A Building Moisture Load Theory for Improvement of Whole House Durability

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Abstract

Structural engineering theory guides building designers in designing the various structural components of buildings to withstand the live, dead, wind, and earthquake loads to which they will be subjected. Architects and engineers also have thermodynamic theory to guide them in designing the mechanical systems to modify nature and therefore provide thermal comfort and a healthy environment for a building's occupants. The structural and thermodynamic theories have been developed over a long period of time, and along with the laws of physics, seem to be rather well defined at this point in history. Certainly, there will always be improvements in these theories, but for the most part, they allow designers and constructors to build buildings adequate for human occupancy. Since the early 1990s, much parallel research has been done to define the physical characteristics of moisture in its various forms and how it too puts a load on building components and systems. Moisture content changes cause components to expand and shrink, impacts the insulating capacities of materials, changes rates of moisture diffusion as the materials themselves change their moisture content, gravity affects it, temperature affects it, and so it is theorized moisture follows the laws of physics much like thermodynamics and structural engineering theory. Development of a Comprehensive Building Moisture Load Theory should lead to improvements in the durability of many of the materials, components and systems of our buildings, including our housing stock. More research is needed to develop moisture load theory, however, and this paper will describe some of the elements necessary for continued study leading to a more complete moisture load theory.

Keywords: Diffusion, loads, moisture, structural design, thermodynamics, laws of thermodynamics, theory, vapor.

Introduction

Contemporary knowledge of the effects of moisture in buildings suggests that it is possible to describe a comprehensive building moisture load theory. The thesis of this paper, however, is that while such a theory may exist, it is not completely developed and therefore, more research work is needed to fully develop such theory.

Building designers have structural engineering theory to guide them in designing the various structural components of buildings to withstand the types of loads they will be subjected to. Structural loads such as live, dead, wind, earthquake, along with time and moisture, affect the

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way buildings perform in service, and how they should be designed and constructed to properly manage those forces and effects.

Architects and engineers also have the laws of thermodynamics - i.e. thermodynamic theory - to guide them in designing the mechanical systems of buildings to modify nature and therefore provide thermal comfort and a healthy environment for the occupants. Heat exchange, diffusion, entropy and other forces known from research and experimentation guide professionals in the design of mechanical systems.

The structural engineering and thermodynamic theories have been developed over long periods of time, and along with the laws of physics and nature that are incorporated in them, seem to be rather well defined. Certainly, there will be improvements in these theories and ultimately in how the structural and mechanical systems for buildings are designed, but for the most part they allow designers and constructors to build buildings that are quite adequate for human occupancy.

Since the early 1990s, much parallel research has been done to define the physical characteristics of water (i.e. moisture) in its various forms and how it too puts loads on building components and systems. Unfortunately, these loads are not accurately modeled in the design of material, structural and mechanical systems of buildings. The large number of moisture-related problems reported in buildings over the past 15 or so years is evidence of this fact.

Changes in moisture content within the components of buildings causes them to expand and shrink, there are impacts on the insulating capacities of materials, and there are changes in the rates of moisture diffusion as the materials themselves change their moisture contents. Gravity affects moisture, temperature affects moisture, pressure affects moisture, volume affects moisture, and so one could hypothesize that moisture loads follow the laws of physics and nature much like in the other theoretical systems.

Development of a comprehensive moisture load theory should lead to improvements in the durability of the materials, components and systems of our buildings. It should give designers the tools, and in fact, awareness of and appreciation for, moisture loads, so it will become first nature to consider them when buildings are being designed.

Perhaps the potential for improvement of durability in buildings is the greatest in housing. Numerous efforts by the U.S. Department of Housing and Urban Development, the U.S. Department of Energy, and other agencies, have been undertaken in recent years to define the limits of durability in our housing and how to improve it for a better housing stock. This paper will review the basic characteristics of thermodynamic and structural engineering theories, and lay the groundwork for future research activities that could lead to a more complete moisture load theory.

Thermodynamic Laws

Thermodynamics is the study of relationships among heat, work, and internal energy of a system. The British scientist and author C.P. Snow had an excellent way of explaining the three laws (http://www.physlink.com/Education/AskExperts/ae280.cfm on 3 January 2004):

1. You cannot win. That is, you cannot get something for nothing - matter and energy are conserved.

2. You cannot break even. You cannot return to the same energy state - there is always an increase in disorder; entropy always increases.

