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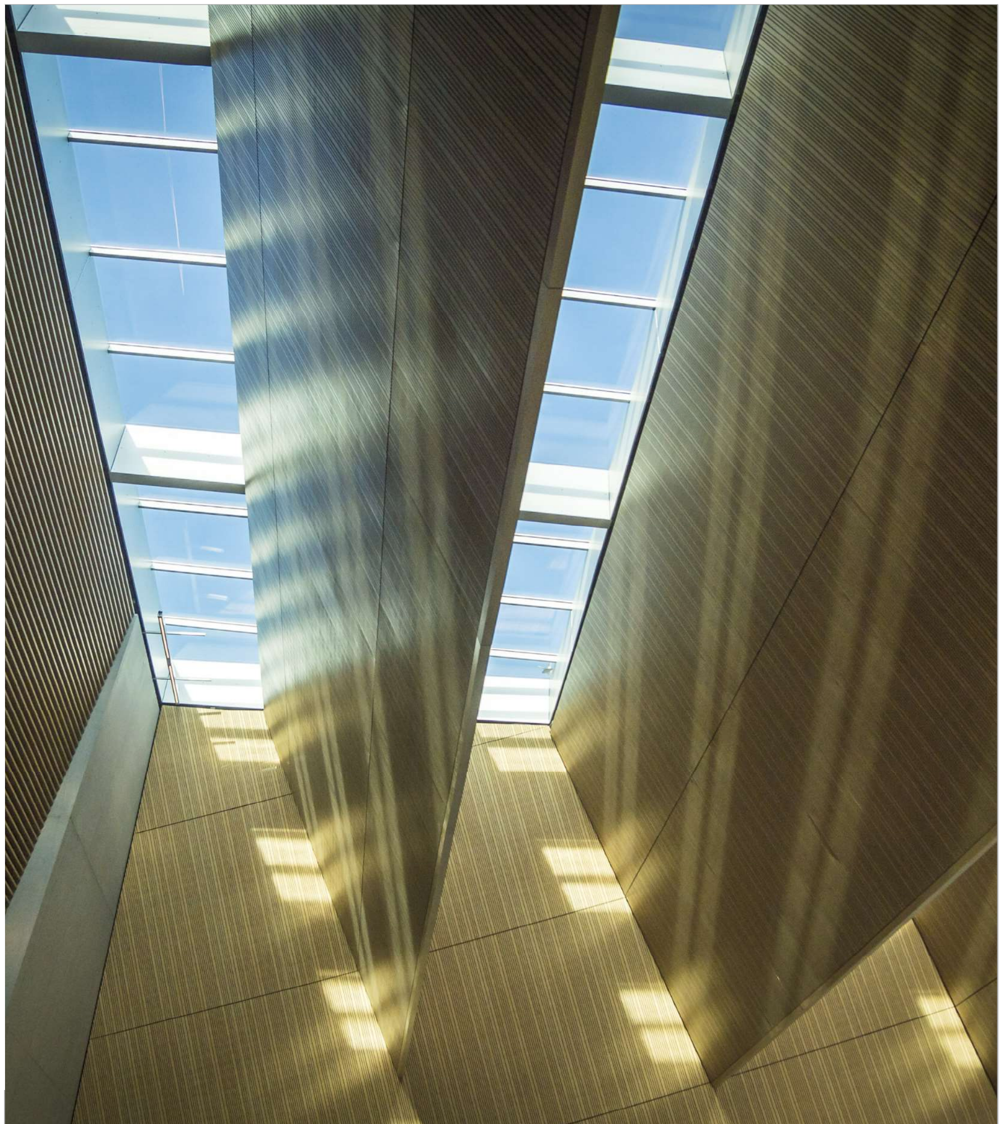

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HOW LITERATURE REVIEWS INFLUENCE THE SELECTION OF FATIGUE ANALYSIS FRAMEWORK

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Abstract: *Prediction models for fatigue in engineering applications are developed within a fatigue analysis framework, deliberately selected in some cases, but mostly chosen without substantiation. The proposition of this paper is that selecting the most appropriate framework can only be done with the knowledge and a complete overview of existing frameworks and their systematic categorization. In particular for composite materials, where due to the coexistence of different mechanisms and their complex interaction under fatigue loading, only a unified approach can characterize the complete fatigue phenomenon.*

Keywords: Fatigue analysis frameworks; Thermodynamics; Damage mechanics; cyclic inelasticity.

