Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1287

# On Multi-Hazard Considerations in Design of Structures

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## ABSTRACT

Civil infrastructure is vital to economic development and critical to response and recovery after extreme events. However, they are also quite vulnerable to natural and man-made hazards such as earthquakes, storm surge, fire and terrorist threats; especially highway bridges. Therefore, there is a need to move toward multi-hazard design methods of structures. A multi-hazard approach to design of structures will require emphasis on vertical strength and stability to ensure collapse prevention. Consequently, structural elements' response in the vertical direction and their connection details will require special consideration. Collapse of an intermediate support (due to fire or terrorist acts), buoyancy pressures from an storm surge (such as hurricanes and typhoons) or vertical motion of earthquake ground motion all exert demands on structural components (such as building transfer girders or bridge deck superstructure), bearings, and load transfer mechanism to the foundation that are not considered within the existing design guidelines. The commonality among various hazards and critical parameters are highlighted through specific research and design recommendations.

## INTRODUCTION

Many engineered structures must be designed to account for the risk of being subjected to one of multiple types of natural or man-made hazards over their service lives. The traditional method of designing for extreme hazards is to follow prescriptive codes, which stipulate a set of fixed values and methods based on the structure's classification, intended to provide a reasonable standard of life safety (FEMA 2004). However, prescriptive codes often "tie the hands" of design engineers: some code requirements may seem arbitrary or unreasonable, or specifications to meet the requirements for one hazard may conflict negatively with the requirements to safeguard against another (FEMA 2007). Additionally, due to the classification-based nature of the codes, they do not ensure specific structures will respond predictably to a given hazard (Freeman 2004).

These limitations have led to the need for and development of *performance-based* design criteria, which are based on the idea of "acceptable risks", the extent and types of damage that the structure's owner and its occupants can tolerate for given types and recurrence rates of hazard events, beyond the single level of safety provided by prescriptive codes. For example, an owner of an office building may require that her building survive a relatively frequent hazard event with minimal damage that does not affect its occupancy or function (a "mild impact"), but may accept nonstructural damage requiring a brief delay of re-occupancy for repairs (a "moderate impact") for a rarer one (International Code Council 2009).

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Government agencies, universities and code authors provide a variety of detailed resources regarding the historical magnitude and incidence rate of various hazards, both natural and man-made. Design engineers can use these resources to determine the significance and probability of each hazard to a structural design. Two example maps – a contour map of the peak ground acceleration with a 10% probability of exceedance in 50 years (Figure 1) and a map detailing the incidence of Presidential Disaster Declarations for floods from 1965 to 2000 (Figure 2) – are presented below.