3. You cannot get out of the game - absolute zero is unattainable.

In their simplest terms, the Laws of Thermodynamics dictate the specifics for the movement of heat and work. Basically, the First Law of Thermodynamics, for example, is a statement of the conservation of energy. The Second Law is a statement about the direction of that conservation, and the Third Law is a statement about reaching Absolute Zero (0° K). A fourth law of Thermodynamics, called the Zeroth Law, describes the unique relationships between the first three laws.

Historical Evolution of the Laws of Thermodynamics

Much of the following discussion about the historical evolution of the laws of thermodynamics came from www.rfcafe.com, a website rich with a variety of physical and engineering information. The laws of thermodynamics have become some of the most important laws of all science. A brief review of the history of their origin is instructive. Prior to the 18th Century, society favored developments in the life sciences (largely for medical research) and astronomy for navigation and a record of the passage of time (also a source for early mythology and folklore). Plagues, diseases and other life-threatening maladies were a constant concern to societies during these centuries. Science was viewed as purely a philosophic endeavor, where little research was conducted beyond the most useful fields. Indeed, philosophy and science, different by nature, were inseparable in emerging disciplines such as medicine, engineering, and architecture. This is always true of new fields where no firm basis of study has yet been conducted.

European society was about to experience unforeseeable rapid changes as the paradigm shifts from an agrarian society to an industrial society began to emerge. Prior to the mid-18th Century, the general European populace randomly dotted the land in small agricultural communities, industry was run out of country cottages, and scientific developments were nearly at a standstill. Suddenly, with little transition, new pockets of industry arose, focusing towards larger-scaled machines rather than small hand tools. Larger industrial complexes often overwhelmed small agriculturally centered communities, and in many areas, a more attractive city life rendered country life obsolete. Coinciding with vast social and political changes, this historic event would later come to be called the Industrial Revolution.
If necessity were the mother of all innovation, then the Industrial Revolution of the 19th Century would be the "mother of all necessities" as it brought a new set of needs to society. Horrendous living conditions in the overcrowded industrial cities of the Northeastern United States, England, and the rest of Europe bred a plethora of diseases and viruses. These conditions, along with other results of spontaneous industrial-induced urbanization, demanded that science address the problems of an ever-changing human civilization.

As in the periods before, science of the Industrial Age responded to such needs by centering on medical advances in the early stages of the revolution. Such was the era of crucial medical breakthroughs, and age of the greatest physiologists - such as Marie Curie (radium), Wilhelm Roentgen (x-rays), Louis Pasteur (pasteurization), Edward Jenner (smallpox vaccination), Joseph Lister (bacteria antiseptic), and Charles Darwin (evolution). Even the designs of buildings changed, as the health, safety and welfare of the public became increasingly important in response to the deplorable living and public health conditions caused by industrialization. The Tenement Laws of New York in the 1880s and other attempts at building regulation were efforts to try to provide the public with healthier housing and working environments.

Once the medical crisis was adequately addressed, science could concentrate on the heart of an industrial society – that is, large-scaled machinery. True of 19th Century mass production industries, the company with the greatest machines produced more products, made more money, and was consequently, more successful. Fierce competition arose to find the most industrious machinery possible, and research into how far the limits of these machines could be pushed so as to achieve maximum productivity without consuming much energy was undertaken.

Again, society would fuel scientific advancement. The 19th Century scientists were encouraged to study the machine and its efficiency. To do this, physicists analyzed the flow of heat (energy) in these machines, and the chemical changes that transpired when they performed work. Thus was the establishment of modern thermodynamics. First on the agenda of this new discipline was to find a means to convert heat (as produced by machines) into work with greater efficiency. In theory, if full efficiency could be accomplished, a machine could run off its own heat, producing a never-ending cycle of heat to work, rendering heat, converting to work, and so forth indefinitely.

The idea of a machine that could run continuously off its own exhaust, or a perpetual-motion machine as it was dubbed, excited the industrial entrepreneurs which contributed much funding for its development. However, as the research was completed, the results were all but pleasing to the sponsors. As it turned out, the very same research oriented to create a perpetual-motion machine proved that the very concept was not possible. The proof lies in two theories (now three) that are currently considered the most important laws in the whole body of science - the Laws of Thermodynamics.

