Abstract

This paper provides a summary introduction to the emerging area of Architectural SuretySM applications for buildings and infrastructures that are subjected to dynamic loads from blast and naturally occurring events. This technology area has been under investigation to assist with the definition of risks associated with dynamic loads and to provide guidance for determining the required upgrading and retrofitting techniques suggested for reducing building and infrastructure vulnerabilities to such dynamic forces. This unique approach involves the application of risk management techniques for solving problems of the as-built environment through the application of security, safety, and reliability principles developed in the nuclear weapons programs of the United States Department of Energy (DOE) and through the protective structures programs of the German Ministry of Defense (MOD). The changing responsibilities of engineering design professionals are addressed in light of the increased public awareness of structural and facility systems' vulnerabilities to malevolent, normal, and abnormal environment conditions. Brief discussions are also presented on (1) the need to understand how dynamic pressures are affected by the structural failures they cause, (2) the need to determine cladding effects on columns, walls, and slabs, and (3) the need to establish effective standoff distance for perimeter barriers. A summary description is presented of selected technologies to upgrade and retrofit buildings by using high-strength concrete and energy-absorbing materials and by specifying appropriately designed window glazing and special masonry wall configurations and composites. The technologies, material performance, and design evaluation procedures presented include super-computational modeling and structural simulations, window glass fragmentation modeling, risk assessment procedures, instrumentation and health monitoring systems, three-dimensional CAD virtual reality visualization techniques, and material testing data.
The X and Y axis accelerometers were implemented using a comb structure in which the fingers of a compliant comb are interdigitated with fixed comb fingers to provide an output differential signal from the capacitive coupling between individual fingers. The Y–axis comb structure is about half the mass of the X–axis.

The Z axis accelerometer is implemented differently with a hinged plate as a proof mass. The proof mass forms a capacitor with the ground plane polysilicon structure of the device.

A fixed reference capacitor plate was designed into the Z axis channel to provide a differential output in conjunction with the moveable plate.

The accelerometer die is shown in Figure 1.

The initial fabrication yielded two devices suitable for further characterization in Sandia's inertial sensor test facility. The Y–axis on both test devices was not functional and only the X and Z axes were characterized. Only the results of the X-axis accelerometer are reported in this paper.

![Figure 1: Three Axis MEMS Accelerometer](image-url)

The electrical output of an accelerometer channel is a pulse train. The acceleration sensed by the device is contained in the pulse density of the output pulses. By design, an output or bias frequency is present even at zero input acceleration. The scale factor or density of output pulses per unit time per unit acceleration input is a function of the device clock frequency. Stability of the clock for the accelerometer directly affects accelerometer performance therefore maintaining good clock stability is essential for measuring accelerometer capability. This issue was addressed by clocking the accelerometer with a low &i& (Al 00 ppm from -10 to +70 °C) crystal oscillator.

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Introduction

Security, safety, and reliability principles of the United States Department of Energy (DOE) combine with data developed through the protective structures programs of the German Ministry of Defense (MOD) to further the developing field of Architectural Surety℠. The combined effort can be applied to select building materials and address structural design issues that improve the safety and performance of buildings subjected to dynamic loads from blast and naturally occurring events. Both programs are working toward defining the risks associated with dynamic loads and determining appropriate design and retrofit approaches for reducing building and infrastructure vulnerabilities to such dynamic threats as terrorist attacks and earthquakes. Sandia National Laboratories in the USA and the Ernst-Mach-Institut in the GDR are addressing the changing responsibilities of engineering design professionals. The design professions, the insurance industry, and the public are demanding safer buildings. This paper discusses managing the risks associated with structural responses to dynamics loading. Failures are unavoidable, but in the absence of risk management, failures can become disasters, as shown in Figure 1.

Figure 1: Alfred P. Murrah Federal Building, Oklahoma City, Oklahoma, After the April 19, 1995, Bombing
Requirements

Structural components of a building must be stiff enough to contribute positively to the evaluation of the ability of the building to withstand dynamic loading. The stability of the whole structure must be achieved. Progressive collapses and single-point failures must be avoided.

Incorporating surety concepts in design should be cost-effective. The aim is to minimize the costs and optimize the safety. (See Figure 2.) Just as the dynamic loads are not the same for all buildings, the costs of addressing the risks inherent in those loads are variable. Architectural Surety\textsuperscript{SM} provides tools for assessing, managing, and mitigating the risks associated with individual structures.

Approaches

New buildings with designs that incorporate a risk management approach and probabilistic risk assessment methods will reduce vulnerability by using a modular structure system (MSS) in special dynamic load threat situations, according to EMI research \cite{1}. This MSS is illustrated in Figure 3.

Figure 2: Optimized Risk-Costs

Figure 3: Modular Structure System (MSS)
Materials used in the MSS include:

- Foam concrete or plastic concrete as energy-absorbing material.
- Reinforced slurry-infiltrated fibre concrete (Sifcon) for structural elements with particular importance for structural stability.
- Bonded fibre tapes or fibre sheets (carbon, glass or aramid) in retrofits.
- Additional exterior layer as ballistic protection.

