UNIFIED MECHANICS THEORY

Unification of Newtonian Mechanics & Thermodynamics

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Objective

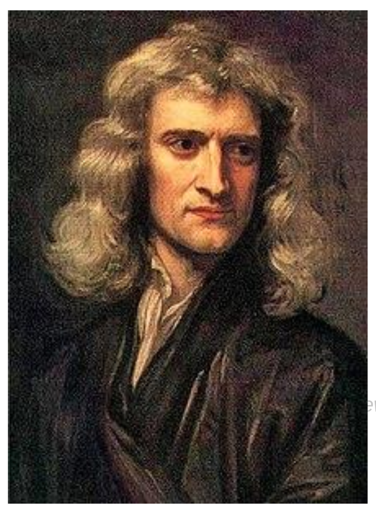
- Establishing laws governing response of structures during their life time, without the need for empirical curve fitting degradation, fracture & lifetime prediction models.

Introduction

- Newtonian Mechanics provides the response of a structure to external loads, but it does not take into account past-present-future changes, such as initial defects and lifetime degradation.
- Thermodynamics, provides information about the past-present-future changes happening in a structure over time, i.e. the state of degradation.
- Historical efforts to introduce Thermodynamics into Newtonian Mechanics have all been based on empirical curve fitting techniques, that introduce a phenomenological degradation function into Newton's Laws.

Newtonian Mechanics

Sir Isaac Newton's work in "The Principia," (1687)



- **Second Law**: the vector sum of the forces F on an object is equal to the mass m of that object multiplied by the acceleration a of the object:
- $F = ma$
- **Third Law**: When one body exerts a force on a second body the second body simultaneously exerts a force equal magnitude and opposite in direction on the first body
- $F = ku$
- According to Newtonian Mechanics Laws initial acceleration "a" and stiffness "k" never degrade. As a result, only displacement degree of freedom is necessary in continuum mechanics analysis.

Thermodynamics

Rudolph Clausius & W. Thompson (Kelvin) (1850)

1st Law of Thermodynamics – Conservation of Energy

2nd Law of Thermodynamics – Entropy Law

- The Second Law states that there is a natural tendency of any isolated system, whether living or non-living, to degenerate into a more disordered state. When irreversible entropy generation rate becomes zero the system reaches "THE END" (fails/dies).

Relation Between Entropy and Disorder

- **Ludwig Boltzmann (1872 and 1875)**
- Using statistical mechanics, formulated the connection between the probability of disorder and the entropy and it was put into the final form by **Maxwell Planck (1900).**

Where S is entropy, k is Boltzmann's constant and W is probability of disorder.

Unified Mechanics Theory

Cemal Basaran (1997)

Proposed using entropy generation rate as a degradation metric and as a bridge to unify Newtonian Mechanics Laws and Thermodynamics Laws

Displacement u, and $\dot{s}$ Entropy generation rate both must be dual nodal unknowns. Because they can't exist alone. As a result stiffness "k", acceleration "a" change continuously following second law of thermodynamics.