The historical evolution of these laws finds that the First Law of Thermodynamics is really a prelude to the Second. The First Law, which is really about *conservation,* states that the total energy output (as that produced by a machine) is equal to the amount of heat (energy) supplied. Generally, energy can neither be created nor destroyed, so the sum of mass and energy is always conserved. A mathematical approach to this law produced the equation $U = Q - W$ (the change in the internal energy of a closed system equals the heat added to the system minus the work done by the system). This finding did not restrict the use of perpetual-motion machines. However, the Second Law would deal a blow to all believers of such a wonder machine because it was impossible to create.

The Second Law of Thermodynamics states that "in all energy exchanges, if no energy enters or leaves the system, the potential energy of the state will always be less than that of the initial state." This is also commonly referred to as *entropy*. For example a spring driven watch will run until the potential energy in the spring is converted, and not again until energy is reapplied to the spring. A car that runs out of gas will not run again until someone goes to a gas station to secure gas to refuel the car. This movement requires the input of energy. Once the potential energy locked in carbohydrates or hydrocarbons is converted into kinetic energy (energy in use or motion), the organism will get no more until energy is input again. In the process of energy transfer, some energy will dissipate as heat. *Entropy*, then, is a measure of disorder in the system: cells are NOT disordered and so have low entropy. The flow of energy maintains order and life. Entropy wins when organisms cease to take in energy and die.

Zeroth Law	First Law	Second Law	Third Law
When each of two systems is in equilibrium with a third, the first two systems must be in equilibrium with each other. This shared property of equilibrium is the temperature. The concept of temperature is based on this Zeroth Law.	Because energy cannot be created or destroyed (with the special exception of nuclear reactions) the amount of heat transferred into a system plus the amount of work done on the system must result in a corresponding increase of internal energy in the system. Heat and work are mechanisms by which systems exchange energy with one another. This First Law of thermodynamics identifies caloric, or heat, as a form of energy.	Entropy—that is, the disorder—of an isolated system can never decrease. Therefore, when an isolated system achieves a configuration of maximum entropy, it can no longer undergo change (it has reached equilibrium). Additionally, it is not enough to conserve energy and thus obey the First Law. A machine that would deliver work while violating the second law is called a "perpetual-motion machine of the second kind." In such a system, energy could then be continually drawn from a cold environment to do work in a hot environment at no cost.	The Third Law of thermodynamics states that absolute zero cannot be attained by any procedure in a finite number of steps. Absolute zero can be approached arbitrarily closely, but it can never be reached.

Figure 1. The Four Laws of Thermodynamics

Source: Used with permission; from http://www.rfcafe.com/references/general/thermodynamics.html on 3 January 2004.

The Third Law of Thermodynamics refers to the inability to approach the temperature of absolute zero with a finite number of steps. Some heat will almost always be present in natural systems or materials, even if it is very little. To take all of the energy or heat out of materials requires energy itself.

Thermodynamics, then, is the field of physics that describes and correlates the physical properties of macroscopic systems of matter and energy by relating such qualities as temperature, pressure, and volume. It also takes in energy, heat, and work. When a physical system moves from one state of equilibrium to another, a *thermodynamic process* is said to take place. The laws of thermodynamics were discovered in the 19th Century through painstaking experimentation. Large sums of money were spent in support of the research leading up to definition of these laws. From the studies of energy use in the Industrial Revolution, we know that energy exists in many forms, such as heat, light, chemical energy, and electrical energy. Energy is the ability to bring about change, or to do work. Thermodynamics is the study of energy.

The Fourth Law of Thermodynamics, the Zeroth Law, was added during the 20th Century to more accurately describe the potential relationships between the other three. It followed the Third Law wherein studies of absolute zero were undertaken. Figure 1 describes the relationships between the four Laws of Thermodynamics.

Structural Engineering Theory

Structural mechanics forms the basis of structural design (Parker 1975, 3). *Mechanics* is the science that studies the actions of forces on materials, including material bodies such as structural components. *Statics* is the branch of mechanics that treats bodies held in equilibrium by the balanced external forces acting upon them. *Dynamics* is the branch of mechanics that treats structural bodies when external forces act upon them and momentarily, at least, disturb the equilibrium conditions of the materials.