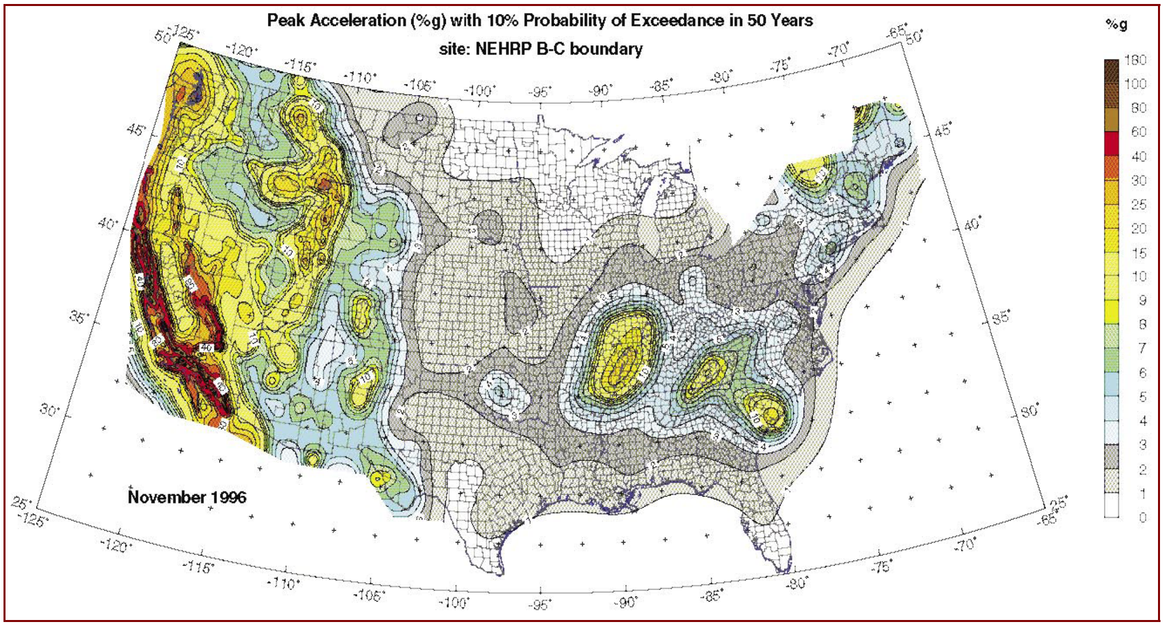


Figure 1 Peak ground acceleration,10% prob. of exceedance in 50 years (FEMA 2004)

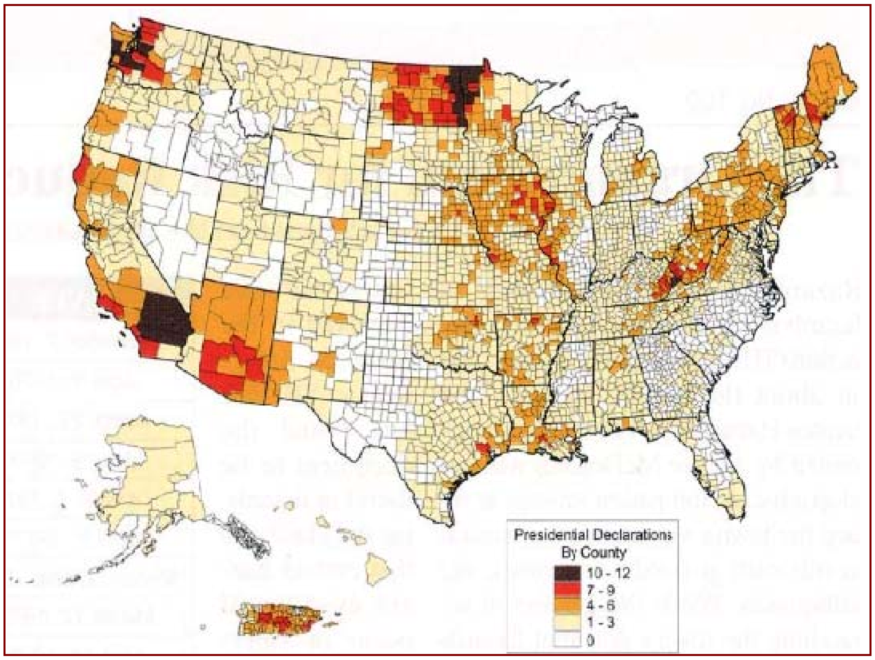


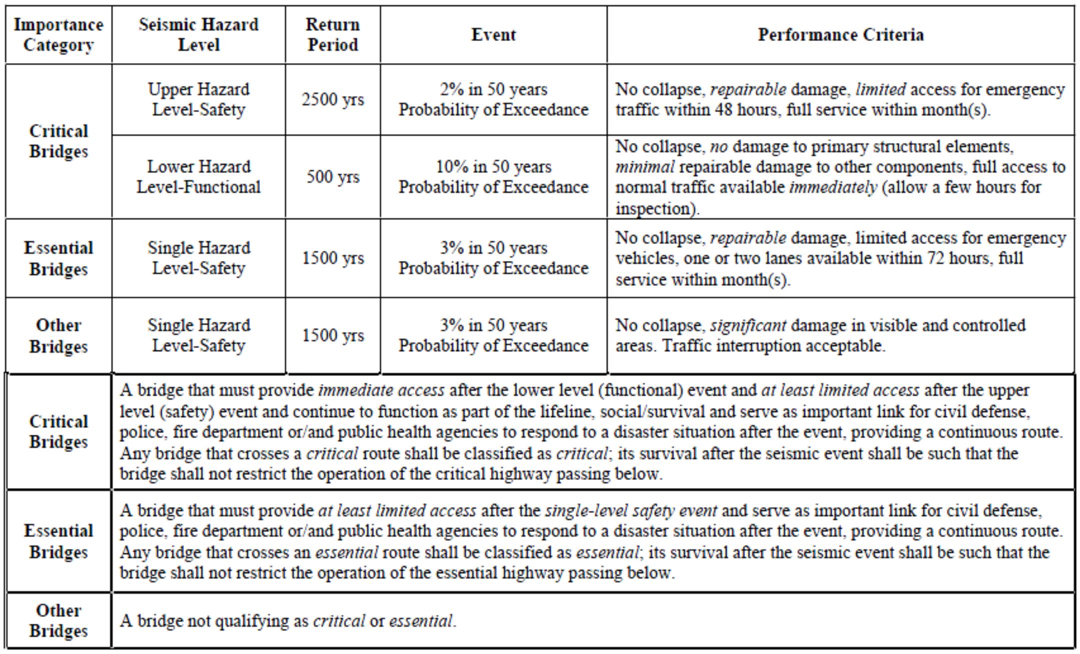
Figure 2 Flood disaster declarations per county, 1965-2000 (FEMA 2004)

