A proposal and methodology for the accelerated implementation of probabilistic approaches in the nuclear sector

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Summary
Probabilistic approaches allow the uncertainties and variabilities present in reactor design, operation, material properties and degradation mechanisms to be understood and the reliability to be quantified. Improved knowledge in the structural integrity field continues to highlight that the unquantified margins associated with current deterministic methods do not provide a consistent measure of component risk, sometimes resulting in unexpected failures but more often resulting in over engineered structures. The benefit of probabilistic methods, in conjunction with setting target reliabilities, is a more consistent approach to ensuring safety by quantifying margins. This approach enables system-level analysis within which the individual contributions of material, manufacturing, inspection and operational load variability to the overall reliability to be evaluated and optimised to ensure safety. The nuclear community, in particular, would benefit from applying probabilistic methods to structural assessment more widely and implementing general probabilistic frameworks for design, analysis and assessment in engineering structural integrity. The transition from determinism to probabilism is a natural one, but requires considerations of user knowledge, method choice, computational intensity and accuracy of outcome, as well as selection and use of case studies for training and benchmarking. This paper proposes a methodology to implement probabilistic approaches specifically in the nuclear sector and explores these drivers for implementation acceleration. The research draws on a number of case studies to demonstrate the probabilistic methods utilised in recent years by the authors as well as proposal for benchmarking cases. Case studies are taken from a range of relevant applications and will be tailored towards features also expected to be critical in the design of new Advanced Modular Reactors (AMRs). The main output of this research will eventually be a UK guidance document on probabilistic approaches which will reflect best practice and will provide advice on what would be suitable for inclusion within international codes and standards, supported by engagement and dissemination activities with stakeholders and wider industry.

Key Words
Structural integrity, deterministic, probabilistic, implementation, Advanced Modular Reactors, case studies, codes.

Introduction
Probabilistic approaches for structural integrity started to be developed in the 1960s [1], in order to facilitate a more complete understanding of the probability of failure of components. Essentially, the practitioner of the probabilistic approach is required to incorporate known uncertainties in input parameters, such as loads and geometry, and propagate these through physics-of-failure type models reflecting the problem objective e.g. stress, fatigue, creep etc. comparing this uncertainty to uncertainties in the material's strength and other properties at the service environment required to determine failure probability. The demands on the practitioner to implement a probabilistic approach are greater compared to conducting the more traditional deterministic approach where, all the uncertainties are typically catered for using subjective factors of safety. Determinism results in little knowledge about the impact of uncertainty and does not promote the idea of a probability of failure prediction at all. Much has been written about the benefits of probabilistic over deterministic approaches [2,3], however, it remains that its adoption and utilization is inconsistent and not as widespread as deterministic approaches currently in any major sector due to several major implementation issues and inhibitory factors, including structural integrity in the nuclear industry.

The focus of the paper is to help aid the rapid adoption, implementation and diffusion of probabilistic approaches in the nuclear sector, with a specific focus to provide efficient probabilistic approaches suitable for the design and assessment of components and features relevant to future AMRs [4]. AMRs are expected to be more cost effective and faster to build than larger, more conventional nuclear power stations and are therefore seen by many as the future solution for the nuclear power sector to deal with capacity increases against a legacy of aged nuclear fleet Worldwide [5]. It was estimated in 2018 that there were 50 advanced or small modular reactor design in various stages of development in over 10 different countries [4], with some potentially being operational by 2021. Although some generic details are known about the new small and advanced modular reactor designs, different designs will demand different operating temperatures [6]. Temperatures for certain plant components above 450 °C are high for traditional ferrous-based alloys (low alloy, stainless etc) used in plant, causing susceptibility to creep rupture. Nickel based alloy development in the future could see creep free operational temperatures reach 750 °C [7]. High-temperature variant designs of gas cooled reactors could push operating temperatures between 800 and 1,000 °C [6] for some plant components. However, together with thermal cycling over many years of likely operation, including transient as well as steady state conditions (which could be more accelerated and demanding than usually experienced), suggests the highly complex phenomenon of creep-fatigue will be an important failure mode to address.

In the UK, where Advanced Gas Cooled Reactors (AGCR) dominate nuclear power generation [6], increased efforts have recently been focussed on plant life extension to help manage future energy generation [8,9]. This has driven the use of probabilistic approaches in order to increase the confidence in structural integrity assessments through the effective management of uncertainties, compared to deterministic zxapproaches used, which dominate design codes still. The UK, as well as many other countries, are putting funding in place for potential vendors and researchers to demonstrate the technical and economic viability of AMRs. In the context of a future nuclear capability in the UK, this will not happen through collaboration of government and industry alone, but also requires commitment from regulators e.g. The Office for Nuclear Regulation (ONR) in the UK [10]. It is also timely to promote the use of probabilistic approaches as mandatory for future nuclear design, analysis and assessment of AMR plant, including high or very high temperature AMR designs. For example, current Probabilistic Safety Assessment (PSA) guidance from the ONR states in Section 4.6.3.3 [11]:

