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Building Design Considerations to Support Immediate Occupancy Performance Objectives

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ABSTRACT

The intent of current building codes for typical commercial and residential buildings is to safeguard against loss of life to building occupants by minimizing the probability of structural collapse during natural hazard events. However, preserving building functionality after a natural hazard is not the primary consideration in current codes. Widespread building damage, and degradation or loss of building functions, can have severe social and economic impacts on a community. To reduce the likelihood and severity of potential property damage and to enable more rapid recovery for communities impacted by natural hazards, the U.S. Senate tasked the National Institute of Standards and Technology (NIST) with identifying research needs and implementation activities to develop a multi-hazard immediate occupancy (IO) performance objective for commercial and residential buildings. This new IO performance objective would provide the technical criteria needed to design a building to retain its function following a design level hazard event. With input from subject matter experts and stakeholders participating in a national workshop, NIST developed a report to fulfill the Congressional mandate. This paper highlights key research needs and implementation activities that pertain to designing a building to meet IO performance objectives. The research needs and implementation activities discussed in this paper articulate the steps necessary to develop the engineering design criteria for the new IO performance objective. For successful development of IO objectives, these topics need to be addressed with cooperative efforts among researchers, engineers, standards and code officials, and community stakeholders.

Keywords: immediate occupancy, performance objective, building design, performance objective, adoption consideration.

INTRODUCTION

Current building codes mainly focus on preserving lives of building occupants, and generally do not address continued functionality after a hazard event. However, societal needs are quickly outpacing the performance goals for which current building codes have been developed. Communities, owners, and residents can benefit from buildings that are more resilient to natural hazard events to avoid lengthy and costly repairs or rebuilding, as well as minimizing the need for long-term evacuation of building occupants. To address this issue, the U.S. Senate directed the National Institute of Standards and Technology (NIST) to identify engineering principles, research, and implementation activities needed for a new "safety building performance objective for commercial and residential properties" [1].

In response to the congressional mandate, NIST developed a report identifying the research needs and implementation activities required to develop immediate occupancy (IO) performance objectives [2]. This report was developed through a collaborative process with a steering committee of subject matter experts and a national expert stakeholder workshop hosted by NIST. In the NIST report, IO performance is considered as the building's condition after a hazard event where damage to the building's structural system is controlled, limited, and repairable while the building remains safe to occupy. The building's ability to function at full or minimally reduced capacity is also affected by the functionality of the non-structural systems of the building (e.g., building envelope, equipment, interior utilities), as well as the infrastructure that connects the building to its surrounding community. Although other terminologies such as functional recovery may sound suitable to relay this concept, the term IO is used to highlight a potential range of functional levels, and for consistency with the congressional language. The role of lifelines in supporting the operation of functional buildings is acknowledged, but not addressed in detail in the NIST report. The NIST report covers improvements to building design, as well as community, economic and social, and adoption and acceptance considerations. This paper highlights research needs and implementation activities identified in the NIST report that pertain to designing individual buildings for IO performance.

BUILDING DESIGN CONSIDERATIONS

There are significant challenges associated with designing new and retrofitting existing commercial or residential buildings to meet IO performance objectives. General challenges and research needs associated with designing a building for IO are presented within six subtopic areas: 1) Functionality Levels; 2) Damage Levels; 3) Design Practice; 4) Building Materials and Technologies; 5) Maintenance, Repair and Retrofit Methods; and 6) Monitoring and Assessment. Research and implementation activities that apply to each subtopic are presented in the proceeding section.

Functionality Levels

One of the primary differences between IO performance objectives and current building code design objectives is the consideration of the functionality level of a building following a hazard event. Because the post-hazard functionality of a building is not typically considered in the design process, building designers currently lack the tools and expertise necessary to assess a building's potential functionality for different loading scenarios, as well as the tools needed to determine the timeframe required for a building to return to its pre-hazard functionality level following a hazard event. Major challenges in incorporating functionality of the building to the design process include a general lack of understanding of the diverse factors that can impede building functionality, and the lack of adequate data to relate functionality and recovery time to building damage. Recommended research and implementation activities to achieve these goals are summarized below.

Functionality Classification: Building functionality classification levels that are appropriate to meet IO objectives need to be established. The functionality levels should describe the ability of the building to meet its intended purpose prior to a hazard, and to retain essential functions and return to pre-hazard functionality within a predetermined, acceptable timeframe following a hazard.

