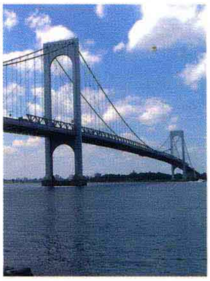

ISSI 2012

FROM FAILURE TO BETTER DESIGN, MANUFACTURE AND CONSTRUCTION

S. T. Tu
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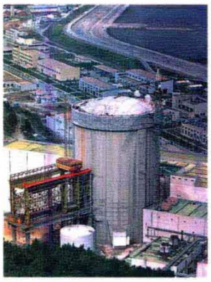

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FROM FAILURE TO BETTER DESIGN, MANUFACTURE AND CONSTRUCTION

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From Failure to Better Design, Manufacture and Construction

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Proceedings of 2012 International Symposium on Structural Integrity

Preface

Failures and accidents in industries have been repeatedly reported in the course of rapid development of national economy in China. As the Chinese saying goes, failure is the mother of success. The failure can advance our engineering knowledge than all the successful machines and structures in the world. Many theories were actually developed based on the lessons learned from failures. Fracture mechanics, as an example, were developed after a series of fracture failures in ships, aircrafts, pressure vessels and so on, which in turn has supported the successful development of many new products of high reliability. New failures in current extreme engineering will surely give birth to a new generation of theories. The 2012 International Symposium on Structural Integrity (ISSI2012) is thus held in Jinan, China during October 31-November 4, 2012 with the theme *From Failure to Better Design, Manufacture and Construction*.

This book presents the proceedings of ISSI2012. As the successor of Fracture Mechanics symposium series (from 2003 to 2009), ISSI2012, continues the tradition of small scale but of high quality in discussion and exchange. Various sessions are planned for presentations and discussions on theoretical aspects and practical applications in the area of structural integrity in general.

The symposium (ISSI2012) is co-organized by member organizations of China Structural Integrity Consortium, including Shandong University, East China University of Science and Technology, National Engineering Research Center of Pressure Vessel and Pipeline Safety Technology (Hefei General Machinery Research Institute), MOE Key Laboratory of Pressure Systems and Safety, Nanjing University of Technology, Zhejiang University, Zhejiang University of Technology, Zhengzhou University, Changsha University of Science and Technology, Southwest Jiaotong University, Beihang University and co-sponsored by China Pressure Vessel Institution, China Materials Institution, National Natural Science Foundation of China, General Administration of Quality Supervision, Inspection and Quarantine of China, Engineering and Technology Research Center for Special Equipment Safety of Shandong Province, MOE Key Laboratory of High Efficiency and Clean Mechanical Manufacture (SDU), MOE Engineering Research Center of Large-scale Underground Cavern Group (SDU).

On behalf of the organizing committee, we would like to thank the above co-organizers and co-sponsors who made ISSI2012 possible. We also wish to thank Professor George C. Sih and Professor Zhengdong Wang for their passion to the symposium and efforts made to ensure the success of the event.

Weiqiang Wang
Executive Chairman
Shandong University

Shan-Tung Tu
Symposium Series Chairman
East China University of Science & Technology

October, 2012

Contents

Anomalies of monoscale notion of failure in contrast to multiscale character of failure for physical processes

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Abstract

The failure problem remains undefined without specifying the multiscaling or multi-dimensional aspects of the system. Three requirements, dubbed as "where-when-how", are needed. They refer, respectively, to the spatial (location), temporal (time) and failure mode (how). The absence of any one of the three can be interpreted as *solution generation without a problem.*

Failure is a preconceived notion referring to a threshold, deviating from the norm. Anomalies and ambiguities, however, can arise when criteria based on the presumption of monoscaling are applied to multiscale systems. Micro-macro effects when analyzed using the monoscale fracture criterion of energy release rate (ERR) or the equivalent of the path independent integral can give negative results violating the First Principle. The surface energy density (SED) can reflect micro-macro effects simultaneously and remains positive. The invariant property of SED is usable for relating the microstructure properties at the different scale ranges to explain the *evolution of failure*. The sustainable and reliable time to assure the microstructure stability have not received the attention it deserves, particularly for the manufacturing of ultra high strength materials. This is also true for high temperature resistance nanomaterials.