Thus, the challenge, for engineers designing structures possibly subject to multiple hazards within their service lives, is to develop a robust scheme to translate qualitative statements of acceptable risk into quantitative response criteria for each type and recurrence rate of the pertinent hazards. The ideal case would be to formulate a response criterion that enables the straightforward comparison of the structural effects of dissimilar hazards to determine the critical hazard case at each level of acceptable risk, creating a simplified, unified framework for expediting a multi-hazard design.

## PRIOR DAMAGE AND RESPONSE CHARACTERISTICS

### Earthquakes

As prescriptive seismic design codes have developed since the first recommendations of the Structural Engineers Association of California to the Uniform Building Code (UBC) in the 1960's, each update to the provisions has generally brought an increase in design forces and additional specific prescriptions on design. However, Freeman's study (2004) of buildings subjected to the unusually high ground motions of the 1994 Northridge, CA earthquake finds that attentively-designed, well-constructed buildings meeting their contemporary seismic code requirements survived the substantially more intense ground motions of the Northridge event. Freeman states that "that structures that have the capacity to behave in a ductile fashion can survive the demands of the Van Nuys [station record] ground motion, even those designed prior to 1976", the date of the first major revisions to the seismic provisions of the UBC, and concludes that "increasing forces prescribing strict limits can not substitute for good design practices".



| Importance Category | Seismic Hazard Level | Return Period | Event | Performance Criteria |
|---|---|---|---|---|
| Critical Bridges | Upper Hazard Level-Safety | 2500 yrs | 2% in 50 years Probability of Exceedance | No collapse, *repairable* damage, *limited* access for emergency traffic within 48 hours, full service within month(s). |
| | Lower Hazard Level-Functional | 500 yrs | 10% in 50 years Probability of Exceedance | No collapse, *no* damage to primary structural elements, *minimal* repairable damage to other components, full access to normal traffic available *immediately* (allow a few hours for inspection). |
| Essential Bridges | Single Hazard Level-Safety | 1500 yrs | 3% in 50 years Probability of Exceedance | No collapse, *repairable* damage, limited access for emergency vehicles, one or two lanes available within 72 hours, full service within month(s). |
| Other Bridges | Single Hazard Level-Safety | 1500 yrs | 3% in 50 years Probability of Exceedance | No collapse, *significant* damage in visible and controlled areas. Traffic interruption acceptable. |

| | |
|---|---|
| Critical Bridges | A bridge that must provide *immediate access* after the lower level (functional) event and *at least limited access* after the upper level (safety) event and continue to function as part of the lifeline, social/survival and serve as important link for civil defense, police, fire department or/and public health agencies to respond to a disaster situation after the event, providing a continuous route. Any bridge that crosses a *critical* route shall be classified as *critical*; its survival after the seismic event shall be such that the bridge shall not restrict the operation of the critical highway passing below. |
| Essential Bridges | A bridge that must provide *at least limited access* after the *single-level safety event* and serve as important link for civil defense, police, fire department or/and public health agencies to respond to a disaster situation after the event, providing a continuous route. Any bridge that crosses an *essential* route shall be classified as *essential*; its survival after the seismic event shall be such that the bridge shall not restrict the operation of the essential highway passing below. |
| Other Bridges | A bridge not qualifying as *critical* or *essential*. |

Figure 3 New York City DOT performance-based criteria and classifications

In response to these perceived disadvantages of prescriptive seismic design codes, performance-based seismic design criteria have been developed by the U.S. Federal Emergency Management Agency (FEMA 2006), the International Code Council (ICC 2009), and state departments like the New York City Department of Transportation (Figure 3). These codes, though they are robust and reward careful engineering design, still have some shortcomings, one of which is the fact that performance-based seismic design, like the prescriptive codes which preceded it, still focuses on lateral force methods. However, performance criteria for severe impacts require the preservation of vertical stability to protect life safety, which lateral stability may not necessarily ensure.

