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TRANSLATIONAL RESEARCH IN MECHANICS AND MATERIALS WITH EMPHASES ON SUSTAINABILITY AND DURABILITY

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Abstract: Sustainability is defined as the “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” according to the Brundtland Commission, 1983 in “Our Common Futures”. Sustainability includes all aspects of the society, such as building and civil infrastructural systems, energy, environment, health, safety, life-cycle analyses, etc. The Hakka rammed earth buildings (Tulou) are good examples of sustainability over the ages. There are many challenges and barriers for sustainability. In addition new technologies such as nanotechnology and smart materials play a key role in achieving sustainability. Durability and accelerated tests are essential for new materials. A promising process in new material design is using reinforcement via the placement of hard particles in a matrix. Here we present the modeling and prediction of the elastic response and damage propagation in composites reinforced by stochastically-dispersed particles. The microstructure of the composite, such as particle size, shape and distribution, plays an important role in mechanical behavior. Based on a microstructure finite element model, a simple theory is developed to predict the mechanical behavior of particle-reinforced composite material. The internal detailed stress distribution and damage propagation in the composite can be obtained. This work presents a comprehensive understanding of the mechanics of composite material reinforced by stochastically-dispersed particles. Other research and challenges in mechanics and materials, including multi-scale/multi-physics modeling and nanomechanics are to be discussed.

Keywords: Sustainability, accelerated tests, durability, Chong cycle, nano-technologies, semi-circular bend (SCB) specimen, material mechanics, material design

1 INTRODUCTION

Nano science and engineering is one of the frontiers in transformative and translational research. Nanotechnology is a very efficient way in the creation of new materials, devices and systems at the molecular level - phenomena associated with atomic and molecular interactions strongly influence macroscopic material properties with significantly improved mechanical, optical, chemical, electrical and other properties. As for new materials, due to the lack of data, accelerated tests are essential to assess durability and performance of material systems. On the other hand, the Hakka rammed earth buildings (Tulou) are sustainable over centuries. The research in Tulou will yield useful data and concept on sustainability and harmony with nature.

A promising process in material design is using reinforcement via the placement of hard particles in a matrix. Therefore, composite material, as a inhomogeneous material, has some kinds of uncertainty in geometry or orientation of the reinforcement, which will greatly influence the material property of the microstructure. In order to evaluate reliability of a composite structure, the randomness of the microstructure must be investigated. For this purpose, Bazant (1990) and Jirasek (1995) considered the random geometrical configurations and locations of the particles. Also, some results on the stochastic homogenization analysis have been reported by Sakata et al in 2008. They proposed a perturbation-based homogenization analysis method to solve the stochastic microscopic stress analysis problem with an assumed microscopic random variation. This method reduced the computational cost compared with the Monte-Carlo simulation. Moreover, they proposed the inverse stochastic homogenization analysis method for identifying a microscopic random variation. In addition, the mechanics of the composites reinforced by randomly dispersed particles have already been discussed by Li et al (2011).

Here we present the modeling and prediction of the elastic response and damage propagation in composites reinforced by stochastically-dispersed particles. This is a very complex problem, since the microstructure of the composite, such as particle size, shape and distribution, plays an important role in mechanical behavior. Based on a microstructure finite element model, a simple theory is developed to predict the mechanical behavior of particle-reinforced composite material. In this work, a three-dimensional material body is decomposed into many unit cells. Each unit cell is reinforced by a disk particle, of which the orientation is characterized by three Euler angles generated by the Monte-Carlo method. To begin with, we evaluate the effective material properties of a representative volume element (RVE). Eventually the internal detailed stress distribution and damage propagation in the composite can be obtained. This work presents a comprehensive understanding of the mechanics of composite material reinforced by stochastically-dispersed particles.

The transcendent technologies include nanotechnology, microelectronics, information technology as well as the enabling and supporting civil infrastructure systems and smart materials. These technologies are the primary drivers of the twenty first century and the new economy. Structural sensing, sustainability, energy, modeling and simulation, environmental concerns are also some of the challenging areas. Research opportunities, education and challenges in mechanics and materials, including multi-scale/multi-physics modeling, nanomechanics, as well as design of materials are to be presented.