> *"The methodology used for the calculation of probabilities of structural failures should be justified and the details of the analysis should be transparent…If use is made of probabilistic fracture mechanics codes, the codes should be state of the art and should have been validated against operational experience and/or experiments…."*

From this statement, the mandatory use of probabilistic approaches is not guaranteed, but suggested; yet no guidance on what approaches to use or what constitutes a methodology for probabilistic structural integrity currently exists in order to calculate probability of failure for plant. However, there has been a great deal of interest in advancing probabilistic approaches in the nuclear sector recently, particularly in the UK. For example, EDF's recent appendix to R5 V2/3 [12, 13] provides advice on probabilistic approaches to structural integrity assessments. A guidance document for probabilistic structural integrity was also published by the Nuclear Structural Integrity Probabilistics Working Group and hosted by the Forum for Engineering Structural Integrity (FESI) in 2019 [14]. A joint seminar between FESI and the Institution of Mechanical Engineers (IMechE) on the Application of Probabilistic Structural Integrity was also held at IMechE headquarters in 2018. These activities culminated in the funding of a research project by BEIS from 2020-21 called Establishing AMR Structural Integrity Codes and Standards (EASICS) [15], building upon the work previously conducted by Rolls Royce, EDF Energy, NNL, Wood, Fraser-Nash Consultancy and the University of Bristol as partners.

This paper will first introduce some of the known implementation issues and barriers for probabilistic approaches. It will then present selected results from a review of probabilistic approaches applied to industrial case studies and literature in the public domain to gauge current practice in the nuclear sector. Finally, through the outcomes of recent research, several guidance routes and approaches for helping the practitioner progress a probabilistic approach for a problem in structural integrity are presented, before concluding the way forward.

Implementation Issues

It is regarded that all probabilistic methods are mature, in the sense that their development has reached a plateau where it is doubtful that there will be any major theoretical improvements in the foreseeable future. There are many different types of probabilistic methods available, each with its own set of merits and demerits, and these have been reported previously [2,3,16]. This presents a choice issue for the practitioner, and so guidance on which methods are appropriate, not only for the problem type considered (analytical, Finite Element or empirical models representing failure mode), the objective to be achieved, but also at what stage in the development cycle the methods are best aligned, commensurate with the accuracy required. In practice, selection is also driven by the level of and type of input data available, associated statistical modelling required, computational intensity demanded and time to build the probabilistic version of the problem with time and cost constraints [16,17]. Most of the knowledge, procedures and even computational software/code for many of the probabilistic methods is available in the public domain at little or no cost. Further consideration is the need for appropriate computational tools (high-level programming languages such as Matlab, Python and R being considered appropriate), and it is advised that practitioners need to establish not only which tools are available to them, but also consider which ones require a degree of expertise for efficient implementation. The added benefit of the above-mentioned high-level languages is that they provide effective visualisation tools, which can be essential for communicating and interrogating probabilistic results in a familiar form.

Other factors which have found to inhibit implementation of probabilistic approaches are generally related to availability of data and resources and culture within the organisations. Significant challenges face the practitioner if they wish to adopt probabilistic approaches to a problem, and they are not supported in this process. The perception is that probabilistic approaches slow down the design or assessment process, it is too time consuming and tedious to follow, and there is scepticism of the results. Supporting data can also be difficult to collect or timely, and there is a mismatch between ownership of supporting data and those conducting the probabilistic approach. Highlighting and justifying the need for further data acquisition, where sparse, is also a common issue which inhibits a solution. Finally, there is a lack of management support and resources for continued use, or it is perceived as being too costly by management [18]. Less tangible factors are associated with awareness of available probabilistic methods and supporting data, as well as education background and confidence with statistics. One overriding importance factor is having a 'Champion' in the organisation to push through change, command resources and staff, and press management for change. Not being able to change an existing culture of determinism is the obvious threat to implementing probabilism.

Substantial thought must be devoted to bringing practitioners up to a baseline level of understanding and awareness of probabilistic and statistical concepts through training and provision of verified supporting documentation, and therefore it is considered that some training should be conducted as part of the implementation process. With regards to practitioners, extensive use, testing and verification of probabilistic methodologies are required, which can be done in the form of collating a host of case-studies ranging in complexity to provide contextual knowledge. Low risk or 'breakthrough' case studies can help trialling and disseminating probabilistic methodologies, as they serve to identify requirements, problem types, required resources and computational issues internally. On the other hand, there is a need for the scale-up of applications to higher risk case-studies, but their dissemination may be limited by their sensitive nature. Regardless of the level of sensitivity, case-studies will invariably form an important part of training practitioners and promoting further implementation. This will also have the benefit of continuously developing and evolving the probabilistic approaches adopted through feedback on their use and verification, and promoting the emergence of a unified approach, a methodology.