The effect of vertical ground acceleration on the seismic response of structures is relatively poorly understood. Vertical ground acceleration is relatively smaller compared to horizontal acceleration at locations distant from the originating fault – the rule of thumb is that the V/H ratio of vertical acceleration to horizontal is approximately ⅔, but this varies widely, as shown by Kim and Elnashai (2008) – but is a predominant component of ground motion for locations near the epicenter, especially for thrust events; in the case of the Northridge 1994 event, the earthquake combined the two as a near-fault blind-thrust event, resulting in major vertical ground accelerations.

It is difficult to consistently attribute which structural failures came about as the result of vertical acceleration as opposed to that caused by horizontal drift, but many recent earthquakes have provided evidence that vertical ground motion may cause critical structural damage. For example, due to the Northridge 1994 seismic event, the Collector-Distributor 36 bridge of the Santa Monica Freeway demonstrated significant effects of vertical motion on its support piers: the piers "experienced spectacular failure", the most critically damaged pier's lower half spalling and completely disintegrating internally most likely due to the "instantaneous reduction of shear strength caused by vertical motion and the resulting fluctuation of the pier axial load" (Papazoglou and Elnashai 1996). Additional structural failures caused by other recent earthquakes, such as the Loma Prieta (1989), Northridge (1994), Hyogo-ken Nanbu (1995) and Yogyakarta (2006) earthquakes, have provided additional evidence of the importance of vertical ground acceleration (Kim and Elnashai 2008).

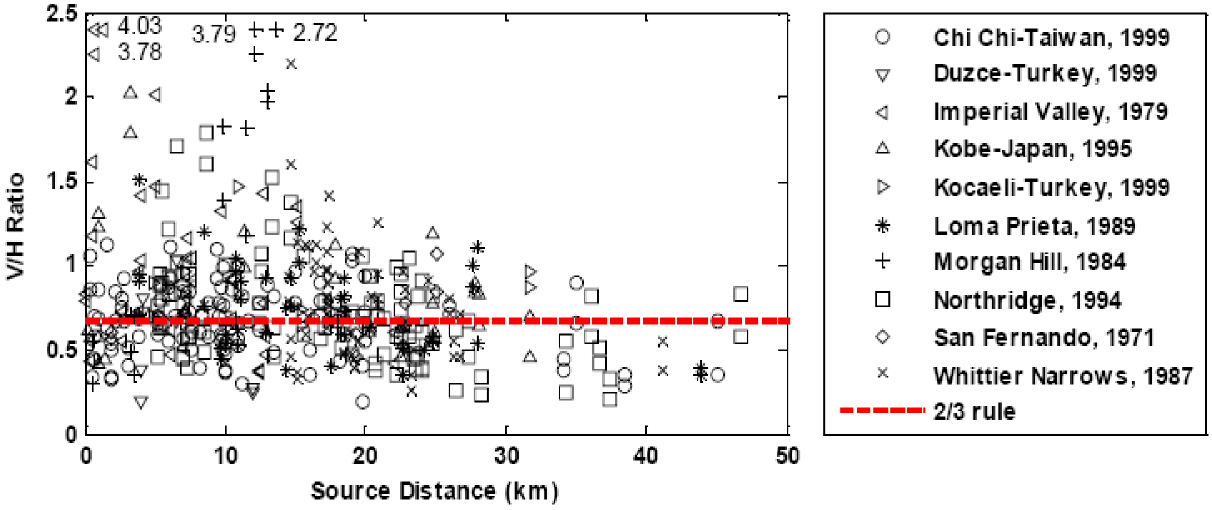


Figure 4 Acceleration ratio vs. source distance (Kim and Elnashai 2008)

## Blasts

While some explosive events are accidental (the ignition of the gas leak that caused the Ronan Point collapse, for example), the typical blast event a structural designer wishes to safeguard against is the intentional, malicious detonation of an explosive device. The most dangerous explosive events involve the use of car- or truck-borne explosives, which enable the relatively inconspicuous delivery of large amounts of explosive material directly to the target. The effects of the compressed air blast wave released by the explosion are summarized in Figure 5; the duration of the blast event is usually on the scale of milliseconds, as compared to the usual duration of some minutes for seismic events. Note that a blast event affects vertical stability as well as lateral stability of a structure, both through the damage or removal of columns and the direct imposition of distributed loads on floor elements.

