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A COMBINED CREEP AND FATIGUE DAMAGE ESTIMATION TOOL FOR POWER-PLANT MONITORING

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ABSTRACT

A user-friendly creep-fatigue damage calculation tool is developed in Visual Basic for Applications (VBA) with the familiar Microsoft Excel® user interface for power plant operators. Operational pressure and temperatures (steam and pipe exterior) are directly input and automatically converted to stress-time histories based on the summation of thermally- and mechanically-induced stresses. The stress history is automatically analysed and segregated into periods of sustained stress levels (creep range) and periods of fluctuating stress (fatigue range). Total damage is determined by summing the creep damage fraction (via Larson-Miller equation and Robinson's rule) and fatigue damage fraction (via a rainflow cycle counting subroutine, the Smith-Watson-Topper fatigue parameter and Miner's rule). Pre-existing damage fraction can be incorporated into the calculations. The remaining life estimates based on repetition of the load profile are outputted for the user. Finally, the estimated damage and remaining life are compared to that determined via the ASME, EN and TRD codes, where applicable.

INTRODUCTION

Monitoring the accrual of power plant creep damage (at operational conditions) and fatigue damage (during start-up, shut down or load change events) are key aspects of power plant management, particularly due to the introduction of increased cycling operation. This includes the ability to accurately predict component life, in order to minimise plant downtime due to unexpected failure. Recent advances in the characterisation of constitutive and damage behaviour of power plant materials at varied temperature ranges, and under static and dynamic thermomechanical loads have improved predictive capability [1-3]. However, in practice, plant infrastructure is designed to and monitored via industry standard codes (ASME, EN, TRD etc.) that are based on relatively conservative estimations of life span and safe operational temperatures and pressures. Such codes were developed primarily with creep failure in mind with anticipated near-continuous operational mode. However, a recent shift in the power generation industry has seen a considerable number of power plants operating under frequent load changing and start-up shut-down cycle conditions. It is anticipated that in the future, fatigue damage will play a greater role in plant component failure, particularly in the hotter end of the cycle where P91, P22 and X20 steel are used.

In industry, the codes specify a step-wise or multi-level analyses, as outlined by Brear [4], where a low level inspection and low cost damage calculation is first made. If this simple calculation predicts the possible occurrence of damage, a more detailed level of analysis (e.g. finite element analysis and component inspection) is performed. There is a requirement for improved accuracy and automation of the low-level calculation tools for estimating creep and, in particular, for inclusion of fatigue, in order to ensure the safe running and maximum efficiency of power plants under such new operation modes.

In general, industry codes tend to be based on linear damage summation approaches, where damage due to creep and fatigue are calculated after categorising the operational parameters (pressure, temperature, time) into simple ranges and then referring to standard creep and fatigue curves appropriate to each range. Commonly used codes include the TRD codes (301, 508), ASME-III-NH, and EN 12952 code sets [5-9].

There are many similarities between these codes but also noted differences, e.g. each uses different stress derivatives, and differs in whether design margins are included within the reference creep and fatigue database curves themselves, or are applied prior to use of the material's creep curves. The recommended threshold for "allowable damage" also varies between the different codes.

The critical stresses due to the static operational parameters can be calculated in a number of ways, depending on the level of analysis required, as described above. The simplest method is to use analytical formulae for standard geometries (e.g. thin walled circular tubes etc.) to give values for hoop, radial and axial stress based on the internal pressure. In general, only the operational pressure is used to determine this static stress, i.e. thermal effects are assumed negligible. A more advanced level of analysis may include finite element modelling of the 2D or 3D structure in question, to give the critical stresses and their precise locations. This is particularly useful in complex geometries that include welds, such as at T-joints [3].

EN and TRD codes calculate creep damage in a nearly identical manner. First, the temperature and pressures operational profiles are divided into bands and the number of hours of operations within each band is counted. The mean temperature is used in each band to select the appropriate creep curve, and the mean pressure is used to determine the "mean" membrane stress. The membrane stress for each band is determined since secondary and peak stress relax during creep conditions [10]. For each band, the maximum number of hours before failure in continuous operation at that particular fixed temperature and pressure is found in the creep reference curves. The number of hours of actual operation is divided by this maximum service life to give a measure of creep damage fraction [11]. The creep damage from all bands in the profile is then totalled using Robinson's rule.