When one studies the strength of materials, one studies the behavior of material bodies in resisting the actions of external forces, the stresses developed within the bodies, and the deformations or changes in shape or position that result from the external forces (op cit., 3). Altogether, these subjects constitute what Parker calls the field of *structural mechanics.*

For the sake of simplicity, the study of statics and strength of materials about structural components and materials of buildings, is usually concentrated on single members (French 1996, 3). Buildings and their supporting structures are not built of single components, however, as building structures may consist of literally thousands of components. From much experience and experimentation, it is known that as one member in a structure is affected by an internal or external force, chain reactions propagate to other members throughout the structure.

Finite Element Analysis of Building Structure Components

The finite element method of structural component analysis has evolved over the past 25 years from a specialized technique for aircraft frame analysis to a solution technique applicable to a wide range of physical problems, including building structures. Beginning with the problems encountered in analyzing the components of high performance aircraft, prediction of the response of spars, ribs, stiffeners and metal skin grew in complexity until algebraic, differential and integral equations could only handle the only the most elementary problems (Grandin 1991, 1-3). The entire region of the skin and its stiffness was perhaps the most difficult component of aircraft structures to model and so engineers and mathematicians developed a method for analyzing the stiffness of the metal skin. The section of metal skin was simulated with a framework of bars of known stiffness. The mathematical analysis of areas of skin worked well as long as the section was rectangular in shape. Irregular areas posed a more challenging problem of analysis. Matrix structural analysis was used initially, and with the invention of the computer, new techniques of analysis allowed for more complexity – for example, irregular wing surfaces.

In almost any physical problem, the region of analysis is divided into small sub-regions – or components – represented by a function very much simpler than that required for the entire region. The sub-regions are joined together mathematically by enforcing conditions that make each element boundary compatible with each of its neighbors while satisfying the region boundary requirements.

When structural components of buildings are analyzed, the same process is followed so that each component is studied in its relationship with its neighboring component or material. This process is called *finite element analysis*.

In the past couple of decades, analyses of the individual components and the forces in them have evolved into the process called finite element analysis. For an elastic, static and dynamic analysis, building and industrial structures can be modeled using a combination of beam, brace, column and wall elements. The theoretical concept of finite element analysis is that it accurately allows the building designer to determine the forces acting upon the individual components of the structural system.

Due to the use and implementation of these fundamental principles and practices of finite element theory in modeling, particularly shear walls, the term “Finite Element-Based” analysis is used for describing analysis procedures used in structural design today. While this approach does not completely define all there is to know about structural engineering analysis, it helps to explain what the latest concepts are for analysis.

Another significant advance in structural theory and design is Load and Resistance Factor Design (LRFD) in structural steel and ultimate strength design in reinforced concrete. These methods of component design are the result of much research and experimentation. It is an improvement over the Allowable Stress Design in steel, and Working Stress Design of reinforced concrete of past periods.

Moisture Theory

Introduction

Water is always present in the air and in most building materials. The term *moisture*, as used herein, applies to all of its states as a liquid, gas or solid (ice). The behavior of water – e.g.

moisture – must be considered in all stages of building design, construction and management to prevent moisture-associated thermal and durability performance degradation (ASHRAE 1985, 21.2). Our understanding of moisture can essentially be classified in two broad categories: thermal properties, and mechanical properties.

Thermal Properties

The thermal conductance value is a measure of the effectiveness of thermal insulation's ability to retard heat flow. Heat transmission in most thermal insulations is by a complex combination of gas and solid conduction, radiation and convection. Heat transfer through building materials or systems is controlled by factors such as the length of heat flow paths, temperature, temperature difference characteristics of the system and environmental conditions (ASHRAE 1985, 20.2).

Although heat transmission characteristics are usually determined by measuring thermal conductivity, this property is not strictly applicable to thermal insulation as it may apply to other building materials. A particular sample of a material has a unique value of thermal conductivity for a particular set of conditions.

Mechanical Properties

The mechanical properties of building materials are important for a number of reasons, and this includes the effects of moisture in or around the materials. One or more of the following properties may be important: strength in compression, tension, shear, impact, flexure, and resistance to vibration. These temperature-dependent mechanical properties vary with basic composition, density, cell size, fiber diameter and orientation, type and amount of binder (if any) and temperature and environmental conditioning (ASHRAE 1985, 20.2).