Keywords: Failure; Energy release; Surface energy density (SED); Monoscale; Dualscale; Multiscale; Nanomaterial; Sustainable; Reliable; Stability; Compatible; Surface-volume effects.

1. Introduction

Costly lessons were learned during World War II when large structures failed suddenly without warning. Monoscale energy release infers the coincidence of local and global fracture, traditionally known as brittle fracture, where fracture initiation and rapid propagation are assumed to be one of the same event. That is the stored energy in the material microstructure dissipates instantly at the macroscopic scale. Strength elevation was the design criterion handed down from the 18th century. Microstructure effects were left out and monoscale design set foot in the arena of design that led to one disaster after the other. Conventional high strength materials lower the energy absorbing capability of the material. This should be distinguished from the nanomaterials where energy is absorbed by the nano grain boundaries. The trade-off between fracture toughness and strength for the conventional alloys was not known at the time. Special task groups of the American Society of Testing Materials (ASTM) were established to find the limits of brittle fracture, referred to as the ASTM Plane Strain Fracture Toughness Value, qualified by a trade-off relation between the yield strength and the K_{IC}. Plane stress is a global average that is not relevant to the ASTM treatment of fracture that is strictly local. The fracture toughness pertains to local energy release. K_{IC} refers to a go-no-go situation such that local and global failure or fracture occurs simultaneously.

The recognition that material microstructure can affect the macroscopic fracture introduced the term ductile fracture where the crack can grow slowly before rapid propagation. The inference is that the material has increased its toughness. The fact is that the material microstructure has been altered to dissipate energy at both the micro and macro scale, a dual scale proposition. Again the term elastic-plastic fracture has added to the al-

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ready confused notion of fracture toughness. Keep in mind that there are distinct difference between the description of micro and macro properties. Their connection are still not known. This period of confusion between the material science (microscopic) and mechanics (macroscopic) lingered on for decades. Reconciliation via dual scaling of the micro and macro occurred only in the past 20 years.

In passing, justice will not be done without mentioning the effects of the atomic structure on the macroscopic properties of materials. After all, failure is a multiscale process. There were visions that the theories of discrete and continuous dislocations could be the mechanisms behind elastoplasticity, a *shoot first and aim later* approach.. Elastic-Plastic Fracture Mechanics (EPFM) were devised and voted into the codes and standards for adoption by the nuclear vessel industry. They replaced the monoscale codes of Linear-Elastic Fracture Mechanics (LEFM). In essence, nothing was changed except for some arbitrary parameters to alter the appearance of the energy release rate or the equivalent path independent integral that is confined to monoscale application. A convincing message of the inability of dislocation theory to support elastoplasicity was made by E. Kröner, a pioneer of dislocation theory in the 1980s [1]. In his later years, he recognized the importance of multiscaling and segmentation involving the micro, meso and macro scales. To quote [1]: "The discovery of dislocations led to an euphoria lasing several decades and to the hope that theoretical mechanics of elastoplastic deformation of crystalline solids on the basis of dislocation theory could be created". The time span for recognizing multiscaling in contrast to monoscaling is nearly 20 years. Moreover, scaling entails not only size but also time. A discussion of the spatial-temporal scaling effects applied to material science can be found in [2].

The concept of dual scaling in material failure implicates the interaction of space-time. It is no less sophisticated than the unification of space and time at the speed of light as proposed by Albert Einstein. Material science delves on a smaller size scale and slower time scale. The material atomic or microstructure behavior is unstable. The behavior of nanomaterials differs from the ordinary alloys, starting from their making. Crystal nucleation for polycrystals controls the grain size in the bulk or volume. The smaller grains near the boundary are removed from the test specimens. Nanomaterials pay attention to the surface or grain interface. *Polycrystalline alloys. concentrate on the bulk and nano crystal materials on the surface or interface.* By tradition, surface effects have been treated separately from the bulk or volume. Interaction of surface energy density (SED) and volume energy density (VED) can be found in the open literature for decades [3,4].

The advent of nanomaterial of the 20^{th}-21^{st}century has showed why monoscale fracture criteria such as the energy release rate (EER) and the equivalent path independent integrals G (same as J) are not applicable for dual scale systems associated with micro-macro cracking that occurs in creep and fatigue. The surface energy density (SED) can reflect micro and macro effects simultaneously and remain positive, without change of sign. Furthermore, SED remains invariant and can be used to transfer the results to other scale ranges. This is vital to understand the sustainability and reliability of material microstructure that determines the multiscale aspects of the evolution of failure, without which no realistic "failure criterion" can be found and validated.

