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Verification and Validation of Life Prediction Software – An Engineering Service Provider Perspective

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Abstract

Many engineering structural components often failed due to fatigue, creep and other environmental damages. In-house and commercial engineering analysis and life prediction software are routinely used to predict the life of structural components and to declare manual life limits. Any engineering software developed is verified and validated before it is deployed and used in a production environment. Generally the Verification and Validation (V&V) details are not shared with users and technical specialists. This is especially true for engineering software developed to predict fatigue and creep life of structural components. However, use of life prediction software by less experience people may often lead to incorrect results and interpretations. In the recent past V&V process has been systematically and rigorously addressed for both computational solid and fluid mechanics software. However, such study is yet to be done for life prediction software.

An engineering service provider needs to work on diverse industry problems using many tools including commercially available tools and client specific in-house tools for life prediction. Such multi-industry and multi-tool environment poses many challenges to engineering service providers. This paper discusses as-is scenario of life prediction software and its usage by engineering service provider to various industrial problems and associated challenges. This is an attempt to provide an engineering service provider perspective on V&V of life prediction software. The needs of engineering service provider are also discussed. Finally the paper discusses the complexities and variability associated with life prediction and guidelines that can be developed for V&V of life prediction software.

Key words: Verification & Validation of life prediction software, Engineering Service Provider, Engineering Software.

1. Introduction

Many engineering structural components often failed due to fatigue, creep and other environmental damages like corrosion, in aerospace, gas turbine, heavy engineering, marine and other industries. Fatigue, Creep and associated environmental damages are important design drivers for many industries for improved life as given in Table 1. Safety and warranty are directly related to the life of the structure. In-house and commercial life prediction software is used in industry to predict the life of structural components. The predicted fatigue and creep lives would depend on the structural geometry and configuration, material characteristics and contact behaviour under various types of loads and its range and the methodology. Life prediction models help the designer to explore alternative designs, arrive at an optimal design in terms of life besides cost, safety, performance and reliability. Further, these models help validate with few prototypes for testing, qualification and certification.

Any engineering software developed is verified and validated before it is deployed and used in a production environment. Many times the Verification and Validation (V&V) details are not shared with users and technical specialists. This is especially true for engineering software developed to predict Fatigue and Creep. Use of life prediction software by less experience engineers may lead to erroneous results and interpretations.

Industry	Components	Design Drivers
Aerospace – Airframe	Wing/Fuselage skins, Frames, Ribs, Spar, Landing Gear struts etc.	Low Cycle Fatigue, Sonic Fatigue, Thermo-Mechanical Fatigue, Damage Tolerance, Engine Shut Wind milling Frequency, ..
Aerospace – Engines (Gas Turbines)	Gas turbine blades, Vanes, Compressor wheel etc.	Low/High Cycle Fatigue, Vibration Fatigue, Creep, Corrosion, ..
Automotive	Chassis, Super charger components, Suspension system, Brake pedal system etc.	Low/High Cycle Fatigue, Thermo Mechanical Fatigue, Fretting Fatigue, …
Turbo-Machinery – Diesel Engines, Steam Turbines	Cylinder blocks, Cylinder heads, pistons, connecting rods, main bearing caps etc.	Low/High Cycle Fatigue, Thermo-Mechanical Fatigue, Creep, Corrosion, ,.
Heavy Engineering	Boilers, Pressure Vessels, Earth Moving equipment etc.	Low/High Cycle Fatigue, Thermo-Mechanical Fatigue, Creep, Corrosion, …
Marine	Ship Hulls, Frames, Skins etc.	Low/High Cycle Fatigue, Corrosion, Erosion, …
Piping Industry	Pipelines, Storage facilities, Pumps etc.	Fatigue, Corrosion, Erosion, …

Table 1: Engineering Design Drivers

The V&V process has matured sufficiently in engineering disciplines like computational solid mechanics [1] and computational fluid mechanics [2-3] and has resulted in development of guidelines and standards for V&V procedures. However, V&V is followed in isolation for life prediction software. Hence, it is essential that similar V&V procedures have to be laid down for life prediction software as well.

The current practice is to build a computational model such as a finite element model which represents the mathematical model of a real world problem. Finite element analysis results are then post processed using life analysis software to assess component life. Usually all the major aerospace, automotive and marine industry customers have well defined processes and procedures to verify and validate the results provided by the life analysis software. Many times they prefer to use customized in house life analysis and proprietary material data to compute component life. It is easy to verify and validate life analysis results for such customers. For other customers, who do not have well defined industry standard procedures/practices, it is quite challenging to verify and validate the life analysis results.