2 SUSTAINABILITY

Sustainability affects all aspects of the society. Sustainable buildings include energy efficiency, health, IAQ (indoor air quality), sensors, durability, renewal engineering, life-cycle performance, intelligent structures, etc. New technologies such as nano and materials engineering play key roles in achieving sustainable buildings and structures. There are many challenges and barriers for sustainability. In addition new technologies such as nanotechnology and smart materials play a key role in achieving sustainability (Chong, 2010 a,b). There have been some successes in the 1960's in the California school building systems and the Canadian super-insulated houses. However IAQ is still a serious problem in all buildings and offices. On the other hand, the natural ventilation, IAQ and earthquake resistance in Tulou can be emulated in the design of modern buildings.

According to NIST, the U.S. construction and building is a $1.2 trillion/yr industry, represents 5 % of the GDP, and employs nearly 12 million workers. The construction industry affects 12 % of the U.S. economy. The vast majority of construction firms are small and do not have the resources to conduct the research needed. Some data suggest a 40-yr decline in construction productivity (-0.6% per yr) while non-farm productivity has increased by +1.8% per year; there is an estimated 25-50% waste and inefficiencies in labor and material control; and the cost of inadequate interoperability in commercial and industrial construction alone is estimated to be $17-36 B/yr. Buildings represent the single largest end-user of energy (40%) and electricity (72%) and contributor of carbon dioxide emissions (39%) when compared with the transportation and industrial sectors. The estimated cost of renewing the U.S. physical infrastructure exceeds $2.2 trillion.

In the mid-1990's, the National Science Foundation (NSF) launched a major initiative on Civil Infrastructure Systems (CIS; Chong and Liu, 1993). Among the major recommendations were: 1. Deterioration Science – examines how materials and structures break down and wear out over time; 2. Assessment Technologies – determine how durable, safe and environmentally benign the (building) structures are; 3. Renewal Engineering – extends and enhances the life of CIS and components; 4. Institutional Effectiveness and Productivity – decision processes on the CIS on the economic and productivity issues. These recommendations in addition to net-zero energy buildings are still very relevant for the sustainable buildings, a major part of the CIS. They resulted in many awards, workshops and books (e.g. Chong, et al, 1990, 2002; Li, et al 2009; Monteiro, et al 2001) and other related initiatives (e.g. Engineering Sustainable Buildings, NSF 09-606, led by L. Bank, 2010).

Nanotechnology on the other hand is a very efficient way in the creation of new materials, devices and systems at the molecular level - phenomena associated with atomic and molecular interactions strongly influence macroscopic material properties with significantly improved mechanical, optical, chemical, electrical and other properties (Chong, 2004, 2009). NSF former Director Rita Colwell in 2002 declared, “nanoscale technology will have an impact equal to the Industrial Revolution”. Europe has been at the forefront of nanotechnology in construction and civil infrastructure systems as can be seen from the several International Symposia on Nanotechnology in Construction (Chong, 2003; Larsen-Basse and Chong, 2005).

2.1 Potential Breakthroughs

U.S. National Research Council identified the following activities with potential for breakthrough improvements (http://www.nist.gov/bfrl/nrc_111709.cfm): 1. Widespread use of interoperable technology applications and Building Information Modeling (BIM). 2. Improved job-site efficiency through more effective interfacing of people, processes, materials, equipment, and IT. 3. Greater use of prefabrication, preassembly, modularization, and off-site fabrication and processes. 4. Innovative demonstration Installations. 5. Effective performance measures to drive efficiency and support innovation. As can be seen from the list, nano technology (e.g. nano clay additives in fire proofing, coatings, structural materials), simulation (Chong et al 2002) and engineered materials play important roles in sustainable buildings.

2.2 Policy Framework and Decision Tools

To achieve net-zero energy buildings, NIST developed the following Policy Framework (see in Fig.1), listing R&D issues, barriers and goals. In addition a useful sustainability decision tool, named BEES 4.0 (Buildings for Environmental and Economic Sustainability, version 4) measures the performance of building products with life -cycle assessment techniques developed by ISO and ASTM has been developed: see following website (http://www.sustainablebuildingcentre.com/forum-topic/ Search for BEES).

Fig.1 Policy Framework

3 DURABILITY STUDIES

3.1 Fracture of Brittle Materials

It is well known that linear elastic fracture mechanics is not strictly applicable for brittle or geomaterials due to the occurrence of relatively large fracture process zones. In these materials, the process zone is made up of a region of microcracks that may be pre-existing and crack bridging may also occur in the process zone. The semi-circular bend (SCB) specimen invented by Chong (Chong and Kuruppu, 1984) is depicted in Fig. 2. It is a core-based specimen, and has certain inherent favorable properties such as its simplicity, minimal requirement of machining and the convenience of testing that can be accomplished by 3-point loading using a standard test frame. SCB is now used worldwide mostly for simple fracture testing and some for specimen size-independent fracture toughness testing based on J-integrals. SCB is being considered as a standard for dynamic and static fracture toughness testing of geomaterials. SCB has also been extended into mixed mode fracture (Ayatollahi et al, 2011).