The EN and TRD code sets include a provision to exempt fatigue from the total damage calculation, if the materials are carbon or low alloy steels and the total number of cycles are below an "allowable" threshold, depending on the pressure ranges and thermal gradients [7, 8]. If these fatigue exceptions are not met, the basic method for determining fatigue damage is to first subdivide the operational history profile into individual simple bands or cycles, with the number of occurrences of each cycle determined. The statically determined stress ranges due to the pressure load are calculated and the corresponding database of fatigue curves is used to give the total number of allowable cycles for each profile before failure. The percentage fatigue damage associated with each profile is then determined by dividing the number of cycle occurrences by the number of cycles to failure. Thus the fatigue damage (in %) for each profile is then calculated and summed using Miner's rule to give the total fatigue damage.

Correction factors

The presence of joints is usually accounted for by the inclusion of a stress concentration factors. The EN 12952-3 code allows for more customisation of the stress concentration factors (e.g. based on geometric ratios etc.) than the TRD code [4]. EN 12952-3 specifies a temperature correction factor in its fatigue calculation method. However, the reference fatigue data curves are still based on room-temperature tests only.

Scientific literature

Damage calculation

There are a number of publications in the literature on the estimation of damage mechanisms of steels under thermomechanical creep and fatigue conditions. Some of these studies utilise industrial standards approaches while others describe novel methods for damage calculation. Many approaches are theory based [12-19] while others have demonstrated their suitability for industry applications [20-24] or the basis for on-line plant management software [11, 25-30]. Such software systems involve live temperature and pressure sensors from the plant components for real-time data input to the damage calculations and monitoring system. Other studies have generated databases of predicted damage behaviour for various component geometries by conducting a large series of finite element analyses [12].

Numerous methods for the calculation of fatigue damage are presented in the literature. Some are similar to industry code approaches where the damage fraction is determined by dividing the number of cycles at a particular load by the total number of cycles permissible at that stress before failure[11]. Regardless of the method used, the first step is generally to characterise the operational stresses into distinct cycles, reversals or transients, and to count the number of occurrences. Complex methods such as strain range partitioning (separating in-elastic strain-range into time independent plasticity and time dependent creep), ductility exhaustion (exhaustion of the static toughness and dissipation of the plastic strain energy) [31, 32], thermodynamic entropy (novel combination of Manson-Coffin and cyclic stress-strain equations) [25] and crack growth and interaction models [28] are found in the literature. Useful summaries of the different analysis methods in the literature are available from Zhuang [33] and Helford [34].

Material data

A recent compilation of experimental creep data of welded P91 steel at various temperatures from multiple Japanese companies and institutes provides a valuable compilation of raw creep data [21]. From the 370 experimental creep tests of welded P91 steel included in that study, the heat affected zone (HAZ) accounted for almost half of the specimen failure locations (48%), followed by weld metal (27%) and parent metal (24%). The experimental dataset has been condensed to a master Larson-Miller parameter (LMP) equation for welded P91 (Eq. 1). The LMP is widely used to relate temperature and stress to creep rupture time [21, 35], although other characteristic equations are also available in the literature [36].

$$(T+273)(31.4+\log t_r) = (34154+3494(\log\sigma)-2574(\log\sigma^2) \qquad (1)$$

A smaller experimental dataset for P91 creep failure was published by Tanner et al [37], who reported that creep failure occurred in the HAZ for 100% of the P91 samples tested. This trend indicates the importance of accurately accounting for weld strengths in damage predictions.

In practice, cracked P91 pipes tend to be repaired immediately once a crack is discovered. However it is considered industry practice that a repair should only be performed a maximum of two times with P91. After that, the part is usually replaced. This is due to the potential for additional material damage/degradation caused by repeating the heat treatment.

