Critical Issues in Achieving a Resilient Transportation Infrastructure

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Nature of Multi-Hazard Damage and Focus on Infrastructure Resiliency

As seen in Figure 1, a major terrorist attack, natural hazard, or accident causes four general types of damage: Human Casualties, Environmental Damage, Psychological Damage, and Infrastructure Damage. All of these also ultimately result in financial losses both directly and indirectly due to the socio economic impact of the short-term or long-term loss of use of critical infrastructure. Although a transportation agency’s main focus may ultimately be to safeguard their assets or infrastructure, in the big picture, the appropriate level of priority must be given to the other three types of damage. A terrorist attack, natural hazard, or accident may have many similarities in their effect and their possible mitigations. In fact it is the objective of terrorists to maximize the four categories of damage, if possible.

Human casualties can result directly from a hazard, and can be increased by structural collapse, the breakout of fire, the release of hazardous effluents, delays in the ability of people to evacuate, or delays in the arrival of first responders to an incident. Human casualties may also result from a lack of preparedness and the inability of the incident commander to understand the danger of further collapse and instability of the situation in general, which also puts the first responders themselves in peril. The preferred way of mitigating human casualties is to prevent the hazard from endangering people in the first place. In the case of terrorism, this is in the hands of the Department of Homeland Security and state and local law enforcement. In the case of natural hazards it can be achieved by early warning to evacuate and disaster planning. In the case of accidents the likelihood of occurrence can be reduced by improved safety practices. However, once a potential hazard occurs, it is the responsibility of the owner to provide protection, facilitate response, and plan for disaster recovery. This can be categorized as all-hazards or multi-hazard preparedness.

To protect users and employees from a potential terror attack the options available are physical barriers to prevent access, screening of users, intrusion detection and response. Each of these means of human protection against violent attack are an extreme challenge to facility owners because they are counter to the purposes and goals of public transportation systems which should be easy to access, should handle large volumes, and should move people and goods quickly and efficiently without delay. Protection of users by transportation facility owners is, therefore, difficult, challenging and requires interdiction by law enforcement to be effective. Transportation facility owners can be more effective in saving human lives by planning for and facilitating rescue and response to reduce potential human casualties. Ways of doing this are preparedness planning, coordination, practice exercises with first responders, and by providing redundant and/or hardened life safety systems for incident management and evacuation.
Traditional Versus Broader Focus of Engineers

Traditionally engineers have designed structures for loadings defined by engineering practice and by the codes. This has gradually evolved. In the beginning, the practice was to limit stresses under live, dead, earth pressure and wind load combinations to an allowable stress level that completely prevented any damage to a structure. This is shown in Figure 1 under the infrastructure damage category as “protect”. As design practices evolved to load factor design and then to load and resistance factor design, and seismic loading was considered, engineers began to take more account of the probability of occurrence of each loading combination and designed to allow some residual damage and excessive deformation of structures provided that there was no instability or collapse so evacuation could safely take place to limit human casualties. This is shown in Figure 1 under the infrastructure damage category as “respond”.

Extreme Events - Anticipating the Unexpected

While codes and standards exist for more conventional emergency incidents on transportation structures such as those of the NFPA for fire, there currently are no codes or standards for terror attacks or other events and loadings which we shall categorize as extreme events or extreme loadings since both the engineering/architectural practice and transportation code officials have not yet found them to be of high enough likelihood to warrant such provisions. As far as terror attack is concerned, various organizations such as the FTA, AASHTO and the ASCE have begun to develop and publish guidelines to plan and design transportation structures and facilities to address security issues.

In this paper we will make a case that designing structures for resiliency shall address all four categories of damage from all hazards. Once the hazard occurs the correct response to the first three categories of damage would be to “respond” as shown in Figure 1. In the case of infrastructure damage the most efficient and cost effective strategy is to design to “recover”. This is intended to mean that measures should be taken, pre-event and post-event, to make the recovery period of the critical infrastructure as short as possible.

Focusing Limited Resources

The primary objectives of multi-hazard mitigation through resiliency are:

- Focus resources ($, people, equipment, and time) on mitigating the number of casualties
- Focus resources ($, people, equipment, and time) on shortening the recovery period (Resiliency)

One way of focusing resources on mitigating the number of casualties can be achieved by limiting propagation of collapse beyond the point of attack/hazard. Another way is to focus on facilitating evacuation, rescue and incidence management. This involves hardening of egress routes, providing incident feedback and protocols for first responders, hardening life safety systems (alarms, lighting, communications), and improving egress way-finding (signage, fluorescent path markings for self evacuation.)

