to set intervals.

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VI. CONCLUSION

Flexible operation exposes base-load-designed 600 MW corner-fired boilers to thermal fatigue, creep–fatigue, corrosion fatigue and restraint-related cracking. A five-phase knowledge-based framework has been presented to identify stress-concentrated areas before they fail: (1) collect operational, maintenance and design data; (2) draw on the experience of operations, maintenance and metallurgy personnel; (3) prioritise weld joints, tube bends, attachment points and thick-walled components using a mechanism–location matrix and a likelihood–consequence risk matrix; (4) select NDT and on-line monitoring to suit each mechanism; and (5) apply operational, design, chemistry and training measures, with root cause analysis of every failure closing the loop. Used as a living register, the framework allows maintenance resources to be concentrated where cracking is most probable and most costly, supporting safe, reliable and flexible operation of the unit.

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