

guidance—to reliably predict the potential for complex failures in structural systems subjected to multiple hazards.

- a. Progressive collapse¹⁹ should be prevented in buildings. The primary structural systems should provide alternate paths for carrying loads in case certain components fail (e.g., transfer girders or columns). This is especially important in buildings where structural components (e.g., columns, girders) support unusually large floor areas.²⁰ Progressive collapse is addressed only in a very limited way in practice and by codes and standards. For example, the initiating event in design to prevent progressive collapse may be removal of one or two columns at the bottom of the structure. Initiating events at multiple locations within the structure, or involving other key components and subsystems, should be analyzed commensurate with the risks considered in the design. The effectiveness of mitigation approaches involving new system and subsystem design concepts should be evaluated with conventional approaches based on indirect design (continuity, strength, and ductility of connections), direct design (local hardening), and redundant (alternate) load paths. The capability to prevent progressive collapse due to abnormal loads should include: (i) comprehensive design rules and practice guides; (ii) evaluation criteria, methodology, and tools for assessing the vulnerability of structures to progressive collapse; (iii) performance-based criteria for abnormal loads and load combinations; (iv) analytical tools to predict potential collapse mechanisms; and (v) computer models and analysis procedures for use in routine design practice. The federal government should coordinate the existing programs that address this need: those in the Department of Defense; the General Services Administration; the Defense Threat Reduction Agency; and NIST. *Affected Standards*²¹: ASCE-7, AISC Specifications, and ACI 318. These standards and other relevant committees should draw on expertise from ASCE/SFPE 29 for issues concerning progressive collapse under fire conditions. *Model Building Codes*: The consensus standards should be adopted in model building codes (i.e., the *International Building Code* and NFPA 5000) by mandatory reference to, or incorporation of, the latest edition of the standard. State and local jurisdictions should adopt and enforce the improved model building codes and national standards based on all 30 WTC recommendations. The codes and standards may vary from the WTC recommendations, but satisfy their intent.
- b. A robust, integrated predictive capability should be developed, validated, and maintained to routinely assess the vulnerability of whole structures to the effects of credible hazards. This capability to evaluate the performance and reserve capacity of structures does not exist and is a significant cause for concern. This capability also would assist in investigations of building failure—as demonstrated by the analyses of the WTC building collapses carried out in this Investigation. The failure analysis capability should include all possible complex failure phenomena that may occur under multiple hazards (e.g., bomb blasts, fires, impacts, gas explosions, earthquakes, and hurricane winds), experimentally validated models, and robust tools for routine analysis to predict such failures and their consequences. This capability should be developed via a coordinated effort involving federal, private sector, and academic research organizations in close partnership with practicing engineers.

¹⁹ *Progressive collapse* (or *disproportionate collapse*) occurs when an initial local failure spreads from structural element to structural element resulting in the collapse of an entire structure or a disproportionately large part of it.

²⁰ While the WTC towers eventually collapsed, they had the capacity to redistribute loads from impact and fire damaged structural components and subsystems to undamaged components and subsystems. However, the core columns in the WTC towers lacked sufficient redundant (alternate) paths for carrying gravity loads.

²¹ A full listing of the affected standards, including the complete names of these standards, is provided in Table 9–2, which is located following the recommendations.