

WHEN MATERIALS MATTER—Analyzing, Predicting, and Preventing Disasters

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Infrastructure and Architectural SuretySM

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ABSTRACT

The mission of the Architectural SuretySM program at Sandia National Laboratories is to assure the performance of buildings, facilities, and other infrastructure systems under normal, abnormal, and malevolent threat conditions. Through educational outreach efforts in the classroom, at conferences, and presentations such as this one, public and professional awareness of the need to defuse and mitigate such threats is increased. Buildings, airports, utilities, and other kinds of infrastructure deteriorate over time, as evidenced most dramatically by our crumbling cities and aging buildings, bridges, and other facility systems. Natural disasters such as tornadoes, earthquakes, hurricanes, and flooding also stress the materials and structural elements of our built environment. In addition, criminals, vandals, and terrorists attack our federal buildings, dams, bridges, tunnels, and other public and private facilities. Engineers and architects are beginning to systematically consider these threats during the design, construction, and retrofit phases of buildings and infrastructures and are recommending advanced research in new materials and techniques. Existing building codes and standards do not adequately address nor protect our infrastructure or the public from many of these emerging threats.

The activities in Sandia National Laboratories' Architectural SuretySM efforts take a risk management approach to enhancing the safety, security, and reliability of our constructed environment. The technologies and techniques developed during Sandia's 50 years as the nation's lead laboratory for nuclear weapons surety are now being applied to assessing and reducing the vulnerability of dams, to enhancing the safety and security of our staff in foreign embassies, and assuring the reliability of other federal facilities. High consequence surety engineering and design brings together technological advancements, new material requirements, systems integration, and risk management to improve the safety, security, and reliability of our as-built environment. The thrust of this paper is the role that new materials can play in protecting our infrastructure. Retrofits of existing buildings, innovative approaches to the design and construction of new facilities, and the mitigation of consequences in the event of an unpreventable disaster are some of the areas that new construction materials can benefit the Architectural SuretySM of our constructed environment.

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Infrastructure and Architectural SuretySM

Overview

Infrastructure and Architectural SuretySM is a risk-management process applied to enhance the performance of buildings and infrastructures. This short paper is intended to provide a brief introduction to Architectural SuretySM by familiarizing the reader with the background, the underlying concepts and terminology, the risk assessment model (Figure 1), and a sampling of applications of the process. The Architectural SuretySM program uses Sandia's risk management methodologies and technical capabilities to examine the vulnerabilities of public buildings and other structures and identifies changes in architectural design, building codes, or construction standards or materials that would improve their performance in natural disasters, terrorist attacks, or other potentially damaging environments. In this overview of Architectural SuretySM, particular attention is paid to the role of materials in this risk-based approach to the design of buildings and facilities.