Recognized only recently is the sustainable time of maintaining stable nano grain boundaries. The nanomaterials can degrade to the ordinary alloys, if the *nano grain sizes failed to meet the sustainable time requirement.* Nano grain structure stability must be qualified and validated in time. The one-month test results cannot be assumed to remain valid for years. Accelerated testing cannot be validated [5] by using mono-dimensional criterion, such as a 90% confidence interval level, a highly controversial procedure. The dependable life span of a system cannot be evaluated from a statistical probability nor an average. A system can fail below the average. It is the useful life that should be found.

2. Vulnerability of failure prediction

Failure criterion is inherently axiomatic in character. It is a proposition to anticipate future events that are subject to changes. The approach presupposes a condition and find the results by logical deduction. The risk involved in the axiomatic approach consists of uncertainties of change. Instead, changes can be observe and extrapolation can be made for limited short-time interval prediction. The latter approach is still not trivial. The underlying philosophy of I-Ching [6], expounded in [7], however, should not be overlooked. Both approaches of prediction are used at present, but not free from contradiction and violation of the First Principle. .Frequent misgivings can be found for analyzing the release energies at the micro and macro scale while using the mono-scale failure criteria.

A real crack releases energy at both the macro and micro scale. The former away from crack and the latter near the crack tip. The path independent integral was given as J in 1958 without derivation. A derivation based on the conservation of energy was given [9] for a moving macrocrack pointing out the kinematic and thermodynamic restrictions. A review could clarify some of anomalies that arise in the application of path independent integrals referred to elastoplastic, viscoelastic, creep and nonlinear fracture mechanics.

Path independent integrals for a moving macrocrack can be deduced directly from a corollary of the First Law of Thermodynamics. Without going into details, refer to Fig. 1 as a reference of the physical model of Eq. (1). A verbal statement of energy balance can be stated as

The rate of work done across C is balanced by the rate at which energy is stored in A plus the rate of kinetic energy of the crack and energy release G of the macrocrack moving at velocity c.

$$\int_C \overset{n}{T}_i \dot{u}_i \mathrm{d}s = \frac{\mathrm{d}}{\mathrm{d}t}\iint_A \rho U \mathrm{d}A + \frac{1}{2}\frac{\mathrm{d}}{\mathrm{d}t}\iint_A \rho \dot{u}_i \dot{u}_i \mathrm{d}A + cG \quad (1)$$

Note that is ρ the density, U the internal energy, $\dot{u}_i$ the displacement rates and $\overset{n}{T}_i$ the tractions. Solving for G, it is found that

$$G = \int_C (\rho U + \frac{1}{2}\rho^2 \frac{\partial \dot{u}_i}{\partial x}\frac{\partial \dot{u}_i}{\partial x})\mathrm{d}x_2 - \overset{n}{T}_i \frac{\partial \dot{u}_i}{\partial x}\mathrm{d}s \quad (2)$$

For a non-linear but non-dissipative material, G reduces to

$$G = \int_C W \mathrm{d}x_2 - \overset{n}{T}_i \frac{\partial \dot{u}_i}{\partial x}\mathrm{d}s \quad (3)$$

The use of $\rho U = W$, with W being the elastic energy density function, implies no energy dissipation. For a stationary crack $c = 0$, Eq. (3) reduces to

$$G = \int_C W \mathrm{d}x_2 - \overset{n}{T}_i \frac{\partial \dot{u}_i}{\partial x}\mathrm{d}s \quad (4)$$

which is identical to J in [8] along with the restrictions:

- *Material is non-dissipative*
- *Crack path is straight*
- *Energy is released at the macroscale only*

The aforementioned restrictions are by no means apparent unless Eq. (4) were reduced step by step from Eq. (1). Energy release at the microscale has been excluded from the derivation of G. It also turns out that G is a component of the energy momentum tensor introduced by J. D. Eshelby to characterize the generalized forces on the dislocations in elastic solids (1949), 19 years prior to its presence in fracture mechanics. Regardless of the nature of application, the physical limitations stated above are the same. Refer to the discussions [10] of J. D. Eshelby and G. R. Irwin in 1989 related to the derivation of Eq. (4).