An engineering service provider needs to work on diverse industry problems using many tools including commercial software and client specific in-house developed tools for life prediction. Such multi-industry and multi-tool environment poses many challenges to engineering service providers. This paper presents an engineering service provider perspective on V&V of life prediction software which includes both engineering software developer and user perspectives.

2. Overview on Life Prediction Analysis

Life of any structural component is usually obtained considering the crack initiation and crack propagation part of the lives. These lives depend on the damage caused due to fatigue, creep and other environmental damages like oxidation damage which depends on many factors such as state of stress, amplitude of stress variations, stress concentrations, surface quality or finish, fretting at joints, environment, temperature, material microstructure and grain size, frequency, residual stresses etc. Various fatigue analysis approaches like stress life and strain life are used to compute crack initiation fatigue lives. Paris law, Foreman law and other models are used to compute crack propagation lives. Fatigue life determination is a complex process which depends on many factors. Hence necessitates many physical tests and substantial validation due to large scatter in life prediction results.

Life is also computed by damage tolerance philosophy. In this methodology, components are assumed to have some initial defect, the size of which depends on capability of defect capturing instrumentation. The time taken to grow this defect to its failure size is taken as the life of the component. Many defect or crack growth studies are carried out on coupons with known defects and different life models have been proposed. By this analysis inspection intervals are fixed based on crack growth prediction so that cracks do not reach critical length before the inspection. This methodology needs crack growth data and critical crack length for validation. On the computational front, the stress singularity at the crack tip is to be captured either by means of using special finite element elements called crack tip elements or very finely graded mesh around the crack tip. For realistic simulation of crack growth, 3D finite element model with stress plasticity spread in and around the crack growth path is recommended.

Airframe structures are designed for longer life period and their certification involves identification of airworthiness limitation items based on life prediction analysis. Mostly the life predictions are performed considering fatigue and damage tolerance philosophies using OEM specific software programs that are driven by the airworthiness regulations. The damage tolerance philosophies assume that the defects exist in the material. However, such damages are detectable before they reach critical length by means of inspection techniques at predefined intervals and the cracks developed do not lead to catastrophic failure. Ultimately, damage tolerant design need to ensure that sufficient residual strength is available in the presence of defects. During emergency conditions like wind milling, additional safety has to be demonstrated for such components that they have good fatigue margins even though they are subjected to high amplitude vibrations.

Gas turbine materials are pushed to new limits for improved performance and reliability. Hence accurate life prediction is very difficult and challenging [4-5]. Gas turbine hot section components are subjected to very high temperature loads and mechanical loads due to pressure and centrifugal loads. Finite element based transient thermal analysis followed by a detailed stress analysis is used to predict metal temperature, stress and strain histories at various critical locations. Using these stresses, strains and temperatures, thermo mechanical fatigue lives are computed with or without superimposed creep and oxidation lives. Isothermal tests are performed at various temperatures have been used traditionally to estimate fatigue lives of hot section components. However isothermal tests may not capture many of the important damage micro mechanisms under varying temperature conditions. Under Thermo-Mechanical Fatigue (TMF) conditions, damage occurs due to fatigue, environment (oxidation) and creep. These damage mechanisms may act independently or in combination and depend upon materials and operating conditions. Various factors influence damage include minimum and maximum operating temperatures, thermal and mechanical strain ranges, strain rates, the phasing of temperature and strain, dwell time, or other environmental factors. Damage due to fatigue, creep and oxidation per cycle is computed and then added to get the total damage using which crack initiation life can be obtained. Similarly crack growth increment due to fatigue, creep and oxidation per cycle is computed by using crack growth analysis techniques and crack length is updated.

3. Verification and Validation of Life Prediction Software

A real world problem is first idealized and a conceptual mathematical model is developed to represent it. A simulation or a computational model is then developed to represent the conceptual mathematical model. Computational solution obtained is then verified and validated before it is used for real world applications. Life Prediction model V&V are the primary processes used to quantify and build credibility in numerical models used for life prediction [6]. The verification and validation definitions given by ASME for computational solid mechanics [1] and AIAA for CFD and Heat transfer [2-3] will also hold good for life prediction software. These are summarized in Table 2.