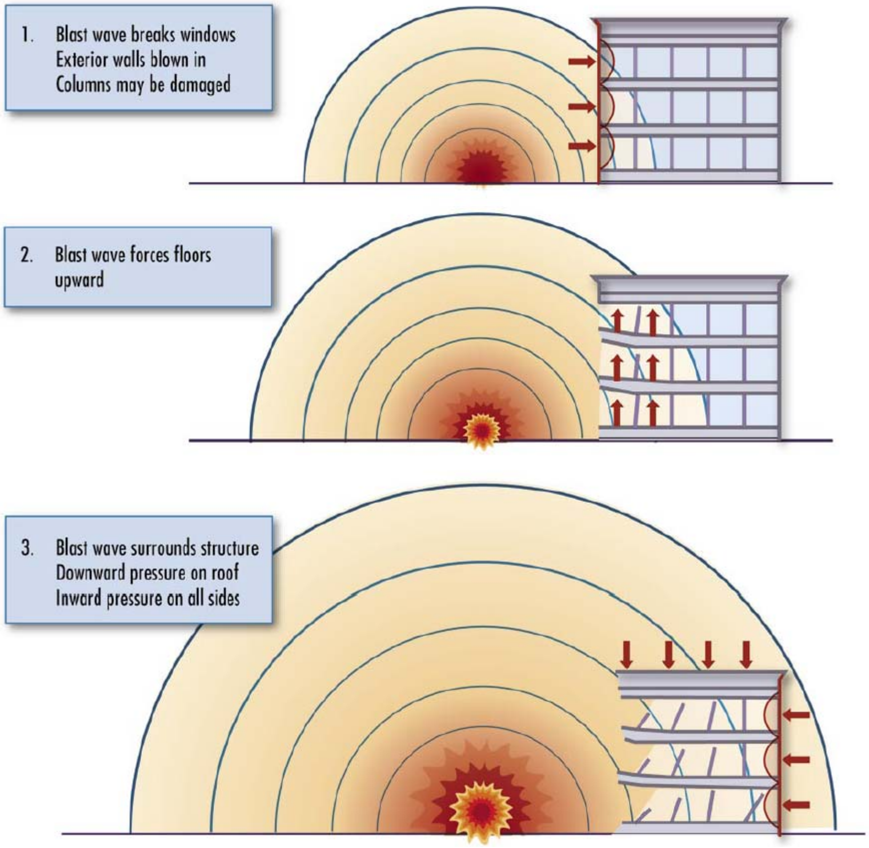


Figure 5 Blast pressure effects on a structure (FEMA 2003)

Blast mitigation design often conflicts directly with seismic design: generally, heavy structures resist blast loads well, since the transient event will have passed before the mass of the structure can respond to the excitation, while light structures are preferable for seismic design to reduce the lateral inertial loads generated by the structure's acceleration, so a multi-hazard design that accounts for both risks requires cautious use of engineering judgment and prior experience. As an example of a method to balance these dissimilar requirements, a probabilistic simulation system to determine the annual risk of collapse for structural designs where both seismic response and blast response are critical has been proposed by Asprone, et al. (2010).

## Storm surges

The storm surges created by Hurricane Katrina, the 2005 storm that devastated the coastal regions of Louisiana, Mississippi, and Alabama, caused the majority of damage to infrastructure and engineered structures along the coast during the hurricane. The damage sustained by this storm provided numerous lessons to aid in the design of structures subject to possible storm surges and tsunamis (Douglass et al. 2006; Robertson et al. 2007).

The authors of both studies attribute the majority of damage to bridge structures, floor systems and precast concrete framing systems to *hydrodynamic* and *hydrostatic uplift*; namely, the uplift forces generated by wave action and buoyancy, respectively.

Structures above the average storm surge height but below the maximum storm surge wave height were predominantly damaged by the upwards hydrodynamic impact forces greater than the dead load of the superstructure, generated by storm surge waves crashing into the underside of the structure. Since the Gulf of Mexico is a low-seismicity region, bridges tended to lack vertical-displacement-preventing ties or horizontal-drift-preventing shear keys that are commonly provided in high-seismicity regions (Robertson et al. 2007), so wave action could easily lift the nearly buoyant bridge decks from their supports with minimal resistance from the structural system, and flip them off the piles (Douglass et al. 2006).