Infrastructure and Architectural SuretySM Risk Assessment Model

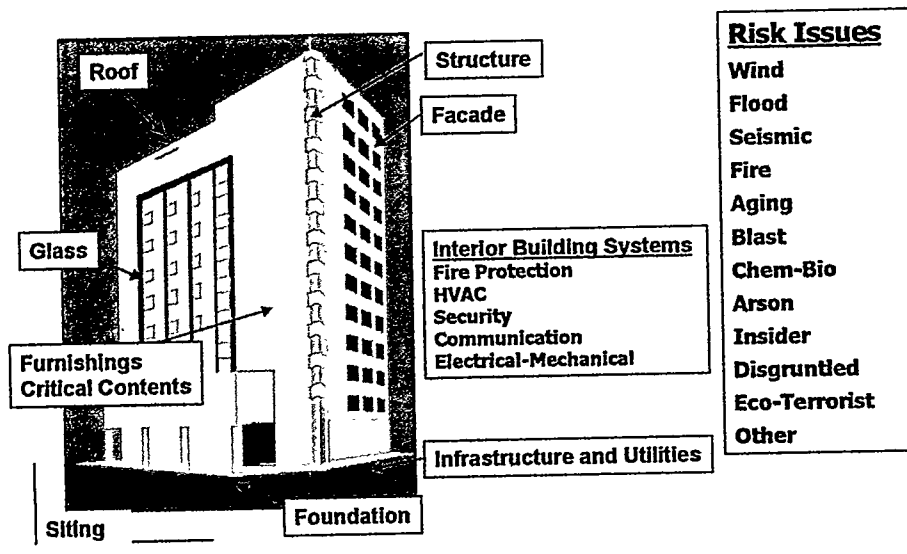


Figure 1. Infrastructure and Architectural SuretySM Risk Assessment Model

Definition / Vision

Sandia National Laboratories (Sandia) has been developing the science and engineering of system surety for nuclear weapons for several decades. Surety is a risk-based approach that provides the confidence a system will perform in acceptable ways in both expected and unexpected circumstances. In 1995 when Sandia began to apply the safety, security, and reliability principles of weapons surety to the nation's infrastructure, we service-marked the term Architectural SuretySM. This program, created to address multi-hazard mitigation, covers the full Research-Development-Application cycle, including an educational program. The objectives of the Architectural SuretySM program are to enhance the safety and security of the general public, ensure the reliability and quality of federal buildings and facilities in the national interests, and incorporate surety concepts in academic curricula for continued applications.

Emerging Threat Environments

The threats to our infrastructure can be identified in three categories, which are tied directly to surety: normal (reliability), abnormal (safety), and malevolent (security). A normal threat is an event or condition that affects the reliability of the day-to-day operations, e.g., mean time between failures or inefficient repair and replacement (maintenance) schedules to offset the effects of aging. An abnormal threat is a natural disaster, e.g., hurricane-force winds or earthquakes resulting in the failure of structural steel frames. A malevolent threat is manmade, e.g., a terrorist act such as bombing a federal facility (Figures 2 and 3). The use of chemical and biological agents in terrorist attacks is another developing malevolent threat. New materials are one prong of the Architectural SuretySM approach to mitigating these emerging threats.

Explosive Blast Attacks

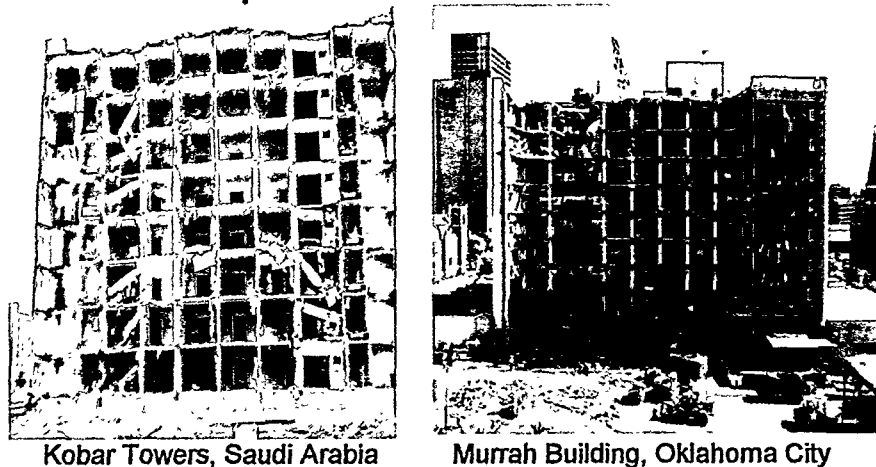
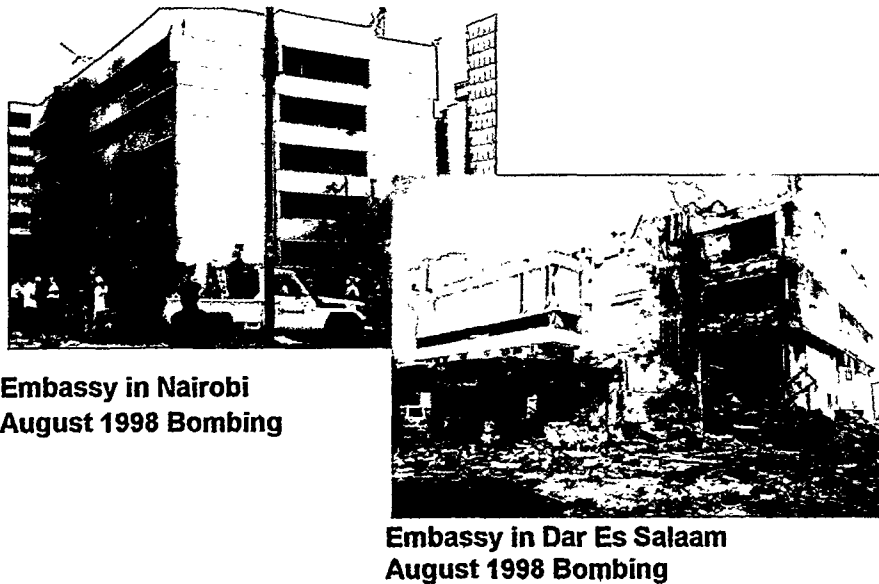