Verification	Validation
Verification is a process of determining a computational model accurately represents the underlying mathematical model and its solution.	Validation is a process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.
Verification is the domain of mathematics.	Validation is the domain of physics.
Verification ensures that the computational model representing the conceptual model is solved correctly and accurately. Hence can be described as solving the equations correctly and accurately	Validation ensures that the mathematical model accurately relates to real world experimental test or field measurements. Hence can be described as "solving the right equations.
Verification precedes validation	

Table 2: Comparison between Verification and Validation

The Figure 2 in reference [1] best describes verification and validation activities and outcomes. A part of it is shown below for illustration in Figure 1.

Verification involves both software code verification and solution verification. Activities involved during the software code verification phase would include finding and removing bugs in the source code, fixing round off and truncation errors in numerical algorithms and use of software quality assurance practices. Activities performed during the solution verification phase would include assuring the accuracy of input data, validity of the assumptions considered during design phase, estimation of the numerical solution errors and assurance of the accuracy of output data for the chosen problem of interest. During validation the life numbers predicted are compared closely with that observed in the field data or physical test data.

A typical process used in the industry for life predictions, verification and validation is shown in Figure 2. FEA based thermo mechanical stress analysis is usually used to compute the stresses and strains under various kinds of loadings. Crack initiation and crack propagation and total lives are computed using various life prediction models at identified critical locations. Using the coupon, component and full scale fatigue life test data and the corresponding finite element model life calculations, the predicted life are validated either qualitatively or quantitatively. The models are assumed valid for real world applications and the life is computed for a complex structural assembly. The computed lives are reduced in the beginning using an appropriate factor of safety. Field data is collected over the years and computed lives are validated with the field data and corrections are done to the life prediction models and life updates are done.

The life prediction model accuracy is industry and product dependent and hence ideally applicable for a specific real world scenario under certain conditions. Purely based on validation for one scenario same model predictions cannot be assumed correct and accurate for any other real world scenarios. However the model verification and validation for one scenario may provide confidence that the model is sufficiently accurate for life predictions for similar scenarios. However, the predictive accuracy of the life predictions model can be validated with additional experiments or field experience [4].

4. V&V Life Estimation Software Challenges of Engineering Service Providers

Engineering service providers need to work with various customers across industries. All major industries have diverse performance, functional, operational, maintenance and regulatory requirements. Hence life estimation methodologies and tools used are diverse. Many times these methodologies are very specific and cannot be generalized. Hence major OEMs have developed their own internal tools based on the extensive analytical/computational studies and tests carried out internally. Thus engineering service providers need to use various in-house and commercially available engineering life analysis software tools for life estimation.

Engineering service providers offer software development services, design and analysis services for improved life of components, subsystems and systems. Software development services typically involve development of software for life estimation. Other services involve estimation of life of an engineering component using life estimation software tools or design modifications for improved life. Some engineering service providers may not have physical test facilities and will have to use customer or external agency facilities of the eco-system.