1. Introduction

More than 150 years have passed since humanity encountered the fatigue phenomenon in engineering applications. Over this time, a transition can be observed in how the understanding of the fatigue phenomenon is developed. Initially, the development of fundamental theories outpaced the experimental observations. More recently, facilitated by the development of sophisticated testing capabilities, the experimental observations outpace the development of theories. Hence today, material deformation theories are developed, and experimental results are generated in different fatigue research communities that are not in synchronization. In many cases, oversimplified theories, that are developed on prior art, are fitted to new experimental datasets without awareness of other (often more) theoretical work.

For example, in the case of composite materials of a wind turbine blade, the international standards [1, 2] accept fatigue verification based on a Goodman diagram [3] which is a simplified approach based on the linear influence of mean stresses (or strains) on the fatigue life. Such acceptance leads to generating a massive amount of experimental data only to fulfil the standard requirements. However, in many cases, this data is not synchronized with the underlying governing theories, ultimately creating a gap between experiments and theory.

An overview with a systematic categorization of different fatigue analysis frameworks can increase the awareness of the other methodologies. A most appropriate analysis framework can be identified based on such knowledge that represents the specific experimental dataset and addresses the gap between the governing theory and experiments.

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The construction of a framework based on a unified approach requires several prerequisites and specific steps to be followed. These prerequisites are discussed in the next section first.

2. Prerequisites to fatigue analysis

Any framework used in fatigue analysis is built upon a specific research objective and corresponding methodology. Before adopting a fatigue analysis framework, sufficient attention must be given to its prerequisites, which in sequence, can be written as

- Prior knowledge of how loading conditions relate to damage mechanisms in the structure and its sub-components during operation.
- Selection of length scale at which fatigue analysis needs to be performed.
- Selection of the analysis methodology.

Once these prerequisites are fulfilled, then attention can be given to the identification or construction of a most appropriate analysis framework.

3. Fatigue analysis frameworks

The best way to get acquainted with different analysis frameworks is by systematic categorization of the methodology, and by learning from surveys and critical reviews in respective categories. In this paper, the fatigue analysis frameworks are categorized by their methodology.

3.1Traditional phenomenological framework

Traditionally fatigue data is analyzed within a very simplified framework based on the empirical (phenomenological) methodology. The simplicity in the application of this traditional framework favoured its widespread use in engineering applications to date. Figure 1 gives a schematic representation of different stages followed within this framework.

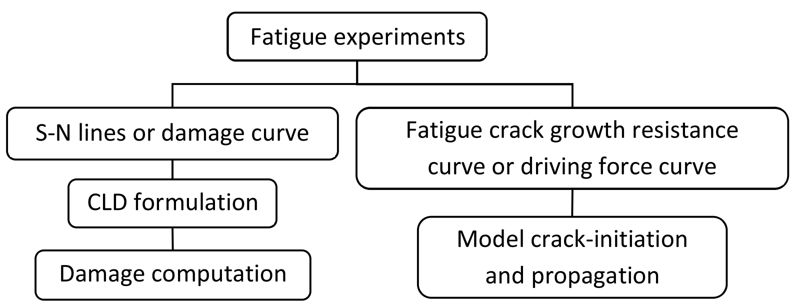

Figure 1 Traditional phenomenological framework of fatigue data analysis

The first stage comprises the execution of fatigue experiments at various stress or strain levels and for various stress or strain ratios. After that, the experimental results are analyzed in different ways, depending on the damage type.

In case a single crack forms the dominant damage mechanism degrading the structure (e.g. ply drop or thickness transitions), its initiation and propagation over time are monitored and studied. The study of crack propagation using methods of solid mechanics is known as fracture mechanics. In this framework, fatigue crack growth rate is studied against either stress intensity factors or strain energy release rates. Such a curve is known as the fatigue crack growth

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resistance curve, and it became the input to the simulation of crack propagation in a finite element environment.