Recovery data: Detailed field reconnaissance data that describe the recovery process for buildings over time following hazard events are needed. The data can be used to inform the development of functionality levels and to develop and validate numerical models for predicting building functionality level. A standardized recovery data collection process should be developed to benefit ongoing efforts to develop and improve IO performance objectives for new and existing buildings.

Factors that influence functionality and recovery time: Research is needed to characterize the building systems that most influence building functionality, including those that are not commonly considered when planning and designing a building. This includes consideration of the impacts of damaged connections to utilities (e.g., water and electricity). In addition, the influence of maintenance and repair on building functionality needs to be better understood.

Analytical tools to predict building functionality: To enable the adoption of new immediate occupancy performance objectives that directly consider post-hazard functionality, building designers would need to be equipped with analytical tools to assess functionality for a variety of hazard scenarios. Building upon findings of the basic and applied research recommended within the Functionality Levels subtopic, analytical tools should be developed to quantify the functionality of a building over time, considering the impacts of hazard damage, degradation of building components, and maintenance, repair, and retrofit. The analytical tools should be developed in a reliability-based format using quantifiable data, from which a level of uncertainty can be expressed for achieving desired functionality levels.

Damage Levels

The functionality of a building depends on the amount of damage experienced by the building as a result of hazard events. In an engineering framework, building functionality needs to be measured as a function of damage to the building's structural components, nonstructural components, and any other components or equipment that can hinder functionality. To develop IO performance objectives, damage levels that are acceptable for IO objectives need to be identified, and relationships that link damage and functionality need to be developed. One of the key challenges of damage quantification is improving understanding of building response under different hazard types. Research to address this challenge includes experimental and field studies to characterize the performance of nonstructural components of a building. In addition, more accurate and simple numerical modeling techniques are needed to simulate the damage response of structural and nonstructural components within a building, including building contents, as well as their interaction. Recommended research and implementation activities to achieve these goals are summarized below.

Acceptable damage levels: Research is needed to quantify acceptable levels of damage for each of the immediate occupancy functionality levels at the component level as well as at the system level.

Field reconnaissance and laboratory data: Detailed field reconnaissance and laboratory data are needed to characterize the damage types and quantify damage levels for individual components as well as the global performance of a building. The data can be used to support the development of appropriate functionality levels for immediate occupancy and to develop and validate damage prediction tools. Reconnaissance data should reflect the performance of a large number of buildings of various age and construction type, with various levels of damage, including buildings that sustained little or no damage.

Understanding damage levels for different hazards: Research is needed to improve the understanding of building response both at the component and systems levels under different hazard types and levels. In addition to studying individual building components, the interactions among and between structural and nonstructural components need to be studied to identify how these responses can affect one another.

Understanding degradation due to aging and environmental effects:
There is a substantial need to understand how buildings and their structural and non-structural components age and respond to environmental factors, such as exposure to ultraviolet radiation, humidity, and temperature. This effort includes experimental as well as field studies to characterize the aging and environmental effects for materials used in new and existing buildings. Research is needed to develop numerical models capable of simulating the impacts of environmental factors on the response and functionality of a building.

Damage prediction models: Research is needed to improve the accuracy of damage prediction models, and to develop numerical models for different materials and components that accurately simulate damage formation and propagation. This effort includes developing physics-based models as well as simplified models that can predict the damage response under different hazard types. The impact of cumulative damage from multiple hazard events needs to be investigated. Development of damage prediction models should include evaluating the impact of secondary sources of damage. Improved damage prediction models will inform the design, repair, and retrofit process, as well as the functionality level and recovery time of buildings.

Standardize data collection:
One of the challenges in analyzing data from different reconnaissance studies is the lack of standardization and interoperability among the datasets. Different teams may collect different types of data and use different collection protocols. Research is needed to identify the crucial data that need to be collected in reconnaissance studies. Research is also needed to minimize the human bias in the collected data from field studies. Protocols and guidelines on sampling and data collection in reconnaissance studies should to be developed to improve the consistency in the data collected by different teams and to ensure that data are recorded in a consistent and interoperable manner.