Like any analytical tool, probabilistic models are as good as the knowledge which they channel, but without an understanding of limitations, the results can be dubious and there is a clear danger that this might lead to disenchantment with their implementation. In any application, clearly stating assumptions is vital and caution is advised in terms of interpreting the results. One might ascertain that probability estimates, like any analytically quantifiable result, might be subject to misinterpretation if the underlying assumptions are not clearly understood. Consequentially, clear reporting must not be overlooked and an acknowledgement that, equal to any analytical exercise, practitioners' bias can be a non-trivial factor that needs consideration. Historically, this bias has been addressed by virtue of independent verification (i.e. conducting the same probabilistic exercise completely and separately by a different practitioner), but with the amount of work required in developing a probabilistic approach to a problem, the same approach might not be viable, prompting the need for more efficient and streamlined verification strategies. Nevertheless, in industries where independent verification is necessary e.g. the nuclear industry, the expense associated with dual working may be an inevitability for the application of probabilistic approaches.

A key challenge is demonstrating the validity of the probabilistic approaches to regulators, which in the UK have shown a degree of reluctance. It can be argued that if industry and academic stakeholders build a consensus on formalising a unified probabilistic approach, that is transparent, accountable and which undergoes perpetual development, in time the air of scepticism and perplexity surrounding this topic will be lifted, thus promoting wider acceptance, implementation and validation efforts. The current state of affairs is such that probabilistic implementation may be hindered by lack of sanction for their use in nuclear safety cases. Nevertheless, probabilistics still has clear benefits, providing insight into major areas of uncertainty.

Review of Current Practice

To assist in the process of identifying current practice in the use of probabilistic approaches in the nuclear sector, reference sources were collated covering the same 20-year period (2000 to 2020) and critically analysed. The reference sources comprised: 12 industrial case study reports (not in the public domain) and 25 publications from the general literature published in the public domain, all being associated with probabilistic creep-fatigue. Any related publications in the public domain associated with the industrial case studies was omitted from the study to avoid double counting.

Half of the publications were found to be associated with probabilistic methodology development, with the remainder shared almost equally between health monitoring (inspection interval) and life prediction objectives (see Figure 1). This is a reinforcement of the point that probabilistic methods are mature, but not probabilistic methodologies i.e. more general method driven procedures which provide guidance for the general problem domain. Just over 50% of publications were associated with actual in-service components, compared to theoretical or experimental (test) based problems. There is always a difficulty associated with the publication of nuclear plant related research, and so theoretical, benchmark or purely experimental (test) cases are all useful to disseminate methodologies in a desensitised manner. There was an even distribution of problems with a focus on crack initiation, growth and rupture (as shown in Figure 2), with tubes and pipes being the most common feature for probabilistic assessment (figure 3); probably due to the volume of such plant components, and susceptibility to loading uncertainties (mechanical and thermal).

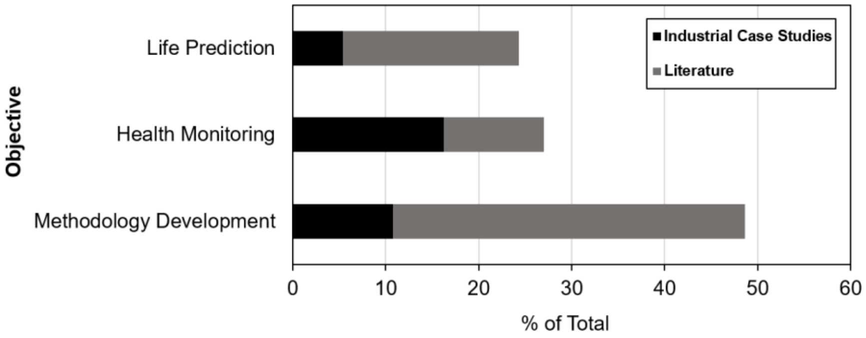

Figure 1 Objective of industrial case study or publication.

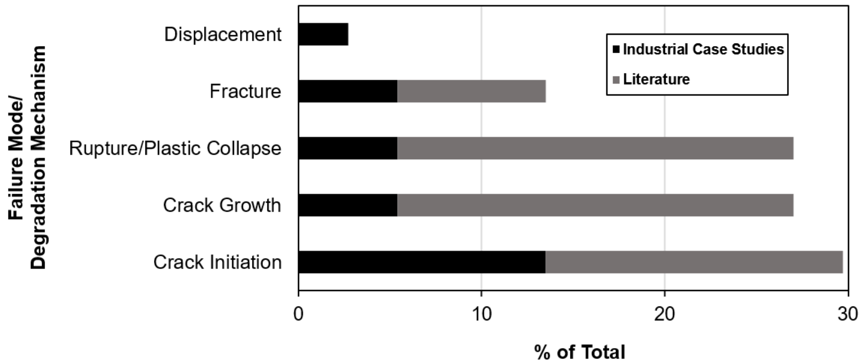

Figure 2 Failure mode or degradation mechanism assessed.

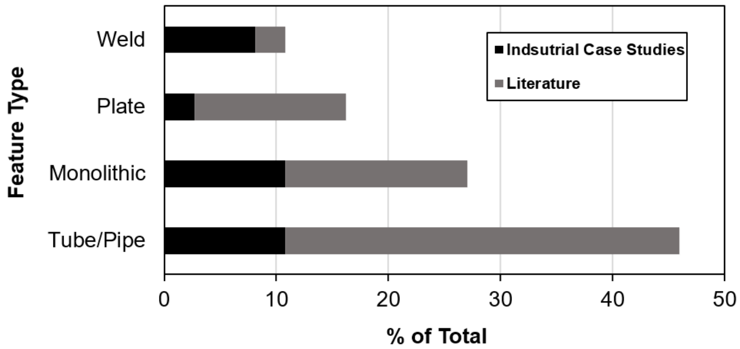

Figure 3 Feature type.