Figure 2. Terrorist Assaults at the Murrah Building and Khobar Towers

Explosive Attacks on Embassy Buildings



**Embassy in Nairobi
August 1998 Bombing**

**Embassy in Dar Es Salaam
August 1998 Bombing**

Figure 3. Terrorist Assaults on U.S. Embassies in Africa

Risk Management Process

Sandia's experience in risk management is extensive, including assessing the risks attached to our nuclear weapons, nuclear power plants, nuclear waste repositories, and chemical/biological attacks on public facilities. Hundreds of Sandia's employees are dedicated to analyzing the risks associated with various high-consequence facilities and systems. Consequences include the loss of life, the loss of property, or negative mission impacts. The Architectural SuretySM program has adapted this risk management program to address the threats faced by our critical infrastructure. New and adapted materials can be an important part of the solutions to these problems.

A risk assessment methodology provides a process to estimate risk and identify system vulnerabilities that are exploitable by defined threats. If this vulnerability assessment indicates the risk level is unacceptable (too high), this methodology provides a framework to address preventive or corrective countermeasures to reduce risk. This methodology enables the quantification of the improvement that would result from specific potential upgrades. For example, it is possible to measure the reduced risk (lives saved, injuries prevented, property protected, or operations uninterrupted) that results from constructing a façade using a blast-resistant rather than a conventional building material. The risk assessment methodology has been adapted to address the physical protection of hydroelectric dams. Work is currently in progress to apply the methodology to electrical power transmission systems. Sandia's risk assessment methodology could also be adapted to provide an integrated decision-support system and architecture to compare and select construction materials that are appropriate for protecting infrastructure systems.

As our ability to prevent or mitigate some of the emerging threats to our infrastructure and the constructed environment becomes clear, so, too, does our responsibility to protect the public, their property, and the continued functioning of our infrastructure. As technology enables us to understand and reliably predict the human and financial costs of disasters the question of culpability arises. Who is liable for the wildfire that raced through Los Alamos, NM, terrorist assaults like Oklahoma City or the embassy in Nairobi, and collapsing structures like the recent Philadelphia nightclub pier and the North Carolina walkway? Litigation issues can include breach of duty and professional liability. These considerations become another risk to be managed by improving the design, construction, and materials used for our infrastructure. We must ensure our as-built environment is safe, secure, and reliable.

Technology Applications

Modeling and simulation technology is one of the backbones of Sandia's work. The entire weapons program has evolved away from testing and relies instead on this expertise. Recently, Sandia coupled a blast code with a structural dynamics code and, through the use of our supercomputing facilities, modeled three-dimensional, multi-story facilities in a blast environment (Figures 4 and 5). This capability, validated against field-testing (Figure 6) is unique in the world. This ability to model the response of buildings and facilities to explosive assaults enables us to understand how to prevent or mitigate the effects of terrorist events by comparing design options. New blast-resistant materials for facades and structural members can be a significant part of this effort. Hardening conventional materials using wraps or cladding is another promising avenue for new materials research and development.