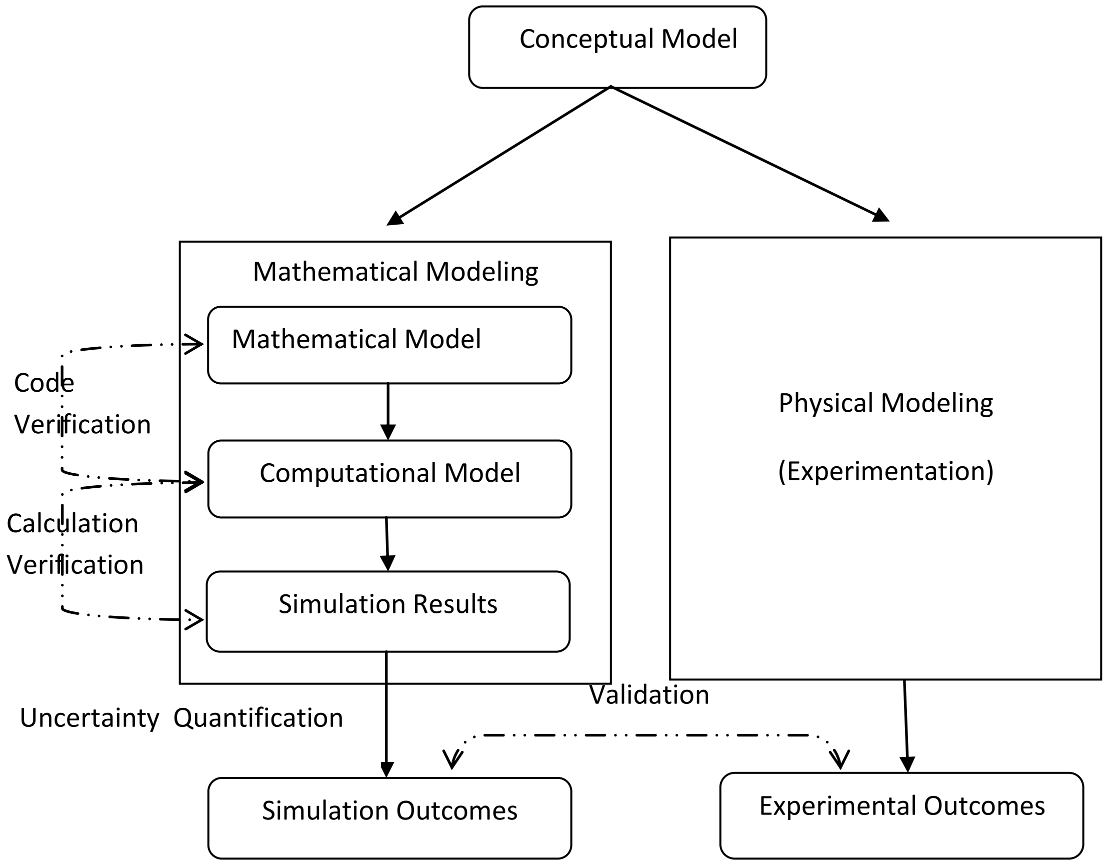

Fig 1. Verification and Validation Activities

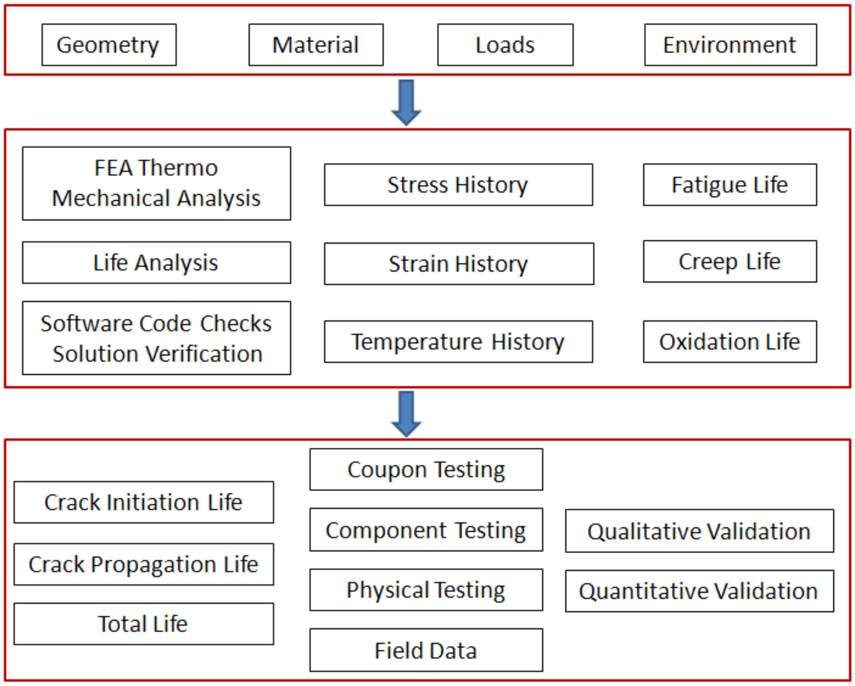

Fig 2. Typical process used for life analysis computations, verification and validation

a. Challenges of Life Estimation Software Development Service Provider

A software development service provider will be involved in code verification, solution verification and validation activities. The code verification and calculation verification is done as part of unit testing and system testing. Validation is part of functional testing. Life estimation procedures are company specific and scenario specific based on type of material used, operating and environmental conditions etc. Further many of the life estimation procedures are still evolving which makes it more difficult to standardize and generalize for implementation. The challenges of life estimation software development service provider are given below:

Software Code Verification Challenges:

Size of the code to be verified will be large due to various reasons and hence is involved. The size of Life estimation software will increase when it is generalized to apply for multiple industry segments. Further, size of the code will also increase due to

- Options to help user to build own their fatigue models
- Incorporation of both deterministic and probabilistic life estimation models. Verification of the code implementing these complex mathematical models is challenging.
- Large database of materials and its characteristics over wide range of temperatures and operating environments. Need to connect to external databases also increases the complexity
- Features to incorporate all types of bolted and bonded joints and welds.
- Features to import stress analysis data from both hand calculations and FE analysis results of multiple COTS
- Features to import experimental fatigue test data and compare with analysis data
- Options to post process analysis data

Solution Verification and Validation Challenges:

Life prediction involves large number of variables compared to standard stress analysis and hence variability of predicted life values is likely to be higher. Hence it is quite challenging to perform solution verification and validation. Some of these challenges include:

- Large number of simulations needs to be performed and evaluated to assess the solution and its effect on discretization errors.
- Many fatigue and life estimation parameters need to be assessed for their sensitivity on the life prediction values.
- For probabilistic models, determination of sample size and convergence criteria is cumbersome and complex
- Solution verification is time consuming
- Non-availability of benchmark problems in each industry is one of the major challenges
- Non availability of industry specific experimental data
- Non-availability of extensive material data under various operating temperatures and environments. Further, non-availability of such data under various industry specific parameters like joint parameters, weld parameters surface roughness, geometry etc is a challenge
- Need to have in-depth knowledge of component to be analyzed, operating conditions, environmental conditions and various field and physical test data
- Inability to generalize effect of various parameters on fatigue and life estimation

b. Challenges of Life Analysis and Design Service Provider

Engineering service typically need to provide support for solution verification and validation activities. Many industry specific problems need to be solved using diverse tools (both COTS and in-house tools). Such multi-industry and multi-tool environment poses many challenges to engineering service providers. Some of these include:

- User should have in-depth knowledge of component to be analyzed, operating conditions, environmental conditions and various field and physical test data
- User should have good understanding of various fatigue and life estimation models and their applicability to various scenarios
- User should have good understanding of various materials and its characteristics under various operating environments like temperature, pressure and mechanical loads
- Good understanding and ability to analyze the physical test data of Fatigue and life analysis
- Good understanding of various joints (bolted, bonded and welded) and its influence on life estimate
- Good understanding of various FE analysis tool file formats like ABAQUS, ANSYS, NASTRAN etc and ability to interpret stress analysis results
- Ability to interpret both deterministic and probabilistic models of fatigue & life analysis
- Knowledge of customer specific methods and tools for fatigue and life estimation
- Consistency of units and applicable constants involved in various analyses procedures
- Typical tests and test procedures to be used for validating the life analysis procedures. Simulating the actual environment close to reality is a great challenge.

Based on our current experience, the test data and the material constants are proprietary to OEM and are not always shared with the service providers. Many timer, in-house life analysis tool or a life calculation subroutine with access to material database only is shared with service providers for carrying out the life analysis. In such cases, calculation verification would only be the responsibility of the service providers and the validation part would primarily be the responsibility of the customer.

Skilled and experienced engineers providing life analysis services are few in the market and hence service providers may have to make considerable investments to hire, engage and retain these professionals. In general, product company engineers have the advantage of working repeatedly on similar components and use well defined procedures relevant to those products. In service industry, engineers need to learn continuously on industry specific requirements, life analysis methods and tools. Verification and validation procedures can also be different across industries. Hence, adaptability of skilled and talented engineers is one of the major challenges of a service provider.

5. Needs of Engineering Service Provider

Based on the experience of working with various clients in engineering service space, the following needs have been identified which are however not exhaustive. Engineering bodies like ASTM can play an important role, enabling engineering service providers to meet these needs.

Standardization of Methods

All the challenges involved in using scenario specific and industry specific fatigue and life estimation methods need to be addressed. Hence it is essential to standardize the Fatigue and life estimation methods and procedures across industries. This will help in reducing or eliminating the effort spent by multiple industries and organization. This may involve interaction with various OEMs, Suppliers, Users, MROs, Certification bodies, Associations, Research consortiums and Insurance bodies.