For structures that were completely submerged by the storm surge, submersion in seawater reduces the effective unit weight of reinforced concrete from around 150 lb/ft$^3$ to about 86 lb/ft$^3$, and for traditional girder bridges and double-T precast sections, air trapped in the void underneath the deck and between the girders/web further reduces its effective self-weight (see Figure 6 for example calculations). Post-tensioned slab floor systems were especially susceptible to shear failure due to upwards hydrodynamic forces, even those with properly restrained end conditions (Robertson et al. 2007).

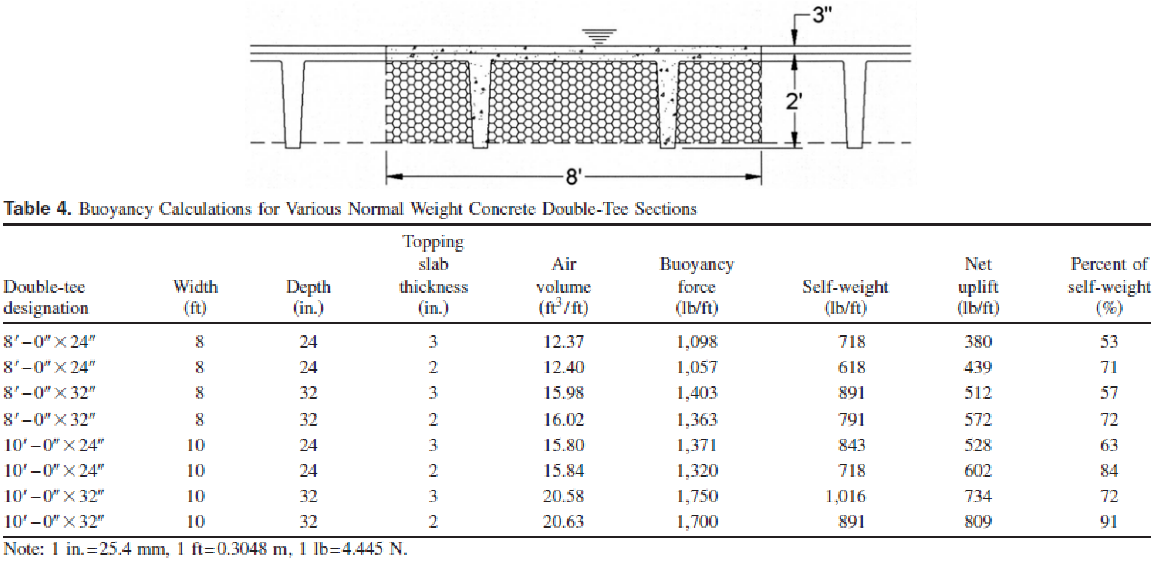


**Table 4.** Buoyancy Calculations for Various Normal Weight Concrete Double-Tee Sections

| Double-tee designation | Width (ft) | Depth (in.) | Topping slab thickness (in.) | Air volume (ft$^3$/ft) | Buoyancy force (lb/ft) | Self-weight (lb/ft) | Net uplift (lb/ft) | Percent of self-weight (%) |
|---|---|---|---|---|---|---|---|---|
| 8′−0″×24″ | 8 | 24 | 3 | 12.37 | 1,098 | 718 | 380 | 53 |
| 8′−0″×24″ | 8 | 24 | 2 | 12.40 | 1,057 | 618 | 439 | 71 |
| 8′−0″×32″ | 8 | 32 | 3 | 15.98 | 1,403 | 891 | 512 | 57 |
| 8′−0″×32″ | 8 | 32 | 2 | 16.02 | 1,363 | 791 | 572 | 72 |
| 10′−0″×24″ | 10 | 24 | 3 | 15.80 | 1,371 | 843 | 528 | 63 |
| 10′−0″×24″ | 10 | 24 | 2 | 15.84 | 1,320 | 718 | 602 | 84 |
| 10′−0″×32″ | 10 | 32 | 3 | 20.58 | 1,750 | 1,016 | 734 | 72 |
| 10′−0″×32″ | 10 | 32 | 2 | 20.63 | 1,700 | 891 | 809 | 91 |

Note: 1 in.=25.4 mm, 1 ft=0.3048 m, 1 lb=4.445 N.