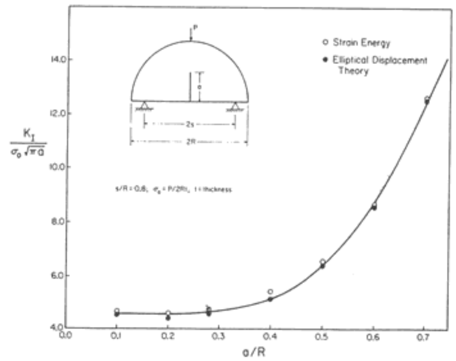


Fig. 2 Mode I stress intensity factor

3.2 Durability Issues, Chong Cycle and Accelerated Tests

Fundamental research in durability of materials and structures have shown great potential for enhancing the functionality, serviceability and increased life span of our civil and mechanical infrastructure systems and as a result, could contribute significantly to the improvement of every nation's productivity, environment and quality of life. Innovative short-term laboratory tests are developed, which allow accurate, reliable prediction of long-term performance of new materials since such data are hard to come by. For new materials (Chong, 1996) accelerated tests are needed to assess durability (Monteiro, et al 2001) and sustainability. One of such accelerated laboratory test, named as the “Chong Cycle” by coating communities (Aragon and Frizzi, 2002), has been developed to predict the long-term performance of coating materials in bridges (Chong and Yao, 2009; Chong and Chong, 2009). The test includes alternating cycles of freeze, ultraviolet/condensation, and salt-fog/dry air; and it has been added to the ISO (International Organization for standardization) method for testing coatings for structures.

The intelligent renewal of aging and deteriorating civil and mechanical infrastructure systems includes efficient innovative use of high performance composite materials for structural and material systems including nano materials (Chong, 2004) and smart and high performance materials (Chong et al, 1990, 1996, 2002).

3.2.1 Durability Issues

Demands for better-performing, longer-lasting, safer, more economical, and more environmentally friendly structures and machines are constantly pushing the envelope of technological capabilities engineering practice (Chong et al 2002; NSF 1998; Monteiro et al 2001; Chong et al 1996). As a result there are relentless moves towards close tolerances and use of realistic life-cycle design, condition-based maintenance, and performance-based design.

Durability of new materials involves the synthesis, laboratory and field testing, accelerated tests, modeling, etc. Table 1 illustrates the size effects and mechanics involved (Boresi et al 2011).

Table 1 Scales in material systems

Material	Structures		Infrastructure
Submicro-level *Molecular scale*	Meso-level *Microns*	Macro-level *Meters*	Systems integration *Up to km scale*
-nano-mechanics -nanotechnology -NEMS	-meso-mechanics -MEMS -interfacial mechanics	-beams -columns -plates	-bridges -buildings -airplanes

Its stated aim was: " ... developing innovative short-term laboratory or in situ tests which allow a reliable prediction of long-term performance of materials, machines and structures ... " based on understanding of the fundamental nature of deterioration processes and innovative ways to model processes as they affect life and long-term performance. NSF project awards have been made in these areas and the findings have been presented in a book (Monteiro et al, 2001).

3.2.2 The Chong Cycle

The annual bridge maintenance and rehabilitation costs billions of dollars in the US alone; therefore reducing corrosion is a critical task for bridge engineers and owners in order to ensure a sustainable critical infrastructure. Coatings have been applied over offshore platform/structures, and steel bridges to reduce corrosion which affects the structure integrity and load carrying capacity of bridges as well as ultimate failure; the coating durability of course is a critical issue for bridge maintenance. Field testing takes long time to determine the lifetime of bridge coatings; therefore, any reliable accelerated laboratory test method within relatively short time would be very beneficial for estimating the long term durability of coatings over steel bridges. A more realistic laboratory accelerated test, named by the research communities as the Chong Cycle (Aragon and Frizzi, 2002) has been developed to predict the long-term field performance of bridge coatings. In conjunction with a powerful evaluation technique, the relative performance of various bridge coatings can be easily distinguished (Chong and Chong, 2009). Various accelerated laboratory test methods have been developed to evaluate the relative performance of offshore platform/structures coatings and bridge coatings, especially for newly reformulated low volatile-organic-compound (VOC) content and high solid bridge coatings. Prior to 1990, salt-fog test was the primary method for testing coatings. Later, bridge engineers and coating industry have found that the salt-fog testing, as designated in the American Society for Testing and Materials (ASTM) B117 method, does not accurately predict the field performance of many of the new low-VOC coating systems, particularly for waterborne coatings showing unrealistic premature failures. Later Chong S-L (1995; 1997) created a variation of ASTM D5894 and added a low temperature cycle. The results were better correlated with a natural marine exposure of 28 months than those obtained from salt-fog (ASTM B117), and QUV*/cyclic salt-fog. This test cycle was named as "Chong Cycle" by Aragon and Frizzi (2002). Due to the importance of low temperature thermal stress, a new freeze cycle has been added in the International Standard (ISO) 20340 method in accordance with the "Chong Cycle".