Tools and Infrastructure

It is also essential to standardize the tools available for fatigue and life estimation. Specific guidelines and procedures need to be laid out to certify the tools. It is also essential to provide mechanisms towards certification of life prediction tools. This includes procedures, guidelines and best practices for verification and validation. Further new tools may need to be developed or existing tools need to be enhanced for fatigue analysis and life estimation for new/advanced materials.

Physical Testing

It is essential to share the physical test data across the industries with due importance given to the IP of each industry. Ay effort towards providing benchmark test cases and its results in each of the industry segments will be valuable. This will help in verification and validation of fatigue and life estimation software before they are used to solve real life problems.

Training and Certification

It is important to provide training and certifications to people on various Fatigue and life estimation procedures and tools. Such certifications will help in developing the necessary skills to engineering professionals. This will go long way to create necessary talent pool.

Collaboration Environment

Any effort towards providing collaborating environments like portals, communities of practices, social networks will help in sharing the best practices of Fatigue and life estimation procedures. This will create necessary knowledge base for the practicing engineers.

Research & Technology Development

Fatigue and life estimation analysis models are still evolving and there is a need to invest in research and technology development. Many new and advanced materials are being developed and their fatigue and damage tolerance characteristics need to be understood. Composite materials are increasingly being used in many industries. Compared to metals, composites are less prone to fatigue failure. But the fatigue can still occur in composites due to environmental factors like temperatures and humidity playing a major role in degrading its properties. Fatigue failure of composite materials is still under development with various failure theories emerging [7-10]. Most of these theories are generally driven by fatigue failure of polymer matrix. Fiber metal laminates have shown improved fracture toughness and fatigue performance over monolithic Aluminium structures. Further, hybrid material research is required to improve manufacturing processes, drilling and assembly methods, damage modelling and in-service repair techniques. Probabilistic design and analysis techniques may be used in the design and certification of composite structures to establish reliability. Development is required in the area of integrating probabilistic methods with the commercially available finite element analysis programs with design sensitivity capabilities [11]. Also, continued research is required to ensure that probabilistic methods are adopted in the design and certification of future composite structures. Structural Health Monitoring will be another area that will be helpful in validating the fatigue methods and life estimation techniques.

6. Conclusions

Many engineering components failure in Aerospace, Gas Turbine, Heavy Engineering, Marine and other industry segments has been attributed to fatigue, creep and other environmental factors. Certification and warranty requirements necessitate accurate assessment of component life. Life analysis takes into account many variables compared to the standard stress or heat transfer analysis and hence the variability of the predicted life is likely to be high compared to the experimental data. Hence, life prediction software should have proven life prediction methodologies which are verified and validated for the intended usage. Life prediction software can also provide facility to simulate additional test conditions and thus help to validate the actual test data.

Verification and Validation (V&V) of life prediction software is laborious and time consuming due to lack of generalized procedures for various industries. Hence it is essential to have in-depth knowledge of components to be analyzed, operating conditions, environmental conditions, field and physical test data. Further, good understanding of various fatigue and creep life prediction models and their applicability to various scenarios is required. Both COTS and in-house tools are used to assess fatigue and creep life. Such multi-industry and multi-tool environment poses many challenges to engineering service providers. A perspective on various challenges involved in verification and validation of life prediction software from an engineering service provider has been presented. Needs of engineering service provider of life estimation software are summarized.

Guidelines are required to identify life analysis methods for a real life problem and corresponding experimental benchmarks that need to be conducted for verification and validation. It is also essential to define standard nomenclature for variables that affect the life predictions. A standard process need to be defined for life prediction software development and allow listing of the variables and associated ranges used during verification and validation phases. The accuracies required for the computation of stresses, strains, material constants and life assessment models need to be outlined. Such guidelines can also help deciding the qualitative or quantitative testing, coupon level, component level and full scale tests as well as field life data collection. A general procedure and standards may be defined for conducting tests, collecting the life data and correlating life data with applied stress or strain values and for development of life assessment procedures, tools and verification and validation. Guidelines to incorporate the uncertainties arising from both experiments and predictions can also be provided.

Based on the current understanding, we suggest that a committee involving technical experts and users from various OEMs, engineering service providers, life prediction software developers and users deliberate on the current day practices on verification and validation of life prediction software. The committee can define general and industry specific guidelines for verifying and validating the assessed life prediction software. This would go a long way in increasing the effectiveness of the engineering services related to life assessment. This would also help OEMs while making the engineering products safer and durable. Engineering bodies like ASTM can play an important role in this initiative.

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