Figure 6 Buoyancy calculations for various precast sections (Robertson et al. 2007)

## Additional hazards

Additional categories of hazardous events may be identified as important to the project, depending on site conditions:

- *Fire*: primary fires, both internal (accidental fires, arson) and external (forest fires), or secondary fires, caused by equipment failure sustained during another hazard event; beyond the usual life safety and property damage concerns, fire can cause simultaneous expansion and softening, greatly reducing the critical buckling strength of columns
- *Collisions:* for example, the 1982 partial collapse of the first Sunshine Skyway Bridge in Tampa Bay, Florida, caused by a freighter colliding with a support pier (Hendrix 2003)
- *Wind*: high winds generated by tornados, tropical storms and other weather events, which generate uplift forces on roofs and exposed floors through the Bernoulli effect
- *Other miscellaneous failure modes*: such as sudden loss of footing due to scour (1987 Schoharie Creek Bridge collapse, Fort Hunter, NY), failure of a support element due to corrosion (1983 Mianus River Bridge collapse, Greenwich, CT), and other events that lead to the loss or removal of a structural element

These events all lead to the severe weakening or removal of intermediate structural elements, leading to a situation akin to the prior three where the vertical stability and integrity of the structure depends on the ability of the frame to resist instantaneous changes in vertical load.

## DESIGN AND ANALYSIS CONSIDERATIONS

### Vertical stability in lieu of/in addition to lateral force design

As discussed above, designing a structure to survive these hazards may require more than traditional lateral force design methods, since in many cases lateral stability analysis does not represent the entire response of the system (vertical seismic acceleration, vertical blast pressure on floor systems) or is not readily applicable (hydrostatic and hydrodynamic force, sudden removal of vertical support member). While performance provisions for vertical stability may be computationally more demanding and require more knowledge of nonlinear dynamic analysis than the descriptive vertical stability provisions in codes like the UK Building Regulations, they can enhance a structure's general integrity and stability without needing to address any specific type of threat (Rahimian and Moazami 2002). Work has been done to formulate simple approximate methods for preliminary analysis of a structure's redundancy and vertical stability (Pujol and Smith-Pardo 2009).

### Design for anti-gravity forces

Many flexural members are designed solely for gravity vertical loads acting downwards. Prestressed reinforced concrete members, for example, are designed for support shear using a nominal design shear $V_c$, equal to the critical shear $V$ reduced by the vertical load $V_p$ developed by the prestressing tendons (Figure 7). In a situation where upwards vertical forces are developed, $V_p$ will instead contribute to the shear at the supports, rather than reducing it, effectively reducing the nominal shear strength and possibly leading to rupture, as occurred due to hydrostatic forces on prestressed deck systems during Hurricane Katrina's storm surges.

Similarly, for flexural design, the design concept relies on the balance of the negative moment developed by external loads with the positive moment developed by the eccentricity of the prestress tendon; upwards forces will instead subject the upper extreme fibers to additional tensile stress. Additional reinforcement detailing and analysis will be necessary to mitigate the unintended consequences of a traditional prestressed concrete design in regards to upwards forces develop during hazard events.

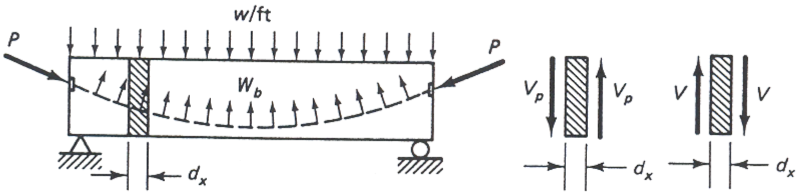


Figure 7 Free-body diagram of shear design for flexural prestressed RC members (Nawy 2006)

**Force redistribution through alternate load paths**

In any situation where the performance of support members is compromised, the frame requires sufficient capacity for force redistribution to safely transfer loads to the supports. A structure with a low redundancy is in danger of undergoing progressive collapse, where a local inability to redistribute loads triggers a chain effect that quickly results in the global instability of the structure, leading to damage that dwarfs the original losses. The most prevalent mode of preserving vertical stability through force redistribution is through the mechanism of catenary or membrane action.