The inclusion of micro energy dissipation can change the sign of Eq. (4), a condition that is disallowed by First Principle. Examples of this can be found in [11,12], just to mention a couple of references.

Path independency is a monoscale concept that excludes micro effects which are inherent in creep and fatigue.

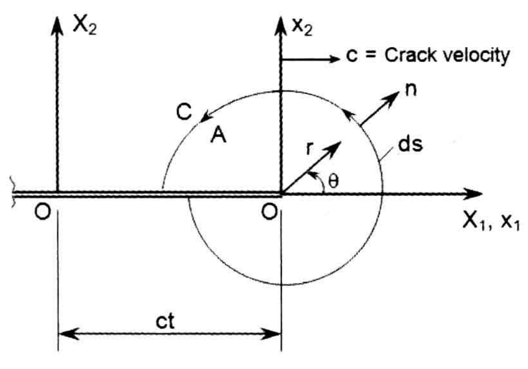

Fig. 1. A constant velocity macrocrack in non-dissipative material.

3. Micro-macro energy release incompatible with mono-scale fracture criterion

Stress-strain solution and failure criterion can always be contrived without revealing apparent contradictions. However, when micro-macro stress strain data are fed into monoscale failure criterion, obvious violation of the First Principle can result. This will be demonstrated for the application of the energy release rate G given by Eq. (4) for the problem [11] of a crack of length 2a in a piezoelectric material subjected to both mechanical stress σ_∞ and electric field E_∞ as shown in Fig. 2. The condition $\sigma_x^\infty = eE_y^\infty$ prevails in the transverse direction, where e stands for the piezoelectric constant of the material. Poling is normal to the crack.

3.1. Dual scaling

The problem depicted in Fig. 2 pertains to dual scaling, where the mechanical stress induce macro effects and the electric field induces micro effects. This is equivalent to near crack tip plasticity induces micro effects, while macro effects are found away from the crack. The axiomatic distinction of macro and micro effects in elastoplasticity, however, is invoked on the "yield criterion" that remains dubious [1]. Micro-meso-macro effects of multiscaling are not considered in elastoplasticity as stated in [1]. Hence, elastoplasticity is inherently a monoscale proposition. *Monoscale elastoplastic solution will not change the sign of the monoscale energy release rate G. This does not mean that two wrongs can make a right.* The form of G in Eq. (4) is not valid when both micro and macro cracking effects are present.

Displayed in Fig. 3 are plots of the normalized energy release rate (ERR) $G/(a\sigma_\infty^2/m)$ and energy density factor (EDF) $S/(a\sigma_\infty^2/m)$ as a function of the electric field to stress ratio E_∞/σ_∞ .The negative portion of the ERR curve implies that the crack is absorbing energy instead of releasing energy. This unphysical result shows that the ERR criterion cannot be used for systems when both micro and macro effects are present. The EDF curve remained positive for all values of the applied electric field and stress. Curves similar to those in Fig. 3 for other values of applied electric or displacement fields and stresses or strains can be found in [11]. Fig. 4 exhibits a plot of normalized EDF versus ERR. The positive definiteness of EDF reflects its ability to treat both micro and macro effects.

The normalized energy density factor remains positive and reflects the energy released by both micro and macro effects. It is a multiscale criterion.

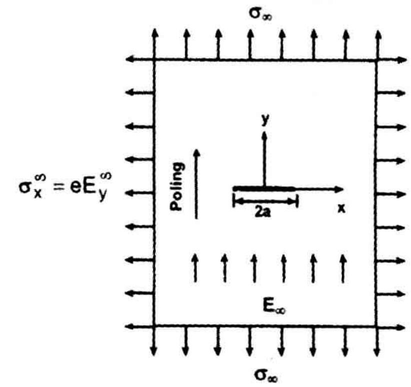

Fig. 2. Line crack in piezoelectric material.