The objective of this work is to develop a new damage calculation tool suitable for use in power plant management systems, with the following features:

- Direct import of real plant operational parameter data logs (pressure, temperature).
- Minimise the use of stress concentration or strength reduction factors.
- Facility to include pre-existing damage (e.g. from a weld repair) that occurred outside of the data log period.
- Comparative analysis with industry standard codes.

It is hoped that this tool will lead to a reduction in cost and increased efficiencies of plant inspection programmes by enabling rapid estimation of damage rates and remaining service life.

NOMENCLATURE

LMP	Larson-Miller Parameter
SWT	Smith-Watson-Topper
T	temperature (°C)
t_r	time to creep rupture (hr)
σ	stress (MPa)
α_m	geometry based stress concentration factor
d_{ms}	internal pipe diameter (mm)
e_{ms}	wall thickness (mm)
p	pressure (MPa)
β_{Lt}	coefficient of linear thermal expansion (K^{-1})
E_t	elastic modulus (MPa)
ν	Poission's ratio
Δt	wall temperature difference
$\sigma_f{}'$	fatigue strength coefficient
$\varepsilon_f{}'$	fatigue ductility coefficient
N_f	number of cycles to failure
$\Delta\varepsilon$	strain increment
σ_{max}	max stress in a fatigue cycle
a_1	LMP constant a_1
a_2	LMP constant a_2
a_3	LMP constant a_3
b	fatigue strength exponent
c	fatigue ductility exponent

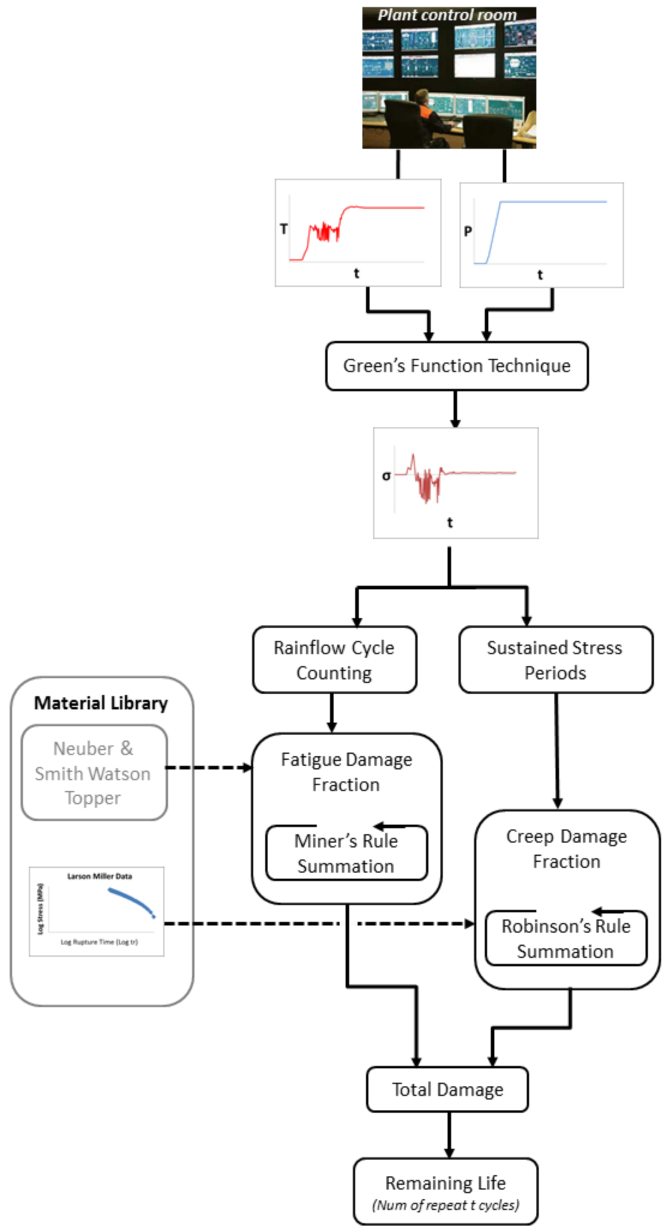

Figure 1: Schematic flow chart for damage tool

TOOL DESIGN

The tool consists of the familiar MS Excel® front end with the damage and lifespan computation implemented in background Visual Basic coding. The suitability of MS Excel® based analysis tools in industry, thereby avoiding specialist software or hardware requirements, has previously been demonstrated [38]. The MS Excel® file contains a series of worksheets, each containing either:

1. A damage calculation.
2. A database of time-dependent material properties and constants.
3. A library of plant component geometries (straight pipe, bends, T-joints etc.).