Laws of Unified Mechanics Theory

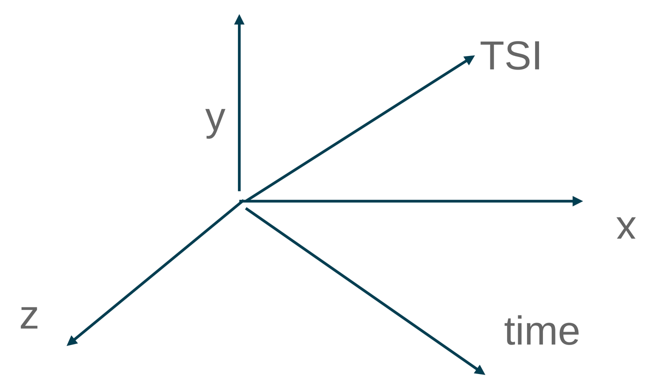
$$F = ma\left(1-\Phi(\dot{s})\right)$$

$$F = ku\left(1-\Phi(\dot{s})\right)$$

Thermodynamic State Index (TSI), $\Phi(\dot{s})$

- In order to relate entropy and "damage", (which is a disorder in microstructural configuration) consider a system in initial state $\Phi = 0$ with a total entropy of S_o and an associated disorder state with a probability of W_o.
- In an alternative disordered ("damaged") state, S is total entropy of the same system with an associated disorder probability of W and a TSI of Φ.
- It is assumed that "damage" is change in microstructural configuration happening due to irreversible entropy generation, hence, difference in disorder between the initial and the current state $\Phi = f(W, W_o)$ is TSI.
- When a material is in initial (reference) state, it can be assumed to be free of any disorder ("damage"). TSI will be $\Phi = 0$.
- *In final stage, material reaches a critical microstructural state such that disorder is maximum, Wmax. At this stage, entropy production rate* will become zero. TSI will be maximum Φ = =1.

Coordinate System in Unified Mechanics Theory



In Unified Mechanics Theory in addition to space-time, TSI is also a linearly independent axis. TSI axis starts from zero (0) and ends at one (1).

Universal "Degradation Evolution Function is defined by the Thermodynamic State Index (TSI): Φ

$$\Phi = f\left[\frac{W-W_o}{W}\right] = \left[1-e^{-\frac{(s-s_o)m_s}{kN_o}}\right]$$

$$\Delta s = s - s_o = \int_{t_o}^{t}\frac{1}{\rho}\dot{s}\,dt$$

Entropy generation rate can be calculated from physics for all micro-mechanisms generating entropy. For example, irreversible entropy generation fin a high power electronics solder joint is given by

$$\Delta s=\int_{t_0}^{t}\left\{\begin{array}{l}\frac{1}{\rho T^2}k_T\left|Grad(T)\right|^2+\frac{r}{T}\\ \frac{C_v D_{effective}}{\rho k_B T^2}\left[Z_i^* e\rho^* j-f\Omega\nabla\sigma_{spherical}+\frac{Q^*\vec{\nabla}T}{T}+\frac{k_B T}{c}\vec{\nabla}C\right]^2\\ +\frac{1}{\rho T}\boldsymbol{\sigma}:\boldsymbol{\varepsilon}\end{array}\right\}dt$$

1- Internal heat generation
2- Diffusion mechanisms (Electromigration, stress gradient, thermomigration, and vacancy (chemical) concentration gradient
3- Internal mechanical work

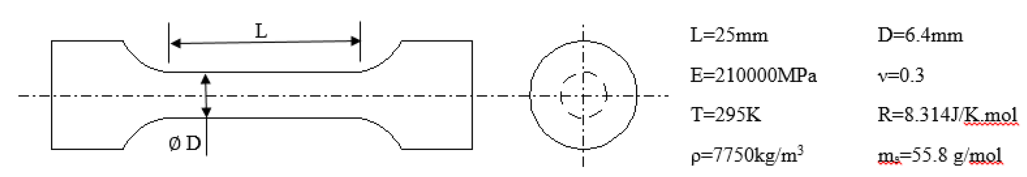
Mathematical Framework & Proof

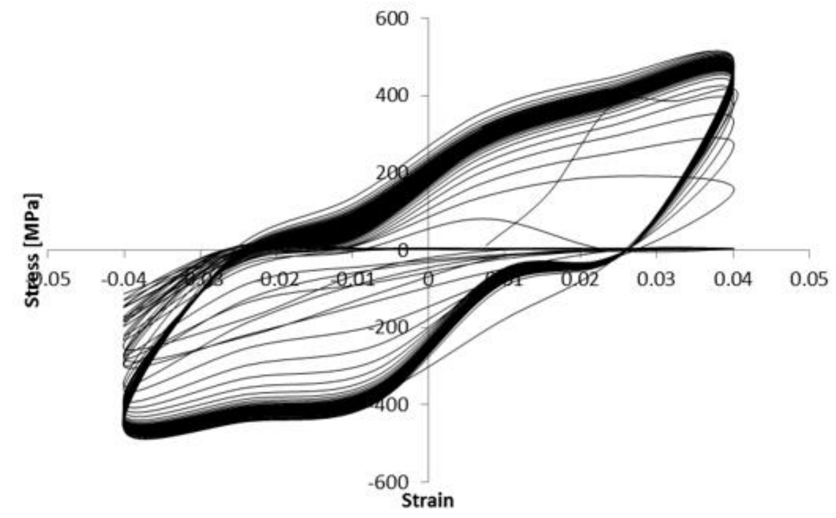
Basaran and Nie (2004)