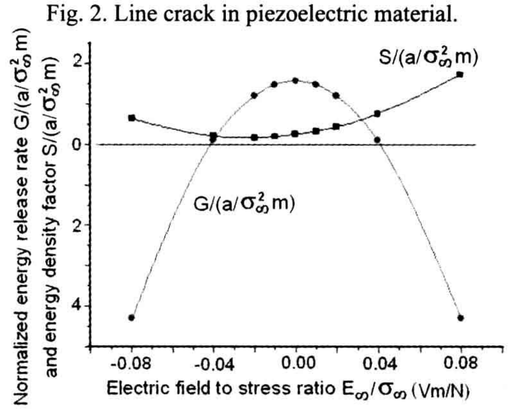

Fig. 3. Normalized energy release rate and energy density factor versus electric field to stress ratio.

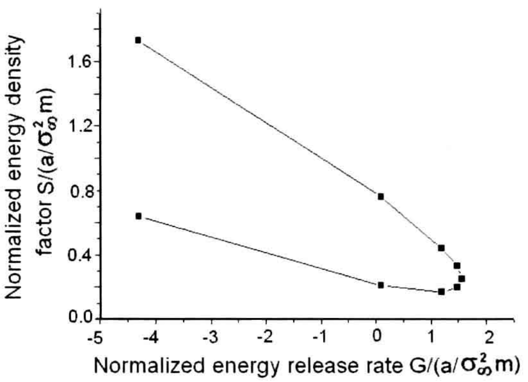

Fig. 4. Normalized energy density factor versus energy release rate.

3.2. Scale shifting

The evolution of failure is a gradual process with the direction of arrow from small to large involving at least two sizes. Refer to the measurement standard of scaling of the *Système international d'unités* or simply the SI system. In Tables 1 and 2, the standard prefixes for the SI units of measure will be used with some modifications for establishing the scale shifting law [3,4] based on the *surface energy density*. The interval between any two successive scales as shown in Tables 1 and 2 are very coarse. Smaller intervals may be introduced using meso scale ranges [13]. Fig. 5 illustrates the scaling of the volume energy density (VED) W versus the length r. The curve suggests a relation between W and r that would provide a way to transfer the results from the pico to the macro scale, referred to as scale shifting. This concept was originated in the 1970s with reference to the "scale shifting factor" [14].

The area under the W versus r curve is in fact the surface energy density (SED) S independent of any constitutive relations or theories in continuum mechanics or the geometry of the system. It applies to problems with or without discontinuities. Discovery of the $W=S/r$ was borne [14] when fracture mechanics embarked on the effects of the microscopic entities. A general scale shifting law can be stated as *Invariant of the surface energy density S relates the volume energy density W and characteristic length r of any two systems, determined within a coefficient of non-homogeneity" denoted by m.*

Here, the script m should not be confused with the symbol for meter m. A mathematical statement of the scale shifting law follows immediately:

$$m_{j/j+1} W_j r_j = W_{j+1} r_{j+1} \tag{5}$$

The subscripts j and $j+1$ can stand, respectively, for micro and macro, nano and micro or pico and nano. In Eq. (5), $m_{j/j+1}$ stands for the coefficients of inhomogeneity, the determination of which will not be discussed here for it will distract the essence of this work on the anomalies of failure prediction in the presence of dual- or multi- scaling. A quick glance of the scale ranges established by the SI system in Tables 1 and 2 show that

$$m_{pi/na} = m_{na/mi} = m_{mi/ma} = 1 \tag{6}$$

This implies that the curve in Fig. 6 is a perfect hyperbola; That is the SI units refer to a "homogeneous" system. This is not surprising since classical treatments rely on homogeneity and equilibrium. This also explains the wide use of monoscaling that misrepresents micro effects. In general, it can be shown that the curve in Fig. 5 is non-hyperbolically shaped. The determination of $m_{j/j+1}$ involves non-homogeneous and nonequilibrium considerations [15,16]. Also, time rate effects, represented by the dot on $\dot{W}_j$ *and* $\dot{W}_{j+1}$, can be important:

$$m_{j/j+1} \dot{W}_j r_j = \dot{W}_{j+1} r_{j+1} \tag{7}$$

Once the solution at the macro scale is known, the results may be transferred to the micro or other scales by means of Eq. (5) or (7). The simplified condition in Eq. (6) may be used as a first approximation. Keep in mind that homogeneity and equilibrium are the rules rather than the exception for finding traditional boundary value problem solutions at the macroscopic scale.

Table 1. Scaling of size or length in meter (m).