Each worksheet has a dedicated column A for action buttons for the user to click on. Each action button corresponds to a background VBA subroutine and will perform a data import, analysis or visualisation function. Firstly raw operational parameters, e.g. time, steam temperature, wall temperature and vessel pressure, from the plant management system are imported, where the data is automatically reformatted into regular timesteps and the operational data histories are plotted for the user. The second worksheet determines and displays the stress profile. The total stress is determined by summing the pressure-induced stress and thermal-induced stress based on EN 12952-4-2011, e.g. for the inside corner of a bore as:

$$\sigma = \alpha_m \frac{d_{ms}}{2e_{ms}} p + \frac{\beta_{Lt} E_r}{1-\nu} \Delta t \qquad (2)$$

The stress profile is automatically analysed to extract periods of sustained stress based on user defined thresholds of “allowable” minor fluctuations within sustained stress periods. The creep damage fraction for each period of sustained loading is determined in the subsequent sheet using the averaged LMP characteristic curve developed by Tabuchi *et al.* for welded P91 [21] (Eq 1), to determine the time to failure at the mean stress of the sustained stress period. The total creep damage is determined by summing all the creep damage fractions.

A rainflow cycle counting subroutine extracts each individual cycle of stress from the remainder of the stress profile. The number of cycles to failure, N_f, for each stress cycle is then determined by iteratively solving the Smith-Watson-Topper (SWT) equation (Eq 3) as follows;

$$\frac{\Delta\varepsilon}{2} = \frac{\frac{\left(\sigma_f{}'\right)^2}{E_t}(2N)^{2b} + \sigma_f{}' \varepsilon_f{}' (2N)^{(b+c)}}{\sigma_{max}} \qquad (3)$$

The fatigue damage fraction per cycle is taken as the inverse of the number of cycles to failure. The total fatigue damage is determined by summing all fatigue damage fractions. The combined creep and fatigue damage and predicted life expectancy based on repeats of the original operational parameter data is then displayed in graphical and numerical form for the user. The predicted damage is then displayed in the creep-fatigue damage envelope (ASME III-NH). Although considered conservative, this reference graph is commonly used in industry, and is included in this tool for reference.

CASE STUDY

An operational data set, based on artificially repeating a cold start-up temperature and pressure profile from a steam header of an operational power plant [3], was used for demonstration of cyclic and sustained loading. The internal and external temperature and pressure profiles are shown in Figure 2. The corresponding stress profile is shown in Figure 3 with the periods of creep damage automatically highlighted for the operator, as well as the accumulated creep damage fraction also displayed. Figure 4 shows the accumulation of fatigue damage over the time period.

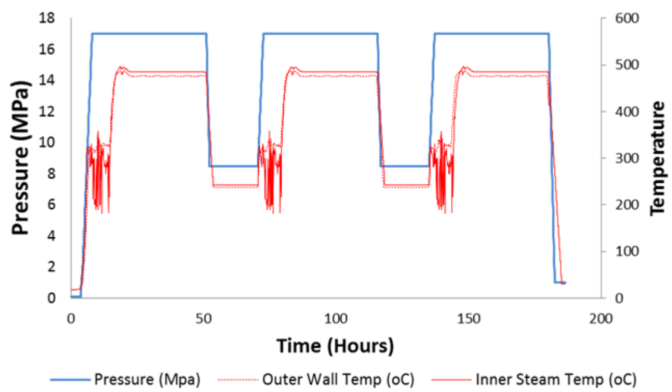

Figure 2: Case study input operational data pressure (left vertical axis) and temperature (right vertical axis)