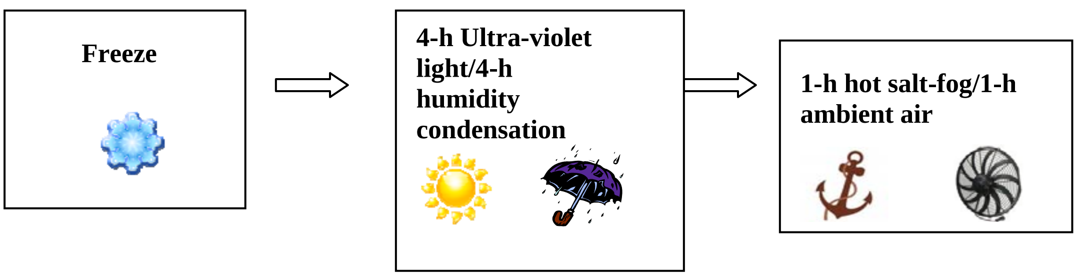


Fig. 3 The Chong Cycle

Laboratory accelerated tests

The Chong Cycle (Fig. 3): 70-h(hour) freeze/215-h QUV/215-h cyclic salt-fog cycle

Freeze temperature: -23 ^{0}C (-10 ^{0}F)

*QUV: UV/Condensation test

Test cycle: 4-h UV/4-h condensation cycle

UV lamp: UVA-340

UV temperature: 60 ^{0}C

Condensation temperature: 40 ^{0}C

Cyclic salt-fog: 1-h wet/1-h dry cycle.

Outdoor marine exposure

Location: Sea Isle City, New Jersey

Annual characteristics

Sunshine: 2,840 h

Relative humidity: 51%

Rainfall: 150 cm
Spray sea water once a week: pH = 7.5
Salt content: 2.7%

The results of this correlation study strongly suggest that the Chong Cycle (Chong et al, 2009), freeze/QUV/cyclic salt-fog test, is comparatively a much more reliable laboratory accelerated laboratory method to predict the field performance of the coating systems in a salt-rich marine environment.

4 MATERIAL DESIGN

Composite materials are usually made by combining two materials where one of the materials is a reinforcement and the other material is a matrix. The combination provides characteristics superior to either of the materials acting alone. A promising process in new material design is using reinforcement via the placement of hard particles in a matrix. It is the dominant material in industries such as architectural, automotive, medical, and industrial equipment.

In order to predict the mechanical behaviors of particle reinforced material, there are two topics need to be considered. One is the dispersed particles in the matrix are of randomness, which means the elastic property is different at different location. The other one is the microscopic stress distribution takes an influence of not only the microscopic random variation but also a macroscopic condition, and therefore a multiscale analysis method is important in the whole process. Outline of the stochastic analysis of microscopic stress and macroscopic damage propagation in a multiscale problem solved in this paper is illustrated in Fig. 4.