**Capability for membrane/catenary action**

In the hazard situations where a vertical support member is damaged or destroyed, the flexure members it supported will sag significantly (Figure 8), redistributing the loads carried by the lost member into axial tensile forces carried by the sagging beams. This catenary action is often the last bulwark against progressive collapse. The ability to successfully develop sufficient catenary action to carry these redistributed loads depends on the members' plastic ductility, especially the detailing and ductility of the connection joints (Liu 2009); for bridges, where the span length makes the support bents especially vulnerable to removal, the bearings must be able to develop sufficient rotation capacity to ensure catenary action (Saadeghvaziri and Feizi 2008) and resist the upwards forces on the resisting piers' abutments (Feizi et al. 2007).

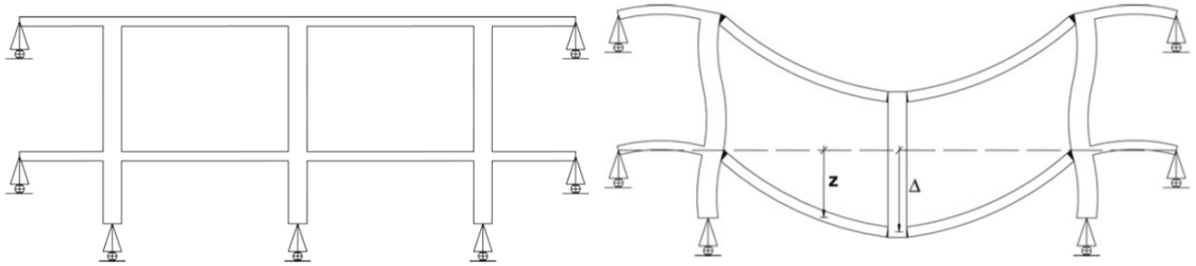


Figure 8 Removal of column resulting in catenary action (Pujol and Smith-Pardo 2009)

In three-dimensional systems where the floor slab is integral to the framing system, the removal of a supporting column will develop a membrane shell action, where the unsupported floor slab deforms into an inverted "dish" shape (Figure 9); a properly designed composite floor system will be able to balance the tensile forces created by the deformation with the compressive hoop stresses developed by the new shape of the floor slab (Rahimian and Moazami 2002).

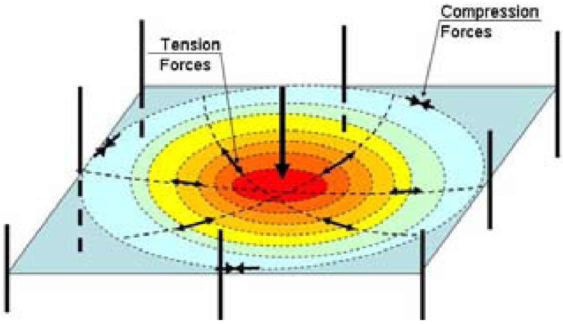


Figure 9 3D catenary shell action of a composite floor system (Rahimian and Moazami 2002)

## CONCLUSION: FUTURE RESEARCH NEEDS

The fields of performance-based design and multi-hazard design have come a long way from the traditional methods of individual prescriptive codes for each individual hazard, but more work is necessary to develop the corpus of research into a robust, usable design framework and/or structural code for use by design professionals. The research needs this paper has identified fall into two general categories:

- *development of multi-hazard criteria and guidelines for design engineers*, such as
  - continuing development of multi-hazard risk assessment models such as the one developed by Asprone et al. (2010);
  - the formulation of an approximate analysis method that can identify pertinent hazards and quantitatively translate their types and probabilistic intensities into total displacement or ductility demands; and
- *practical research into material behavior under dynamic vertical loading,* such as
  - for new designs, the investigation of suitable reinforcement detailing for reinforced concrete framing systems subjected to upwards loading;
  - for existing structures, identification of current deficiencies in existing structural systems, and the subsequent development of retrofitting detailing to enable frame systems to increase their ductility and ensure the development of catenary action;
  - for bridge structures, the design and analysis of bridge deck systems that either resist hydrodynamic and hydrostatic loads, or dissipate them by reducing the effective buoyancy caused by submersion

However, as always, and echoing the sentiments of Freeman, the most important tool to ensure acceptable structural performance is engineering judgment. Advantageously to structural engineers, a performance-based design framework enables design professionals to most readily combine good design practices with analysis and theory to guarantee the safety and performance of their designs.

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