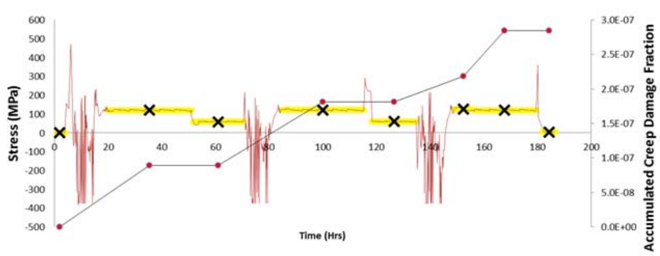

Figure 3: Creep damage periods (highlighted in yellow and with an X) on the stress profile (left vertical axis) creep damage fraction accumulation (right vertical axis).

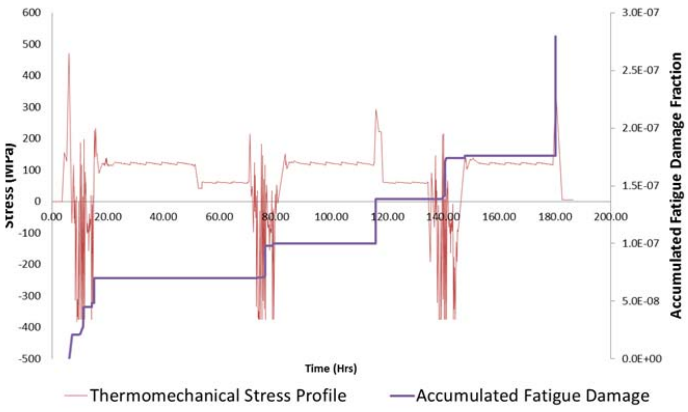

Figure 4: Stress profile (left vertical axis) along with fatigue damage accumulation (right vertical axis).

DISCUSSION

Approximately equal amounts of fatigue and creep damage was generated in the plant component in this case study. The three main periods of fatigue stress were primarily due to a large differential in wall temperatures (up to 120^{o}C). Depending on the running mode, the design of the Boiler or Heat Recovery Steam Generator, and Power Train (whether there is a Gas Turbine, Burners etc.), it is possible for a temperature difference, between the outer wall and the steam side (inner wall) of a superheater tube to significantly differ.

The ASME III-NH code now contains a weld strength reduction factor (WSRF) which lowers the creep-rupture strength of the weld material from the base metal. Currently WSRF are applied to longitudinal seam welds. In this study, WSRF are avoided by using the LMP constants based on welded P91 creep test data. The Smith-Watson-Topper method for calculating fatigue damage is not commonly used in industry but is useful as an alternative to exiting industry code methods.

It is anticipated that this tool will be expanded with additional databases and capabilities over time. Additional geometries, based on the EN and ASME geometry libraries will be added to the tool. The majority of components in power plants operated have been manufactured under EN or AMSE specifications. Parent P91 and forged P91 material properties will also be added to give a wider range of suitable components. Damage calculation methods based on the industry boiler codes (in addition to the piping codes) will also be added to give further functionality. The incorporation of corrosion damage effects may also be considered, given its known contribution to creep and fatigue damage [39]. Currently, Greens function (linear superposition principle) is used to sum independently the pressure and temperature induced stresses; however, it has been shown that temperature dependent properties can significantly influence the maximum peak stresses [40].

The full service history (operational parameters) should be incorporated, as best as possible, to determine the true damage fraction. In the last decade the operating ‘modes’ of large power utility stations has changed significantly to meet demand. As previously mentioned, operations have moved from a base load operation (running non-stop) to a cycling operations mode. Therefore care should be taken not to assume that one particular profile is representative of the entire history of a station.

The MS Excel® tool is designed to serve as a useful analysis tool for industry. It will ultimately contain two damage analysis streams, one that is aligned with the current industry standard codes for calculating creep and fatigue damage. This will allow the plant operator to easily determine if the component has been operated within design code specification. The second stream will allow the user to non-conservatively predict damage formation by minimising the use of stress concentration factors or weld strength reduction factors.

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