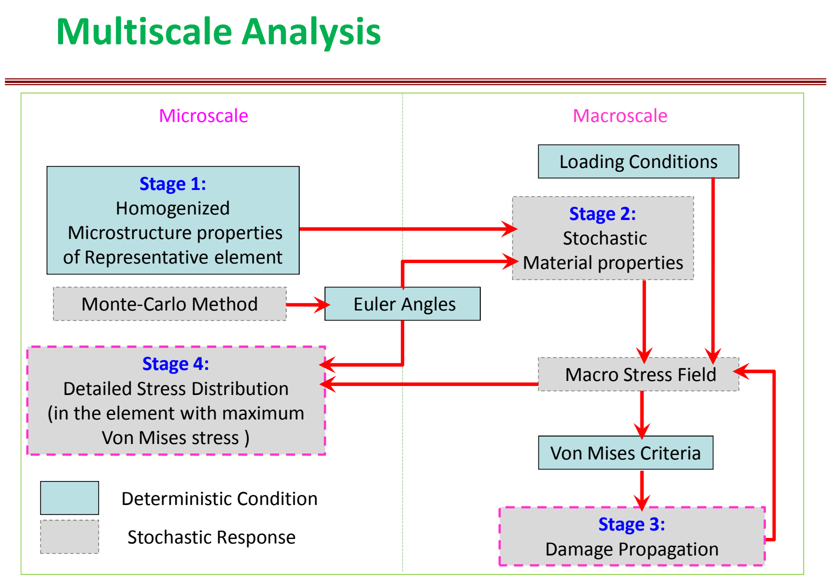


Fig. 4 The multiscale analysis process

In this paper, at first, a three-dimensional material body is decomposed into many unit cells. Each unit cell is reinforced by a disk particle, of which the orientation is characterized by three Euler angles generated by Monte-Carlo method. Fig. 5 shows the distribution of two Euler angles, varying from 0 to 2π randomly. The material constants of the Representative Volume Element (RVE) will be determined by using the finite element method. It is assumed that both the particle and matrix in the RVE are continua of linearly elastic, isotropic and homogenous materials, with given Young's module and Poisson's ratios. It is also assumed that the two materials are perfectly bonded at the interface. Based on the microstructure finite element model, a simple theory is developed to predict the mechanical behavior of particle-reinforced composite material. Eventually the damage propagation in the composite is obtained. This work presents a comprehensive understanding of the mechanics of composite material reinforced by stochastically-dispersed particles.

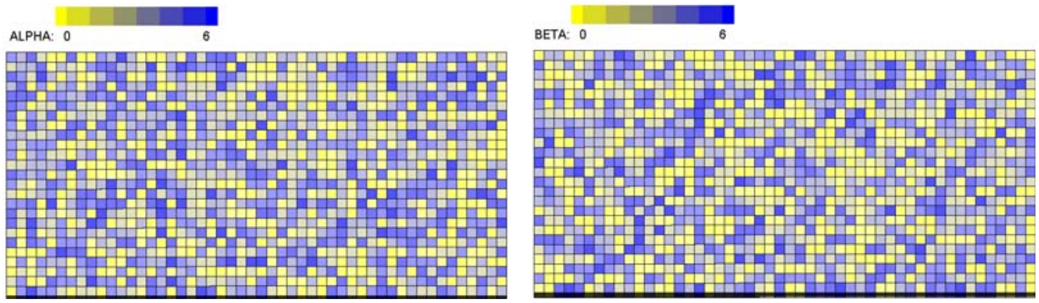
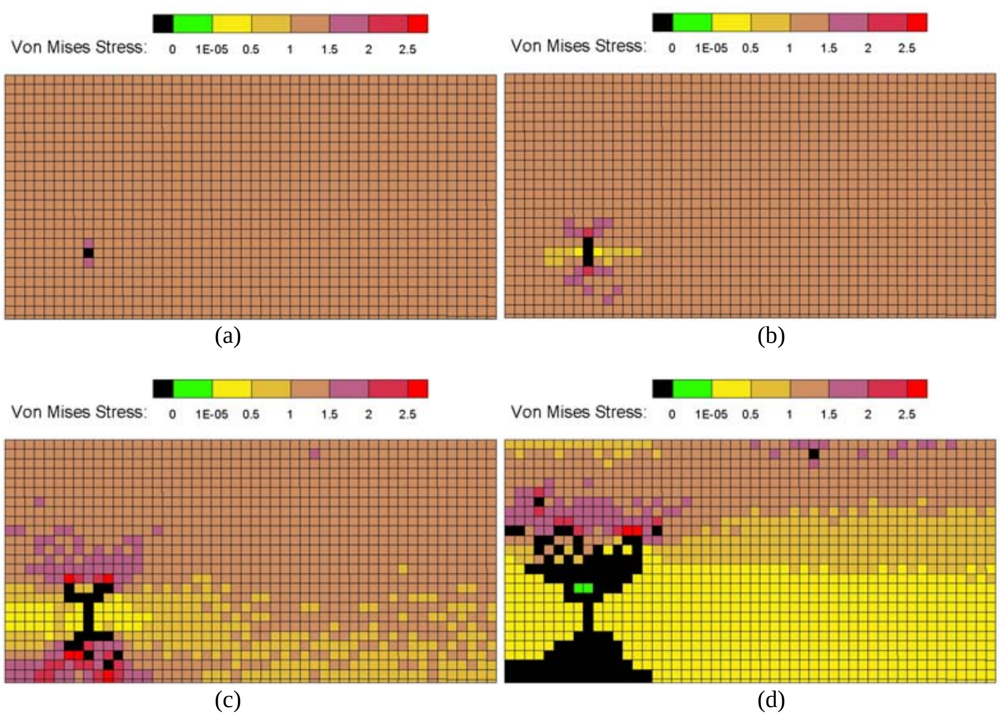