The R5 code is not commonly used outside of the industrial case studies analysed (see Figure 4). In fact, few publications reference any of the other codes either. There is large category of 'Other' which refer to multiple mentions of several standards, empirical rules and models e.g. FAVOR, R66 and ASTM.

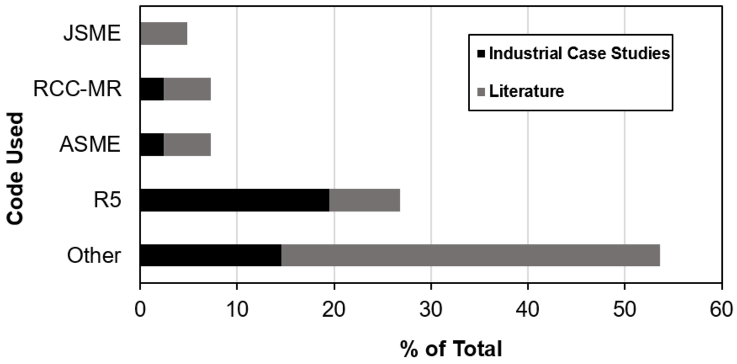

Figure 4 Code used in probabilistic approach.

On average in a third of cases, more than one probabilistic method was used, and overall, Monte Carlo Simulation (MCS) is by far the most popular method, followed by Latin Hypercube Sampling (LHS) and then direct statistical treatment of experimental data (see Figure 5). FORM/FOSM are not popular, possibly due to their unsuitability and inaccuracy when incorporating non-Normal input distributions. Around only 30% of cases used a Sensitivity Analysis (SA) approach, which is surprising for the following reasons. SA is used to prioritise the importance of statistical input parameters from measures which reflect he uncertainty contribution of each parameter compared to the output. In this way, it helps direct further data collection exercises, focusses design effort and helps allocate resources to control certain parameters. Once the probabilistic routine has been developed for a problem, it is also not a great deal of additional effort to derive sensitivity measures, and many different types of approach are available for the practitioner, even allowing intervals to be used to determine sensitivity measures. Software platforms used to conduct probabilistic routines are not stated in the majority of publications, or state the use of commercial packages such as Matlab and FAVOR. The high use of spreadsheets (MS Excel with VB Macros) within the industrial case studies is attributed to a select number of individuals conducting the assessments.

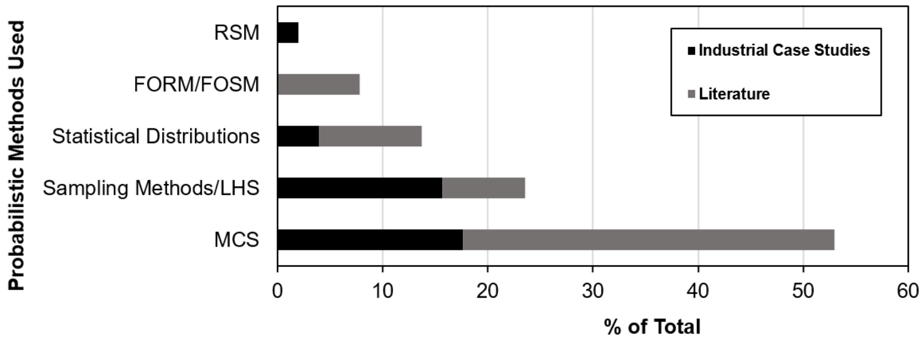

Figure 5 Probabilistic methods used (possible use of more than one).

About two thirds of all cases use fewer than 10 statistically characterised parameters. The complexity of creep-fatigue analysis may demand more, but the obvious inhibitor is available data at statistically relevant sample sizes. Different models also dictate the inclusion of a different number of parameters. The use of SA could be helpful in this respect, and determine which parameters require further data collection, and which parameters have negligible contribution with respect to their variability.

For high-temperature applications, stainless steels are showing to be the dominant material type concerning probabilistic structural integrity assessments of components in service or as part of the theoretical case study. Stainless steel clad with low alloy steel is also popular, though low alloy steels are mostly associated with reactor pressure vessel plate. Data, assumed statistical, were mostly for material properties and loads, and collated from a variety of sources. Standards and codes were the most popular followed by measurements, and historical plant data. A moderate number of publications failed to provide a source for data at all.

As expected, the use of Normal and Lognormal distributions to characterise input parameters dominates with two thirds usage across all cases (multiple responses used). A select number of other distributions types are also used e.g. Uniform, Exponential, Beta, Gamma, Rice etc. The use of Weibull distributions is limited, and possibly reserved for fracture related data. In over 40% of cases, some type of correlation analysis between key parameters was used, and although only stated several times, the strength of correlation was usually high, justifying its inclusion.