Name	Macro	Micro	Nano	Pico
Symbol	ma-m	mi-m	nm	pm
Fractor	10^{-3}	10^{-6}	10^{-9}	10^{-12}

Table 2. Scaling of volume energy denity in Pascal (Pa).

Name	Mega	Giga	Terra	Peta
Symbol	MPa	GPa	TPa	TPa
Multiple	10^6	10^9	10^{12}	10^{15}

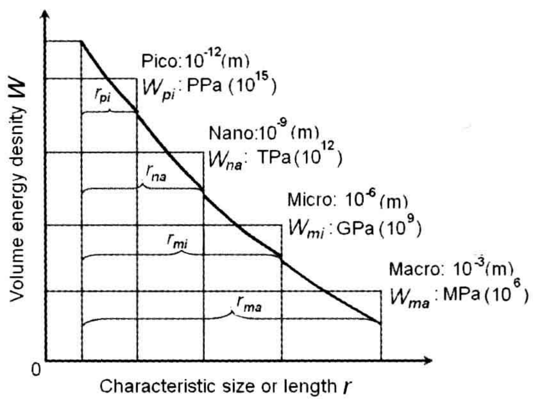

Fig. 5. Volume energy density versus characteristic length.

4. Reliability and sustainability connected with failure

When the maintenance costs of an airplane and nuclear power plant can be several times higher than the cost of manufacturing, the finger points to the deficiency in life prediction. A conservative factor of 5 or more can be assumed over a period of less than 10 years for the difference between the cost of manufacturing (construction) and maintenance. The trade-off between manufacturing cost and that of maintenance should not be hidden from initial considerations. The seed to failure is sawn when the trade-off is ignored.

The ultra high strength and light weight materials used to manufacture air transports will be used to illustrate the importance of material microstructure stability for high performance structures. This takes precedence for air transports where safety is of primary concern. The technology of holding tolerances for ultra high strength materials leaves much to be desired. Machining and assembling can change the dimension of the parts and sub-components in ways that cannot be accurately estimated. Trial and error during manufacturing can be expensive and over run the budget. The off-hand remedy does not cover the long run, where aging and fatiguing are additional factors that can further aggravate the situation. This is a new experience encountered by the manufacturers of Boeing 787 and Airbus A380, before the structure even had a chance to experience extended service. Mitigation of over confidence and uncertainties may be summarized: *Learn from failure to understand failure; anticipate uncertainties and unknowns to mitigate failure.*

However, similar vexing problems may remain in the long for the single aisle Airbus A340neo and Boeing 737 MAX that are already taking orders for sale. Uncertainties remain with the degradation of the material microstructure due to aging and fatiguing. These factors are more pronounced for the new structural materials that make use of both micro and macro properties. In the language of fracture mechanics, both crack initiation and propagation must enter into design even for structural materials, which are distinguished from super-alloys for the engine. In a nut shell, the decision makers of air transports seem to have adopted the philosophy that *Failure in manufacturing and potential risk of accidents can be compensated at the expense of maintenance.* Some of the technical and managerial details related to manufacturing and failure will be discussed in an International Conference on Airworthiness and Fatigue: 7th ICSAELS Series Conference, March 25-27, 2013. This event has been organized jointly by the Chinese Academy of Sciences, Institute of Mechanics and the International Center of Sustainability, Accountability, and Eco-Affordability for Large and Small (ICSAELS) [17]. The foregoing issues related to the manufacturing of air transports are basically similar to those associated with chemical and nuclear power plants where failure and safety are of primary concern. The demand for higher efficiency has required the use of higher temperature resistance materials, the reliability of which depends on the stability of the material microstructure. This in effect calls for the sustainable time of reliable operation of the system.

A few remarks with reference to failure and safety are in order. Failure cannot be predicted. It can be mitigated by anticipating the unexpected. The world environment, economy and government policy change, all of which can influence the decision on manufacturing and failure. The consideration of these factors casts a different view on safety: *Safety amounts to anticipating the uncertainties and unknowns.*

Technically speaking, safety is no more than the commitment to acknowledge the evolution of failure at the different scales, while the material microstructure and system components undergo changes. Philosophically speaking, safety can be used as a camouflage of the uncontrollable factors affecting the failure of a system.

Pay more attention to maintenance and learn by hind sight within the shortest time interval, no more than one year. Do not wait for 10 or 20 years!

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