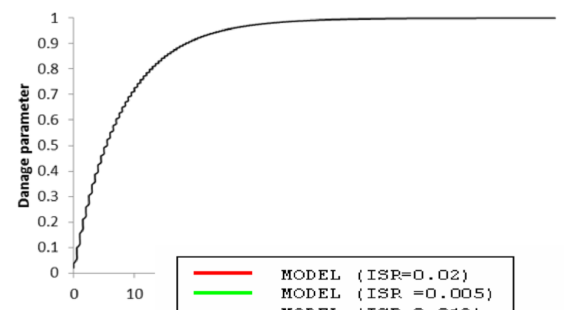
Sosnovskiy, L.A. and Sherbakov, S.S. (2016)

Experimental Proof

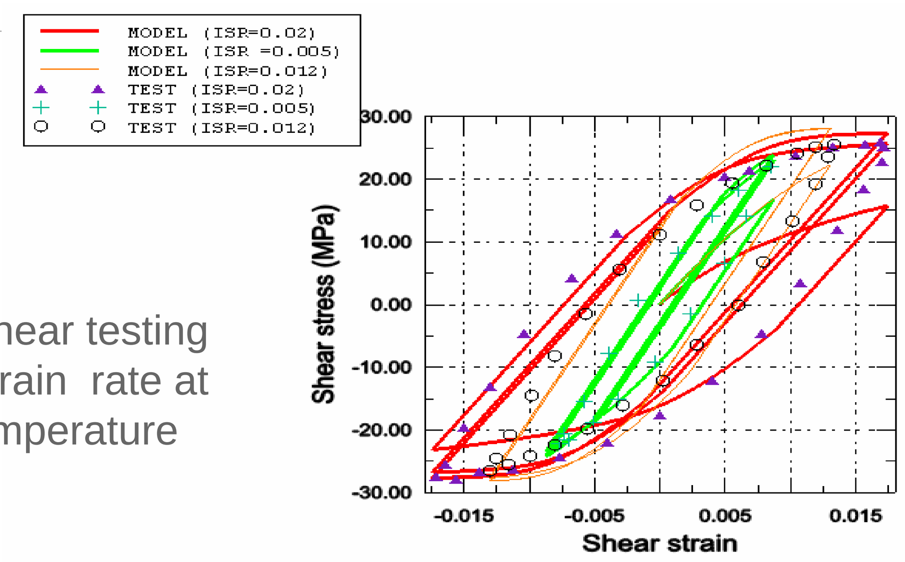
- **Fatigue Loading on A-36 Steel**







Damage Evolution - TSI (Φ)– Calculated from Experiment



Cyclic shear testing under strain rate at room temperature

Conclusions

- **After 150 years** unification of Newtonian Mechanics and Thermodynamics has finally been achieved.
- **Laws of Unified Mechanics** replace **Laws of Newtonian Mechanics** that govern response of structures.
- **Unified Mechanics Theory** provides a physics based universal degradation evolution function which has been validated by testing extensively under all loading conditions, i.e. Mechanical, Thermal, Chemical, Electrical, Corrosion & Others.
- **Assumption**: Everything in the universe is a continuously evolving thermodynamic system obeying Laws of Unified Mechanics **with a mechanical response**.

Select References

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