The probability of failure (and frequency of failure if the plant number is known), is the primary decision making output from two thirds of cases, commensurate with conducting a probabilistic approach. Other measures may well have been determined for these cases too of course. Risk and uncertainties (assumptions being valid etc) is a judgement made from any comments provided by the author(s) in the industrial case study reports and papers and is subjective. However, there is a pattern where papers in the public domain do not comment often on this, whereas industrial case study reports not in the public domain often do. Any assumptions questioned in light of reflections of the risks and uncertainty would be interesting to gauge, but not evident in any case study. The majority of papers do not state any verification or validation of the work presented. However, the ONR specify that structural integrity assessments should be validated against plant data information. This was observed in only 11% of cases [11].

In summary, this study focussed on creep-fatigue, mostly in anticipation of high-temperature operating characteristics of AMRs. In total, 37 reports and papers were analysed using a systematic approach to gauge recent and current practice in probabilistic approaches. In addition, there will be a body of probabilistic work in the public domain which sits outside of high-temperature applications in the nuclear sector, which could also be useful in defining current trends and practice. The extraction of information and data from the reports and papers used in the study is not an exact science, and very much open to interpretation in several cases due to the poor quality of reporting, in particular, in peer reviewed papers. The development of a probabilistic approach to any problem will be more complex and time consuming than a deterministic approach, particularly in the areas of data collation and statistical characterisation for inputs, and the development of efficient probabilistic routines for different types of models and objectives. No assessment of this was made in this study due to the lack of author reflections in this area in both the reports and papers. The popularity of certain attributes seen in utlilisation and implementation across the range of probabilistic case studies collated could validate their inclusion when composing a general probabilistic methodology. It could also be argued that just because it is popular or typical, this does not mean that it is optimum or best practice; what constitutes best practice still remains difficult to define.

New Guidance

Methodology

For high temperature AMR designs, there is no recent precedent on what is expected from structural integrity codes and standards requirements in the UK. For light water reactors, meeting well established design codes, such as ASME and RCC-M, is not sufficient to satisfy UK Generic Design Assessment (GDA) and safety case requirements as in addition the ONR require defect tolerance demonstration. In the case of high temperature nuclear design codes, such as RCC-MRx and ASME Section III Division 5, there are known technical shortfalls for application to AMR reactor designs, as highlighted in the BEIS Codes and Standard Phase 1 Project. One of the main objectives of the EASICS project [15] is to propose procedural guidance to be used in developing the probabilistic aspects of new structural integrity design codes for application to AMR designs, thus supporting UK GDA. A generalised probabilistic framework for structural integrity assessment of AMR components based on probabilistic methods and structural reliability procedures has been produced, and it is anticipated that this guidance be used within the AMR design process for substantiation of the structural design and also as a basis for management of the operational phases of the AMR plant in-service and more generally throughout the lifecycle from manufacture through to decommissioning.

The guidance is not restricted to a particular AMR design, component, material degradation mechanism or structural failure mode. Potentially, fracture, creep rupture, creep-fatigue crack initiation, creep-fatigue crack growth and distortion or deflection-based performance are all within scope, and non-metallic materials such as graphite may also be addressed. Similarly, the guidance is not restricted to components with a particular level of safety classification and can be applied to all components including those with the highest reliability requirements. This guidance has been developed following a state-of-the-art-review of existing probabilistic guidance in current structural design codes and wider literature together with a series of numerical case studies that explore the application of probabilistic techniques at different stages of the product lifecycle for various prototypical AMR component scenarios. It provides a data-centric approach that can be used throughout the AMR product lifecycle, starting with early-stage maturity scoping studies and design trade studies, leading towards the structural assessments required for GDA as design maturity increases and more data becomes available.

A hierarchy of approaches is provided, using the well-established three categories of structural reliability assessment. The procedural guidance is provided in a flowchart format, with numbered stages and accompanying text description for each stage. Flowcharts are provided for the three categories, covering the entire process for derivation of probability together with the accompanying verification, validation and convergence processes. The end-users of the guidance are anticipated to be structural integrity practitioners, engineers or scientists engaged in the AMR component design process with access to structural analysis software and computing facilities.

Application of the guidance extends beyond GDA to the final design stages into manufacture, operation, maintenance and decommissioning by providing a framework for using the data generated throughout the lifecycle. For example, material condition information, manufacturing data, In-Service-Inspection (ISI) data, Structural Health Monitoring (SHM) data etc can all be used to update the structural reliability assessment, should this data be available. This guidance provides a basis for moving away from traditional structural substantiation towards a live and evolving 'digital twin' concept that includes conceptual, as-manufactured and as-operated substantiations for individual components. The guidance does not imply or depend on the use of specialist software and is technology neutral in this respect, although it is anticipated that structural integrity practitioners will have access to standard structural analysis software and coding capability.