Material Properties Related to Moisture

The presence of water as a gas, liquid or solid (ice) in a material reduces its insulating value; it can cause deterioration of the material and eventual structural damage by rot, corrosion or the expansive action of water absorption. Whether or not moisture accumulates in the material depends on the hygroscopic properties of the material, operating temperatures, ambient conditions and the effectiveness of water vapor retarders in relation to other vapor resistances within the composite structure (op cit. 20.2).

Properties that express the influence of moisture include the following: absorption (capillarity), adsorption (hygroscopicity), and water vapor transmission rate (diffusion). Fick's Law for water vapor diffusion through materials is:

$$w = -u\,(dp/dx)$$

Where, w = mass of vapor diffusing through a unit area in unit time
p = vapor pressure
x = distance along the flow path
u = permeability

and hence:

(dp/dx) = vapor pressure gradient

ASHRAE (1985, 21.3) notes that there is a close parallel with Fourier's equation for heat flow which includes factors for time during which the transmission occurred, in hours, and the difference of vapor pressure between ends of the flow path, in inches of mercury. The Fourier equation is somewhat different than Fick's Law, and will not be repeated here, but it can be shown to be an improvement on Fick's Law in terms of defining diffusion of moisture in materials.

Simple vapor flow theory assumes conditions of unidirectional, steady-state flow. Useful calculations can be made where the inflow or outflow of vapor is equal (where no condensation occurs) or unequal (where condensation occurs). In multi-dimensional analytical models of vapor flow, multiple flow directions are included in the analysis, along with time.

Future Research Directions

When one considers the development of thermodynamic theory and structural engineering theory, it is quickly apparent that many years of research and experimentation have been invested to get to the degree of sophistication they now have. Moisture studies, from a scientific and experimental perspective, have a far shorter history of development. By most standards, our understanding of moisture really began to develop in the late 1980's and early 1990's. Trechsel (2001, viii) notes that moisture studies of building envelopes should include, among other things, correct placement of vapor retarders as they may actually increase, rather than decrease the potential for moisture distress in building envelopes; that climate analysis alone is inadequate to understand the performance of building components, indoor relative humidity and the moisture-related properties of all envelope layers must also be considered; and, the two climate categories of "cold' and "warm" have never been adequately defined.

In the course of developing a comprehensive building moisture load theory, the Laws of Thermodynamics, specifically, could be studied to see what the corollaries are in building moisture load characteristics. Whether or not the Zeroth Law fits any aspect of moisture theory could also be studied.

The concept of finite element analysis and the correct procedures for its use could be applied to moisture analysis of building components. Given the realities of moisture dynamics in building components, however, it seems logical to also pursue studies at the whole building systems level, especially at the building envelope, much as the aeronautical engineers do for aircraft skins.

A recent literature review by the author found no comprehensive studies on the actual weight, or structural load, placed on buildings from moisture in materials. How this weight might change the dynamics of the structure during break-in, until the building reaches equilibrium with its environment, or in service, as the moisture content in materials changes, might affect the design of members, fasteners and other structural components needs to be studied. This could be especially true for structures built with light-weight, hygroscopic components subject to large variations in moisture content and therefore weight. Would there be a reduction in allowable stresses for components in moisture-risk locations? Would there be a reduction in allowable fastener reactions for components in moisture-risk locations? Would there be allowable increases for components when moisture management strategies are employed in the design of the house, especially when the whole house is considered?

It is proposed that research be conducted to determine the holistic interfaces between the thermal, mechanical and material characteristics of moisture in buildings. These studies should look at the interfaces among all three systems and could include development of computerized analytical programs capable of modeling or calculating the overall effects of moisture in the building, providing designers the ability to predict durability and energy performance of all building components and equipment three dimensionally. The orders of magnitude of the moisture load and comparisons to other house loads – thermodynamic and structural – might be very helpful in design analyses. Developing the procedures for studying all three load types at the same time and using the data from any one to inform the designer about the other two would be a challenging but potentially rewarding endeavor.

Hopefully, an increase in moisture research will lead to a more detailed, Comprehensive Building Moisture Load Theory. Again, it is hypothesized that development of such knowledge will lead to significant improvements in the durability of all of the components of housing.

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