The required materials and construction types for each structure are dependent upon the anticipated dynamic loading situation, as well as the acceptable damage modes and levels. For normal loads, such as wind, conventional construction methods can be used. In this case, reliability would be defined as no cracks and the design would consider the elastic part of material behavior. For abnormal loading, such as a tornado, the structural elements should be hardened. For examples, masonry should be reinforced and windows should use laminated glasses. The structural safety of the building is required, but cracks are acceptable and the design should consider the plastic behavior part of a material behavior. If blast loading is expected or possible due to terrorist or other malevolent attacks, the structure requires high-strength concrete, additional energy-absorbing material, and retrofit elements. Preliminary experiments in glass fragmentation indicate glass may respond differently in blast-loading events than in other dynamic events [2]. In such an extreme situation, damage must be accepted. If the structure was not destroyed, the threat was successfully mitigated.

The importance of reinforcing masonry is shown in Figure 4. The plastic response of the steel-reinforced masonry results in ductile behavior. The unreinforced brickwork subjected to a sudden dynamic stress responds with brittle or fracturing behavior.

Figure 4a: Brickwork With Reinforcement — Ductile Behavior

Figure 4b: Brickwork Without Reinforcement — Brittle Behavior
The effects of implementing fibre tapes are similar to the effects of reinforcing masonry, as shown in Figure 5 for reinforced concrete beams. Compared to reinforced concrete (RC), beam strengthening using additional glass fibre or carbon fibre increases the maximum load to a factor of nearly 1.5. Using fibre composite (carbon + aramid) provides a factor greater than 2. Both values are valid for static loading.

Figure 5: Fibre Retrofits
In dynamic loading, the applied load can be greater than 4 times the initial load. A marked improvement in structural response can be seen in buildings retrofitted with composite fibres. Such retrofitting results in superior ductile properties and high working capacity.

Other essential structural elements are doors and windows. Strengthening glass with a film or using laminated glass is suitable for most extreme dynamic loadings. Preliminary work in glass fragmentation by Sandia National Laboratories seems to indicate a different response under blast conditions. Understanding the fracturing behavior of treated and untreated glasses subjected to blast loading is the first step toward controlling that behavior. Some examples of treated glass response to dynamic loading are given in Figure 6.

A. Laminated glass without fragmentation

B. Analysis of safety doors

C. Fracture origin (indentation flaw) in blast-loaded annealed glass (Arrows indicate limits of mirror region at tensile surface.)

Figure 6: Window, door, annealed glass pane
Figure 7 shows the use of reinforced Sifcon to create a plastic hinge for a building subject to dynamic loading from earthquakes.

![Reinforced Sifcon as beam hinge](image)

An important consideration in architectural applications is the mechanical response of the structure. To determine this, the mechanical response of each of the constituent structural materials must be modeled to quantitatively describe elastic deflection, plastic deformation, and fracture. The mechanical response must be understood for dynamic events such as storm, earthquake, and blast loading. Thus the materials model must also accurately predict not only the response to high-rate loading, but also how this response might change with age. Structural materials degradations (i.e., aging) may be driven most notably by corrosion (including galvanic, localized, atmospheric, and stress corrosion cracking) and fatigue/corrosion fatigue (driven by such forces as wind loading, diurnal temperature fluctuations, and use stresses). It is challenging indeed to assemble the accurate (static/dynamic/aging) response models for all of the structural materials in a complex design [3].

**Future Work**

Preliminary experimental results for responses to dynamic loading and other behavior of many structural components, such as masonry walls, fibre concrete, reinforced Sifcon, glazing systems, and retrofit or safety doors, are available through the EMI. Further experimentation is required to fully characterize material and structural responses in dynamic loading situations. Early experimental indications are that dynamic loadings are varied, with seismic and blast loadings presenting different structural and material stresses than wind or tornado loadings.

The blowback effect may be just one of the ways that dynamic pressures interact with structures. Further data on the effects of structural response on dynamic loads are indicated. Similarly, the effects of mitigation efforts, such as cladding of columns, walls, and slabs, on structural response are not clearly defined. Further research on structural response to different blast loadings at various distances would also be useful for determining effective standoff distances for structures at risk for explosive threats.
Super-computational modeling and structural simulations, window glass fragmentation modeling, risk assessment procedures, instrumentation and health monitoring systems, three-dimensional CAD virtual reality visualization techniques, and material testing data are some of the science-based knowledge development technologies employed by Sandia National Laboratories to further the goals of the Architectural SuretySM program. Through the protective structures program, the EMI tests the effectiveness of structural components, such as engineered construction materials, systems, and methods. Test results are collected in their database. The international collaboration between these laboratories advances their mutual interest in improving the quality of the as-built environment.

Future work will further characterize the response of particular materials used in different structural components under specific dynamic loadings, expand the experimental database, and implement the results in a PC-based design procedure that determines the local and global structural response of a construction to dynamic loads.

References

1. EMI to provide reference for MSS.