Figure 2 shows how the approach provides the basis for data-centric structural integrity substantiation of AMR component designs, throughout the lifecycle of the component. The section numbers identified in Figure 2 refer to sections of the guidance document [19]. Because the structural reliability approach provides a common framework for assessing all types of data from raw material and manufacturing through to operation and maintenance, the design substantiations developed at the component design stages can be readily updated to reflect the as-built and as-operated conditions as data becomes available. The data can also be used to tune model-fitting parameters using Artificial Intelligence (AI) techniques. This approach is consistent with digital twin concepts where in this case the structural reliability model and underpinning structural degradation models provide the digital twin that is updated with lifecycle data. An output from this is a live design substantiation for each component, that can to a certain extent be automated. This represents a step change from the traditional design process where structural substantiation reports are produced at rigid points in the design process, or when manufacturing or operational conditions are experienced that fall outside of the original design envelope.

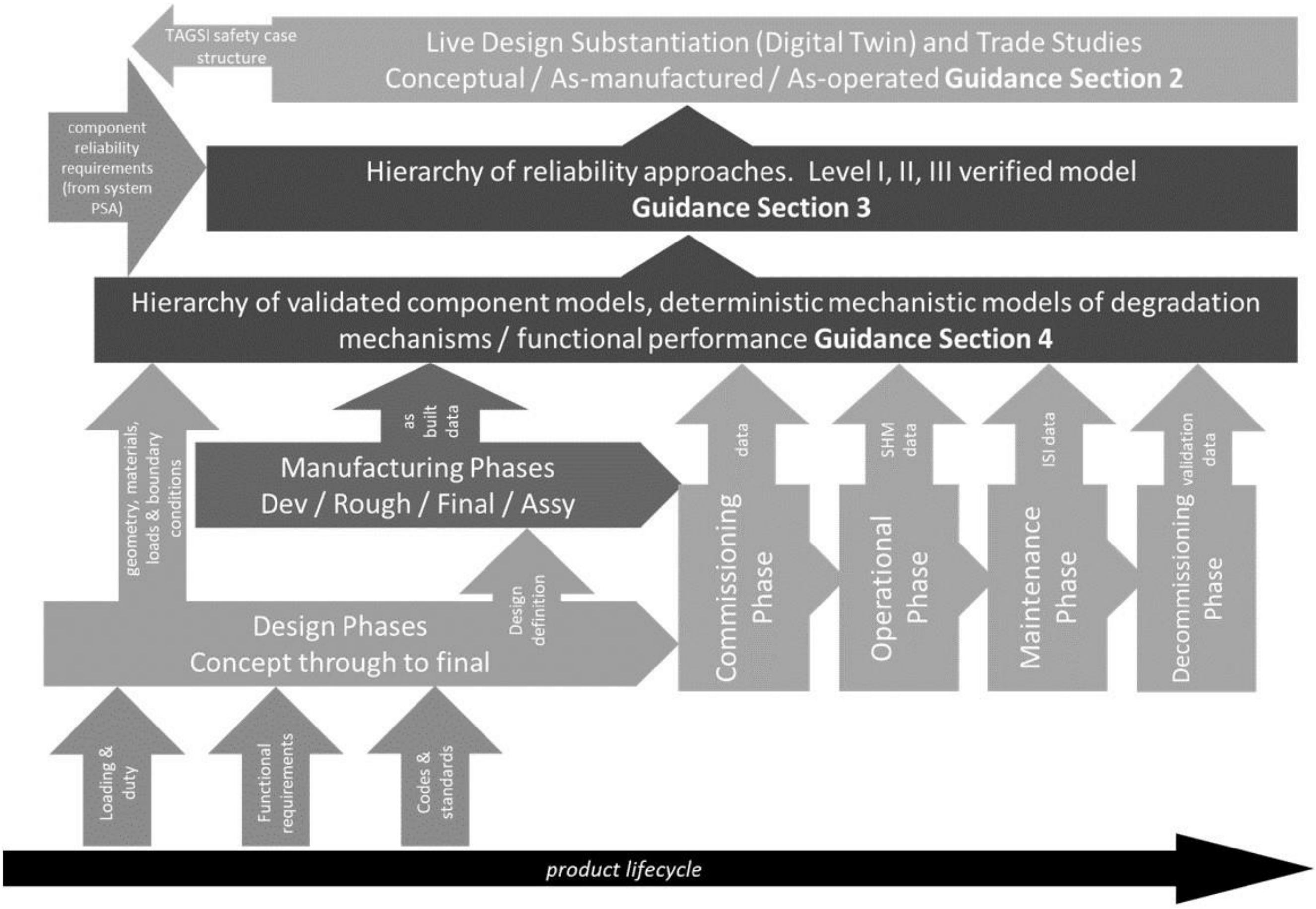

Figure 6 Application guidance to product lifecycle stages [19].

As shown in Figure 2, the failure probability requirement is defined at the component level and is derived by considering the performance of the component with a wider system. For the purposes here, the component is taken to mean a vessel, boiler, pump, valve etc that operated within a wider sub-system or system. It is recognised that there may be repeating units such as tubes within a boiler, multiple interacting regions of interest within a component or synergistic effects between degradation mechanisms such as corrosion and fatigue, all of which contribute to the failure probability at the component level. The aggregation of such factors is within the scope of the guidance, although it is a subject for further exploration to ensure a practical approach. For the highest reliability components, application of the TAGSI four-legged safety case structure is recognised as a best-practice approach. Figure 2 shows a link between the design substantiations generated using the structural reliability approaches described in this document and an overarching multi-legged TAGSI safety-case structure. This is discussed further in Section 6 and is included to highlight that the structural reliability approaches do not preclude application to the highest reliability components although it is recognised that AMR designs should seek to design out the requirement to include the highest reliability components.