Pre-disaster implementation of mitigations to limit propagation of collapse includes:
- Harden, shield, armor, and/or insulate critical elements to prevent catastrophic failure
- Provide redundancy to prevent local failure from progressing
- Provide redundancy to maintain function of the system at reduced level

Post- disaster implementation of mitigations to limit propagation of collapse includes:
- Make provisions to isolate or limit damage in the response mode
- Prepare disaster recovery plans and procedures and arrange for resources to carry them out in an emergency recovery mode
Structural Assessment (Pre and Post Disaster)

In order for engineers to fulfill their broader role to achieve resiliency for critical transportation infrastructure in a multi-hazard event domain there is a need for additional academic research, modeling and testing of complex structures such as bridges under extreme loads. This also requires a much better understanding of how complex structures collapse once key elements are damaged. While progressive collapse has been studied for buildings, there needs to be more investigation of progressive collapse in bridges to develop mitigation strategies. The truck bombing of bridges in Iraq and the study of the explosive demolition of bridges indicates that due to dynamic member loss effects, the sudden loss of one span can propagate across an entire multi-span structure even if the structure is discontinuous (see Figure 2). This is due to lateral pier displacement under dynamic failure of an adjacent span.

It is also recommended that design standards be re-evaluated for structures such as bridges. Currently the AASHTO LRFD specifications for bridges include design criteria for some extreme loadings such as **seismic events**, **vessel collision**, **dynamic wind effects** on long span bridges, but not others such as **hydrocarbon fire**, **terror attacks**, **vehicular impact** (over height trucks and trailers), and **flooding**. Hydrocarbon fires from fuel tanker trucks have destroyed a number of bridges on interstate highways over the years (see Figure 3), and most state DOTs report problems with damage to overpasses from oversize vehicles and payloads reported to have impacted structures with vertical roadway clearances of up to 17 feet. Major bridges with single points of vulnerability to terror attacks must be identified and protected through blast and fragmentation hardening technologies. A large number of bridges that failed from the effects of hurricane Katrina actually floated off their supporting piers due to a lack of venting of trapped air pockets, and the absence of hold down anchors (see Figure 4).

It is important to understand the behavior of structures under extreme multi-hazard loads, especially hydrocarbon fires and explosive devices both to improve life safety features for evacuation (safe evacuation paths, signage, and moveable traffic barriers), to inform first responders of the potential dangers of collapse including “time to failure”, and to extend response time to facilitate rescue where...
possible (supplement standpipe systems with foam capability, use of passive fireproofing). This also requires more extensive study and research.

**Place for Engineers at the Tabletop Exercise**

To make infrastructure resiliency for multi-hazards work there must be a place reserved for the engineer at the tabletop exercises for disaster planning. Preparedness planning should include pre-computed time elapse collapse scenarios from multi-hazards and simulated response and rescue exercises utilizing life safety features. There are a number of cases where disaster planning can include rapid recovery by erecting temporary prefabricated bridge component systems (see Figure 5) in conjunction with emergency traffic re-routing plans. The use of innovative technology solutions for situational awareness and the monitoring of structural behavior during extreme events can be achieved with infrared cameras, thermocouples, chemical sensors, weather monitors, and other instrumentation. This can be programmed along with conventional CCTV systems to give valuable real time feedback to the incident commanders.

**Advantages and Challenges**

The advantages of the **Resilient Infrastructure Approach to Multi-Hazard (Extreme) Events** are:
- Priority on life safety and emergency response issues through pre-event preparedness
- Reducing the socio-economic impact of the loss of critical infrastructure (major C.E. structure) from an extreme event which is more significant than the cost and inconvenience of repair
- Post event, the precise location and extent of damage to a system is known and resources can be effectively and quickly focused only on the location that requires repair
- Overall investment of resources is the most efficient and cost effective (may be more soft costs pre-event and hard costs post-event.)

The challenges for the engineering community are:
- Find cost effective measures to facilitate evacuation, response and rescue, without unknown dangers to first responders.
- Find cost effective measures to restore service (even if interim), and shorten the overall recovery period through means and methods of rapid reconstruction.
- Focus on multi-discipline improvements to life safety systems
- Improve tools for prediction of damage and isolation of damage
- Develop innovative technology solutions for situational awareness and the monitoring of structural behavior during extreme events (infrared cameras, thermocouples, chemical sensors, weather monitors, and other instrumentation).

Most important to reaching the objective of multi-hazard engineering and achieving transportation infrastructure resiliency in disasters is the acceptance of the new and broader role for engineers and a new philosophy for the engineering of transportation facilities and systems. This must be accepted and embraced by transportation code officials and both the academic and practicing engineering community. It aligns well with the current national approach for homeland security which can be a source of DHS funding for preparedness related research and planning, and for implementing technology solutions.