When only final failure or gross damage is considered, the number of cycles to failure or any stress or strain ratio is assumed to follow a power-law relationship with the input constraints. To identify any nonlinearity in the power-law relationship, one of the practices followed in the industry is to perform fatigue tests that give failure lives scattered over at least four orders of magnitude in life. In the case of nonlinearity in the data, the SN line formulation needs to be adapted accordingly. The next step in this framework is to construct a constant life diagram (CLD), which represents lines for constant life in mean and alternating stress/strain space. The CLD construction increases the life prediction capability to non-tested stress ratios. The formulation of constant lifelines and their estimated model parameters are input to structural analysis. The constant life lines merge to a single point when alternating stress/strain reaches a value of 0. Physically there is no explanation possible for such a situation where a single point is representing failure life for any number of cycles. Due to practical difficulties in the execution of tests and very few applications that demand validation at the high mean and low alternating loading, the practice of merging constant lifelines to a single point continued.

The analysis in this framework is based on survival probability only; in other words, failed or not failed, hence does not give insight into how much damage a material has sustained over particular life or vice versa. Many attempts were made in the past to get more understanding from the traditional framework by using either a strength or stiffness reduction rule as input [4, 5]. To date, the application of strength and stiffness reduction rules and the formulation of new ones for different materials continued.

The last step in the traditional framework is the calculation of damage accumulation. Various empirical rules for damage accumulation were proposed and reviewed in the past. Out of these, one popular and the extensively applied rule is linear damage which assumes linear dependency of damage on fatigue life. In almost all materials and particularly in composite materials, the damage does not show linear dependency on life. The simplicity of this rule in terms of computing damage makes their application very attractive even to a complicated structure.

Despite a continuous evolution in methodology, achieving a detailed understanding of material behaviour is still a target to achieve for the traditional framework due to the following shortfalls-

- The fatigue life prediction includes only the final damage level and not the intermittent damage level.
- The fatigue life prediction lacks both qualitative and quantitative descriptions of associated different mechanisms and their coupling.

Hence, the use of another framework needs to be explored to achieve a better understanding.

3.2 The framework from the thermodynamic theory of irreversible processes with internal variables

In search of more understanding, many studies adopt a physics-based methodology. The basis for this adoption is in the similarity of the qualitative mechanical behaviour of most of the materials. Due to this similarity, it is possible to generalize the macro-scale behaviour with the help of macro-scale (bulk) mechanisms (elastic behaviour, yielding, inelastic strain, anisotropy induced by strain, cyclic inelasticity, damage development) that are similar for these materials. One such possibility is provided by the well-established continuum damage mechanics (CDM) framework. This framework requires input from the thermodynamic theory of continuum and general concepts of thermodynamics of irreversible processes with internal variables. The generalization of material behaviour is made by approximating the irreversible process by a sequence of constrained states that are near equilibrium and that can be characterized locally by a finite set of internal variables. Figure 2 outlines the steps followed in this framework.