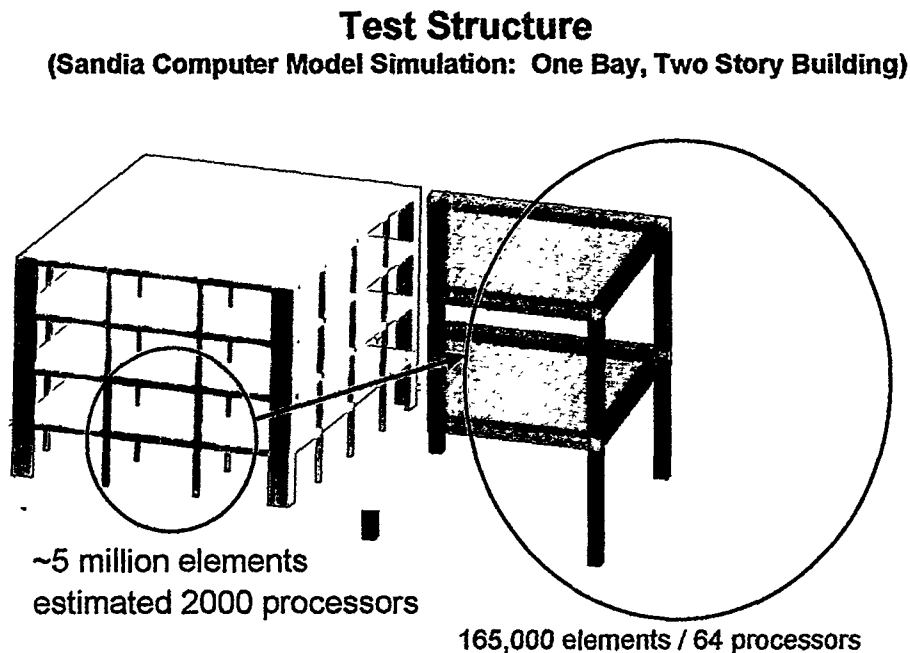


Figure 4. Computer Model of a One-Bay, Two-Story Building

Modeling of Reinforcing Steel

Reinforcing steel is added as beam elements and is embedded in the concrete by co-locating each beam node with a node in the FEM concrete mesh

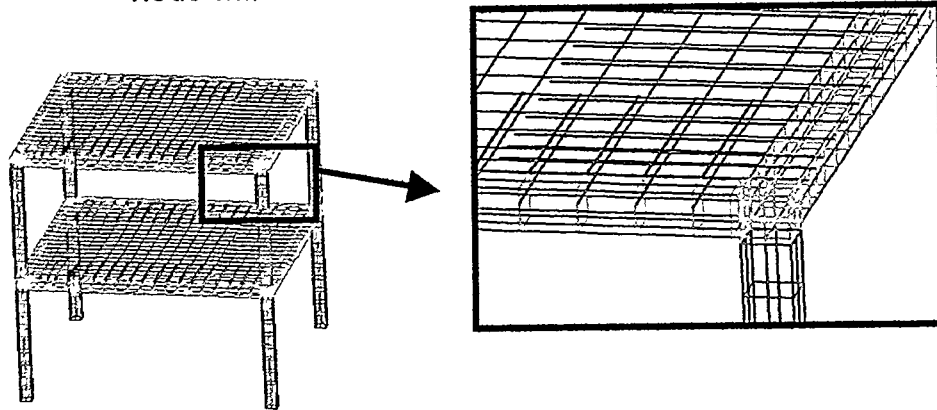
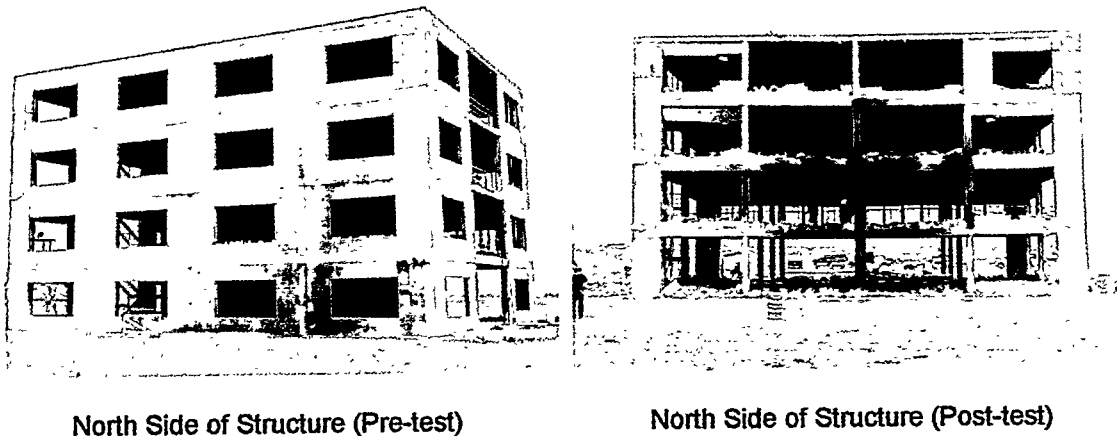