Fig. 5 The distribution of two Euler angles

Fig. 6 shows the von Mises stress distribution in the damage propagation process step by step. The damage is modeled using the element elimination technique. Once the von Mises stress of the elements exceeds their von Mises strength, these elements are considered to be damaged. Therefore, the elements whose von Mises stress is zero imply that they are damaged elements. At step 3 (Fig. 6 (c)), some individual non-connected damaged elements appear. Similar results appear at step 4, step 5 and step 6. This phenomenon has never been observed in homogenous materials. It is caused by the reinforced particles whose orientations are randomly distributed. At step 6 (Fig. 6 (f)), the damaged elements have already spread across the whole specimen, and therefore it cannot bear any loading. The results also show that this kind of composite material can resist the damage propagation effectively and prolong the material's useful life.



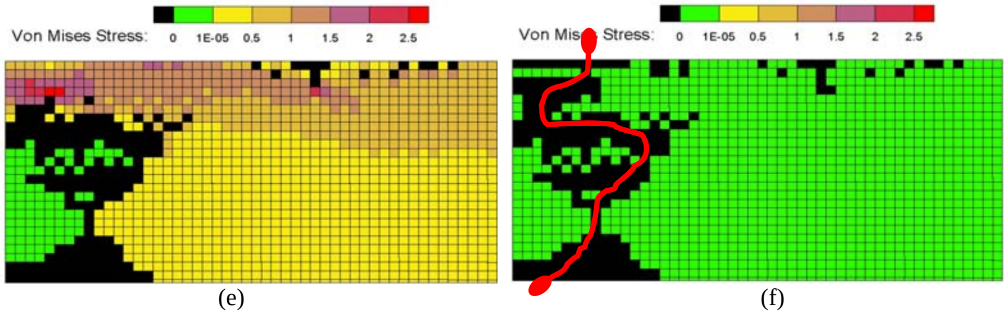


Fig. 6 The von Mises stress distribution during the damage propagation
at (a) step 1; (b) step 2; (c) step 3; (d) step 4; (e) step 5; (d) step 6

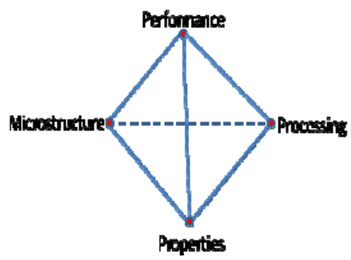


Fig. 7 Materials tetrahedron

5 CONCLUSIONS

Sustainable buildings, important part of a modern society, directly affect the quality of life of all citizens. The Hakka rammed earth buildings (Tulou) are good examples of sustainability over the ages. New technologies such as nano, simulation, and materials engineering play key roles with potential for breakthroughs. The historical perspective, R&D, challenges and barriers for sustainable buildings are presented. Key elements include material mechanics, life-cycle performance, smart materials, durability, nano and other new technologies.

In the NSF Durability Initiative, one may think of the materials tetrahedron (see Fig.7) promulgated by an Academy report (NRC, 1989) where performance, as the ultimate "materials characteristic", is shown linked to microstructure/composition, properties, and processing forming the apex of the tetrahedron. Durability Initiative and the results demonstrate that we are now well on our way to also develop reasonable understanding of the connections of the apex of the tetrahedron, performance, to the topics in the base triangle. The need and rational for short-term accelerated tests to predict realistically long-term performance of structures and materials are presented. This is especially needed for new materials including coatings. The test results demonstrated that the Chong Cycle test produced more realistic coating performance as compared to outdoor salt-rich exposure results than the conventional test methods.

To improve the material property, such as sustainability and durability, composite material is a viable choice. We can choose the reinforcement and the matrix, and also we can design it for certain properties and performance. The simulation results show that composite material can mitigate and arrest the damage propagation effectively and prolong the material's useful life.

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