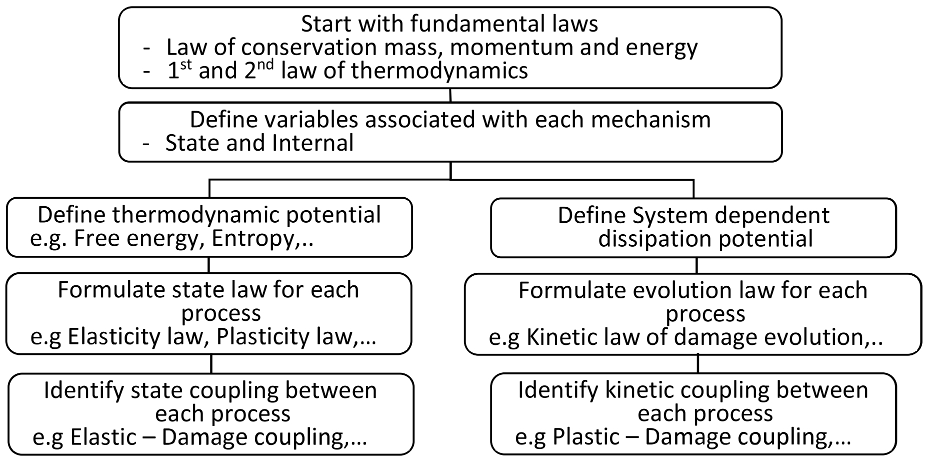

Figure 2 Schematic flow chart followed in the framework of thermodynamics theory

The framework starts with fundamental laws that are central principles of thermodynamics. These laws are general, pervasive and apply to both micro and macro scales of the material as a whole or every element within it. When the material is deformed, its microstructure changes in either a reversible (elastic) or irreversible (inelastic) manner. Here, each change can be characterized as a material's specific property and described by certain parameters known as state variables, because they only depend on the initial and final states of a material. State variables are further divided into observable variables (which can be observed and directly measured) and internal variables (which are not directly observed but derived from observable variables). Maugin [6] gave a critical review on the use of internal variables of state in rational thermodynamics.

During the deformation, the energy involved in any change in state can be linked to its (state) potential. Hence when a state potential is written as a function of the state variable, then it defines the condition of the state and is known as state law. When a change in the state consists of dissipation of input energy in any form, then the process is known as the dissipative process. The description of such a process requires the evolution of such dissipation. Similar to the state potential when the dissipation potential is written as a function of associated variables, then it gives the evolution of dissipation and is known as evolution or complementary law.

The last part of the framework is to identify the coupling between different mechanisms. During the deformation, when two or more different mechanisms simultaneously represent the material's behaviour, then they are considered coupled. In such a coupling, variable(s) associated with one mechanism is modified by the change of the value or the evolution rate of the variable(s) associated with the other mechanism. These couplings can be of direct, indirect, or secondary nature [7]. In the case of direct coupling, the absolute value of one variable influences the other variable. In the case of indirect coupling, the absolute value of one variable influences the rate of another one. Whereas in the secondary coupling, a third variable value is influenced by the second one where the first and second variable shows either direct or indirect coupling.

3.3 Continuum Damage Mechanics (CDM) framework

The framework of irreversible thermodynamics plays a fundamental role in constructing CDM models for various damage mechanisms. Damage during deformation in the physical sense means discontinuities in a material at the micro or macro scale. These discontinuities result in strain dissipation. Depending on the nature of discontinuities, they either are represented by single or multiple damage variables and their associated variable strain energy release rate. Here, damage potential as a function of the strain energy release rate gives the evolution of the damage variable, and this functional relationship is called damage evolution law. The discontinuities in the material can be at the micro or macro level, and hence the definition of damage variables also can be given at respective levels. If the damage variable is defined using continuum level material properties, then the damage state can be treated as a continuum.

Similar to the area of fatigue phenomenon, the area of CDM is having an extensive scope and is interlinked to other mechanisms like elasticity, inelasticity, ageing, and thermal effects. Hence to get acquainted with this area, a systematic categorization of the scope of CDM application is needed. This categorization can be done based on damage types like brittle, ductile, creep, fatigue, and their coupling with other mechanisms[9], as shown in Figure 3.

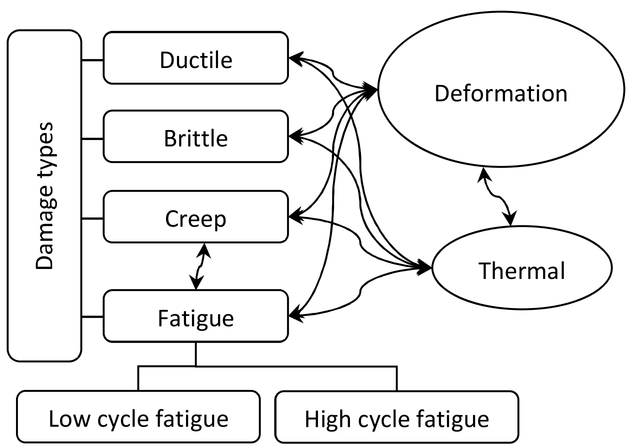

Figure 3 Categorization and coupling of the CDM framework

To date, the CDM framework was applied and matured for various types of damage mechanisms to various materials including metal, rubber, concrete, soil, rock and composite [8]. An extensive amount of literature is available on different damage mechanisms observed in composite materials [10 - 15]. The overall damage development is highly complex, due to the presence of different damage mechanisms with strong unilateral features and their interactions. Hence, characterization of damage at the microscale requires the development of mathematical formulation with anisotropic and unilateral damage evolution. Whereas at the macro scale by ignoring the detailed microstructure, the discontinuity introduced into the displacement field can also be ignored, and the mathematical formulation can be constructed using continuum theory [16].