Figure 5. Structural Elements of Building Model

Field Blast Tests to Validate Model Structural Performance Evaluations



North Side of Structure (Pre-test)

North Side of Structure (Post-test)

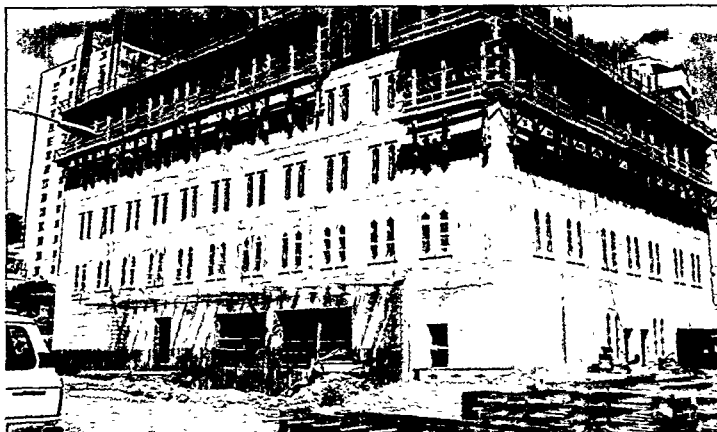
Figure 6. Field Testing to Validate Computer Model

Sandia also developed a chemical or biological agent dispersion model that includes a module to predict the location and number of casualties. Fire modeling codes have also been developed that predict the path and pattern of fires. Modeling the response of new, composite, and adapted materials can reduce the development time and often provides quicker and cheaper results than traditional laboratory and field-testing.

A hand-held chemical detection system, commonly called "chemlab on a chip," and other integrated microsensor systems are being developed at Sandia. The chemlab on a chip, formally called μ Chemlab™, is a Sandia initiative to build a portable chemistry laboratory the size of a palm-top computer. These sensors will be able to quickly detect chemical and biological agents. In addition, Sandia has created a foam that begins neutralizing both chemical and biological agents in minutes. Because it is not harmful to people, it can be dispensed on the disaster scene immediately, even before casualties are evacuated. Sandia has also developed other specialized instrumentation packages that can use state-of-the-art sensor technology, including microsensors and wireless remote monitoring, to measure and record structural responses to normal, abnormal, and malevolent threats. This data indicates avenues for materials research and development, among other benefits. Other methods of non-destructive testing have been developed in the Aging Aircraft program at Sandia.

Using vulnerability assessment and risk management methodologies in the design process enables surety to be built into construction projects. New construction materials, such as fire-proof and blast-resistant building materials, shatterproof and disintegrating glass, and claddings or composite wraps that enable structural members to better withstand seismic, blast, wind, or other loads associated, can significantly reduce the likelihood of loss from structural failure. Figures 7 through 9 show buildings that incorporated surety principles in the design process.