New Design Chart Approach

A new approach for incorporating probabilistic structural integrity assessment which is sufficiently simple to encourage its adoption by design engineers has also been developed [20]. The approach, called 'Three-Term Reference Damage Model (3T-RDM)', is highly desirable to provide an intermediate level of assessment which provides most of the benefits of the probabilistic approach without the drawbacks of requiring specialist analytical skills and lengthy computer runs. The suggested 3T-RDM approach is developed in the context of a particular benchmark problem and a proposed Design Chart (see Figure 7) where the probability of crack initiation by creep-fatigue in a widely used material in nuclear plants, namely 316H austenitic stainless steel, is estimated based on R5V2/3 high temperature procedure. However, the 3T-RDM is not restricted to a particular failure mechanism, i.e., fracture, creep rupture, creep-fatigue crack initiation and growth are all within its scope, and non-metallic materials may also be addressed. To further validate the accuracy and generality of the proposed 3T-RDM and Design Chart, deterministic and Monte Carlo Simulation probabilistic structural integrity assessments are conducted for three nuclear plant case studies and the results are superimposed on the Design Chart obtained from the benchmark problem. The analysis indicates an excellent consistency between the results, justifying the adoption of the 3T-RDM for improved utility and successful application of probabilistic assessment for the nuclear sector.

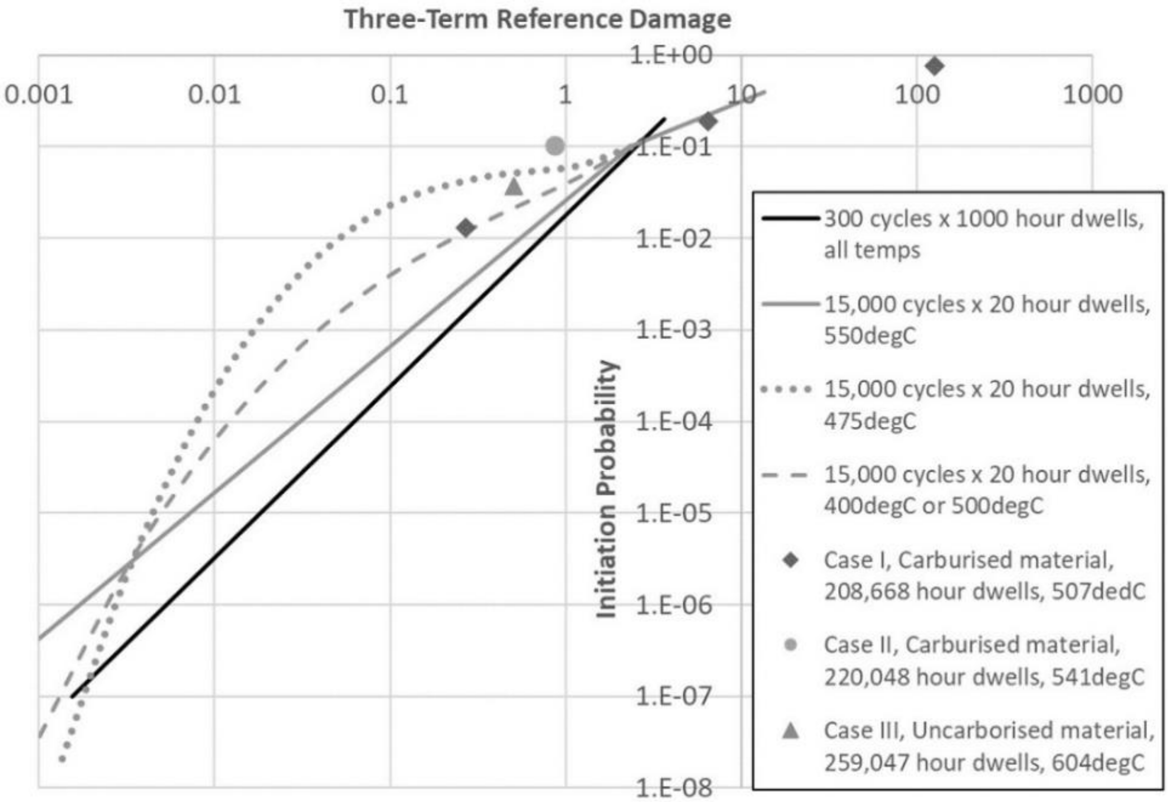

Figure 7 Design chart based on a benchmark problem with superimposed verification datapoints from three industrial case studies [20]

Case Study Pro Forma

Improved consistency in reporting probabilistic applications in structural integrity is required in order to ensure good practice [13], but also to share this practice in a standard manner, a key implementation issue. Table 1 shows a summary of a plant case study (tubeplate) using a proforma; a form-based template with distinct fields of categorised information to be completed [16]. The case study is overviewed in [21] in more detail. The different classifications and category headings in the proforma have been adapted and refined to make them generally applicable to many types of probabilistic problem, and in fact, this pro forma was used to distil information from the 37 reference sources introduced earlier. The proforma can be used in a proactive way to help define a probabilistic approach to a problem, guiding the practitioner from important problem formulation issues to the consideration of uncertainty in the models and parameters, and finally how this might impact on the problem objective. The aim is for the proforma to quickly provide understanding what constitutes an effective probabilistic approach for the case study under consideration, guiding the reader through problem formulation issues to the consideration of uncertainty in the models and parameters, targets to be met, verification and finally how this might impact on the objective.