One key feature of damage development under fatigue loading is its stochastic nature. During fatigue testing for any two coupons from the same material configuration and under the same test conditions, the damage development is not similar. For composite materials, generating the correct damage mode in the specific areas for all loading situations is still a target to achieve [17 - 26]. For the same reason, the fatigue results analyzed are mostly based on failure near or in the clamp region of the coupon.

The damage evolution law derived using the CDM framework is deterministic, which means there is no uncertainty associated with the value of damage or the rate of damage growth. The thermodynamic principles do not include any spatial variability while defining either state variables or potentials; hence the damage law also does not include this variability. To understand the damage growth either this deterministic law needs to be extended into the probabilistic domain [27], or the stochastic nature needs to be represented by some average non-random function.

3.4 Cyclic inelasticity framework

Under fatigue loading, the material deforms in various ways; hence a framework is also required to describe all these deformation mechanisms. The theory of elasticity addresses the elastic deformation, while the cyclic inelasticity theory addresses the inelastic deformation under fatigue loading.

Inelastic deformation in the physical sense means irreversible changes in microstructure that do not lead to the generation of discontinuity during the deformation process. Under non-zero mean stress cyclic loading, materials show more changes in microstructure than monotonic loading because of the presence of two loading situations. The cyclic amplitude load is superimposed on-to constant minimum stress (except the tension-compression loading). As a result of an additional change in microstructure, the material shows either hardening/softening or no change in response to applied loading in the subsequent cycle. The elastic domain defines the threshold state of material between elastic and inelastic deformations and is represented as a surface in the space of stresses [28 P.28].

The inelastic strain consists of two parts: plastic and viscous component. The plastic strain evolution is associated with certain limited stress intensity, and the mathematical formulation is based on the rate-independent formalism [29, 30]. This theory is known as cyclic plasticity theory. If the viscous component is present in the deformation, then the mathematical formulation needs to be adapted for a rate-dependent base, and this theory is known as cyclic viscoplasticity theory [30, 31]. In both theories, the mathematical formulation consists of the following steps [28, 32] -

- First defining the elastic domain, that gives a boundary to the linear elastic region.
- Formulation of flow rule that describes the relationship between stresses and strains development post elastic region.
- Application of consistency condition to get the direction of stresses.
- Formulation of hardening/softening rule to define change of loading surface during flow.
- Determination of inelastic modulus, and
- Calculation of stresses and inelastic strains.

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In almost all materials, Hook's law characterizes the elastic response and the Ramberg-Osgood law [33] characterizes the plastic response. Hence generalization in the elastic and plastic response is possible for most of the materials and derived using thermodynamic potentials. Unlike the elastic response, the post elastic region (hardening/softening) behaviour for multimillion cycles is different for every material. Hence, the generalization of the hardening rule is not possible. So far, an earlier proposed hardening rule from literature is modified to address the changes and differences from new materials. To the author's knowledge, there exists no hardening/softening rule for high cycle fatigue situations, and the field of cyclic inelasticity is still an active field of research.

4. Conclusion

This paper provides an overview of different frameworks followed in the fatigue analysis of various materials. Such an overview enables the selection of the most appropriate analysis framework required for desired understanding and/or application. In the absence of such an overview, the selected analysis framework can lead to incomplete answers widening the gap between theory and experiments or expenditure of extra resources for identifying missing links.

A framework based on a unified approach that addresses the role played by all relevant mechanisms in the development of the overall phenomenon seems the most appropriate choice. As the theory of the thermodynamics of the irreversible processes is generic, and the CDM framework is based on this theory, many material classes like metals and composites can be analyzed using this framework. Such a framework has similarities up to a certain level, and at the detailed level, it differs by addressing the difference in the contribution of various mechanisms and their coupling associated with different material classes.

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