U.S. Embassies



La Paz, Bolivia (SA)
(Under Construction)



Georgetown, Guyana (SA)

Figure 7. New Design and Construction



Embassy in Ottawa

West Entrance

Figure 8. Surety Design of Embassies

**US Federal Courthouse
Albuquerque, NM**



Security Design Upgrades

Figure 9. Surety Design of Federal Courthouses

Material Challenges in Construction

The \$650-billion per year U. S. construction industry represents one-fifth of the world's annual volume. Although the industry is truly global in nature, it continues to be fragmented. Even domestically, no single government agency provides oversight. Building codes are not uniform between areas, and the diverse requirements of the various trade unions that represent construction workers further splinter the industry. The industry does not generate its own materials, relying instead on the petrochemical, chemical agricultural, defense and space, metals, ceramics/glass, and other industries to manufacture its raw materials. Thus the introduction of new materials for construction tends to be a byproduct of materials developed for other purposes. The sophisticated capabilities of materials researchers and developers have bypassed the construction industry. Identifying the needs of the industry and developing materials to meet those requirements is the challenge faced by today's materials scientists and engineers.

The driving forces behind the changes faced by the construction industry go beyond the emerging threats (terrorism, natural disasters, aging) discussed earlier. Technological advances in information technology (computer-assisted design, global positioning systems, networks) and nanotechnology (miniaturization, microelectromechanical systems and other micromachines) are changing the face of construction. Technological advancements in materials sciences, such as new materials (composites, fibers, flexible glass), genetics (molecular grown material), and bioengineering (both organic and inorganic material) can radically improve the ability of our infrastructure to withstand both the emerging threats and the new constraints faced by the as-built environment. These new constraints include energy conservation, security, environmental protection, and the need for structural assessments that detect failures before they occur.

Because the construction industry does not make its own materials, its needs are often underconsidered in materials science research and development. The capability to meet construction requirements exists. Materials science is so advanced that materials can be developed to match nearly any requirement. (Tradeoffs in cost or performance, for example, may render these materials unsatisfactory for construction use, but the science is mature, robust, and sophisticated. Constraints as well as requirements should be included in the problem description.) The materials needs of the construction industry can be determined and addressed, to the benefit of our nation.

An example of a construction industry need that could be addressed by materials science is engineered glass. Just as shatterproof glass, developed to prevent or reduce glass injury in automobile accidents, has become the automotive industry standard, an engineered glass could be designed to reduce glass injuries in buildings and facilities. Tempered glass (also known as safety glazing), while useful against human impact, does not perform so well in blast conditions. One of the concerns raised by terrorist bombings is the large number of casualties caused by flying glass.

In the Oklahoma City Federal Building bombing, many injuries were caused far from the site of the explosion by shards of glass projected at high velocity by the blast wave. A major issue in current efforts to mitigate the effects of terrorist activities and natural

disasters is how to reduce injuries from flying glass. Most of these efforts involve developing ways to control the failure of the glass in threat situations. Sandia scientists are studying prestressing glass using heat and ion exchange as approaches to engineering a blast-resistant glass. The goal is to develop a glass that will fail gracefully, reducing itself to sand particles under explosive impact. Other work to develop penetration-resistant glass for application against wind and debris impact involves laminating and heat-strengthening construction glass. This is a ripe area for materials research.

Summary

Infrastructure and Architectural SuretySM addresses national issues of safety, security, and reliability. The emerging threats of terrorism, natural disasters, and our aging infrastructure are addressed by the life-cycle risk management approach of Architectural SuretySM. Incorporating surety considerations into a life-cycle design process is the best way to achieve safety, security, and reliability in our infrastructure. New technologies applied to Architectural SuretySM include not only the surety methodologies of vulnerability assessment, but also modeling and simulation capabilities, risk management methods, structural dynamics and health monitoring, non-destructive evaluation, and materials research, development, and application. Smart materials and custom-designed materials are an important component of the surety design and construction toolkit.