Table 1 Pro forma summarising for the probabilistic assessment of the tubeplate case study in [21].

CASE STUDY OVERVIEW *(Describe the case study, source, the main objective and relevant codes and standards)*	• Tubeplate is a cylindrical component from the boiler unit header with 37 through holes. • Forged from 316H stainless steel. • Objective is to determine probability of crack initiation. • Failure mechanisms are driven by creep-fatigue, large thermal transients and over-heating due to tube restrictions. • A probabilistic approach is preferable as using a deterministic approach suggested the highest stress always occurs at the same tube location (conservative but not physically possible). The case study improves confidence in the predictions for life assessment. • Crack initiation procedures following R5 Volume 2/3, "An assessment procedure for the high temperature response of structures".
ANALYSIS PROCESS *(Using bullet points, describe the analysis stages involved, failure mode/criterion used etc)*	• Analysis of boiler temperatures and determination of tilts, including steady state and transients loading cycles. • Surrogate modelling of stress components from FEA using Response Surface Method. • Statistical characterisation of all other material properties including any correlations. • Determination of creep and fatigue damage. • Monte Carlo Simulation of surrogate models for determination of probability of crack initiation at any tubehole point. • Sensitivity analysis of key variables.
MODELS *(What are the objective functions/computational models involved at each stage? e.g. closed formulae, empirical model, FEA etc)*	• Creep and fatigue analytical equations following R5 Volume 2/3 for damage (deterministic), including hardening modelled using primary reset (empirical). • Calculation of stress components using FEA.
KEY PARAMETERS *(List the design and service parameters, and which are considered important or sensitive? e.g. materials, loads, geometries)*	• Temperature gradients. • Loading cycles. • HiTBASS creep parameters.
DATA SOURCES *(Is statistical data available for any of the important parameters and in what form is this? e.g. CoV, histogram)*	• Plant data consisting of 30 years of boiler temperature recording, including steady state and transients (start ups and reactor trips). • Statistical analysis of material properties for 316H SS from AGR Materials Data Handbook (generally small number of samples).
CHARACTERISATION AND CORRELATION *(What distributions are used to characterise key parameters and outputs, are any parameters correlated, and coefficients known?)*	• Histograms for temperatures and stresses. • 2-Parameter Lognormal for fatigue cycles and creep properties. • 3-Parameter Lognormal for creep ductility. • Normal for other static and fatigue material properties. • Correlation between creep rate and ductility.
PROBABILISTIC METHODS USED *(What probabilistic routines are to be used and why? e.g. MCS, LHS)*	• Monte Carlo Simulation (computation of probabilities). • Latin Hypercube Sampling (computational time improvements). • Response Surface Method (surrogate modelling of stress components). • Sensitivity Analysis (Delta-approach, correlations approach, variance approach, Finite difference). • Distribution fitting using linear rectification and Maximum Likelihood Method. • Correlation analysis using Spearman correlation and Gaussian Copula Method.
SOFTWARE/ PLATFORM USED *(What software is required to solve the models, fit distributions and calculate reliabilities?)*	• Python. • MATLAB. • Abaqus. • Advanced desktop personal computer. • HPC facilities.
PROBABILITIES PREDICTED *(What is the probability of failure or range determined? Were targets met?)*	• Highest probability of crack initiation calculated to be 10^{-3}. • No targets set.
RISKS *(Are there any risks, assumptions, unknowns or uncertainties involved at any stage?)*	• Temperature measurements not actually from tubehole material positions, but downstream measurements of steam exiting tubeplate, therefore assumed that both sides experience the same conditions and only radial differences, not axial, apply (essentially discretises to a 2D FE model). • Differences in stresses that will be observed between tubeholes can mainly be attributed to geometric constraints. • Small numbers of samples for material properties used, generally less than 15.
VERIFICATION *(How is the analysis verified? e.g. codes and standards used, checker)*	• Deterministic analysis procedure using R5 Volume 2/3 checked.

Conclusion

The ultimate aim of the new research reported in this paper is to produce a UK guidance demonstrating the capability of probabilistic approached for AMRs. The guidance document will reflect current practice based, in part, on this case study review and will provide advice on what would be suitable for inclusion within codes and standards. The findings of this work will also, in time, be presented to key stakeholders, including the regulator ONR, as well as code developers ASME and RCC-MRx, AMR vendors and the wider industry, to seek acceptance of a quite fundamental shift in design code approach and seek changes in international design codes and their future development. It will also be used to provide input to the R5 and R6 assessment methodologies.

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