Design Practice

To design a building, engineers, architects, and building developers must evaluate the building and its systems by a set of technical design criteria that imply conformance with building code and standards requirements. Because buildings designed for IO performance will be required to meet damage and functionality criteria that are more restrictive than current prescriptive code requirements, the development of new guidelines and standards is necessary. These IO-specific design tools should: 1) characterize the hazard types, hazard levels, and hazard scenarios (e.g., multiple hazard events) to be considered for design; and 2) provide guidelines to utilize new design technologies that emphasize damage avoidance and repairability as needed to satisfy IO performance goals. To evaluate a building's conformance with these new design standards, the development of new analytical models that can reliably predict building damage and functionality levels is needed. To support the development of new IO design standards and analytical tools, research is needed to benchmark the performance anticipated for code-compliant buildings under various hazard scenarios. Recommended research and implementation activities to achieve these goals are summarized below.

Hazard levels and considering multiple hazards in design**:** The hazard types and distinct hazard levels that should be considered in the IO design process need to be clearly articulated in the design criteria used by building designers. Improved hazard models and the development of hazard risk maps are essential for the development of IO design guidelines and standards. As hazard risk resources are developed, research should be conducted to express the appropriate hazard levels to evaluate the performance of buildings designed for IO performance. Individual buildings are often vulnerable to different hazard types and multiple occurrences of certain hazards over the building's lifecycle. Research is needed to determine the loading scenarios that are appropriate for buildings prone to various hazards, with consideration of their joint probability of occurrence, and to develop analytical tools and design guidelines for assessing the performance of damaged buildings.

New design philosophies for immediate occupancy**:** A major challenge associated with immediate occupancy is the need to minimize building damage and the impacts of that damage. Research is needed to study the potential performance benefits of implementing new and existing low damage and rapidly reparable alternatives to common building designs. Numerical simulations and laboratory tests are needed to compare the reparability, functionality, and recovery timeframe for traditional building designs to those of low damage alternative for various hazard scenarios. For certain hazard events and certain buildings, damage may be unavoidable. Research is needed to identify methods to streamline the repair and recovery processes for buildings damaged in hazard events. Research investigating the ways in which repair and recovery strategies can be incorporated into the building design process is important. This research should investigate ways to optimize recovery by minimizing the quantity of damaged building components and designing rapid repair methods to be implemented if damage occurs.

***Benchmarking the performance of code-compliant buildings*:** Current building codes and standards are developed to ensure life safety of the occupants and to provide some degree of property protection; however, it is challenging to evaluate the reliability of those codes and standards to meet certain performance objectives (e.g., collapse prevention). These challenges are associated with, among other things: limited field data on the impacts of design level or extreme level hazards on code-compliant buildings; and capacity limitations of structural laboratories that make it difficult to conduct tests on large-scale building models. Nonetheless, research to benchmark the performance of code-compliant buildings should be prioritized, and a thorough evaluation of design standards for Risk Category III & IV buildings should be conducted to determine their suitability in meeting IO objectives.

***Data on the performance of existing buildings*:** Hazard response data from sensors in buildings and similar data from laboratory tests is needed to develop, calibrate, and validate numerical models that assess building performance. As much as possible, building information should summarize building component design parameters (e.g., geometry, materials) such that the hazard resistance of the building systems can be predicted using newly developed damage prediction and functionality prediction models.

***Analytical models to conduct building performance evaluations*:** The development of new analytical simulation tools, or modification of existing tools, is needed to incorporate newly developed damage prediction models and functionality prediction models into the building performance evaluation process. The newly developed tools should be capable of capturing the cumulative impacts of damage and aging on all structural and nonstructural building components, making it possible to evaluate the hazard performance and functionality of a building over its lifecycle. These tools should enable integrated modeling of all of a building's systems, accounting for interdependencies between the systems.

***Design requirements and performance evaluation criteria for immediate occupancy*:** New design guidelines and standards should be developed that dictate the technical criteria, hazard types, and hazard levels appropriate for designing a building for IO objectives. The guidelines should include hazard-specific performance criteria by which new and existing buildings are evaluated for their effectiveness in meeting IO safety and functionality requirements. These criteria should be informed by laboratory data, field data, and numerical studies, considering the appropriate level of risk for different damage levels, hazard types, and hazard levels. Because mechanical systems and envelope of a building play a crucial role in the ability of a building to conduct its intended functions, guidelines and standards for nonstructural building systems should be developed in a manner that is consistent with those developed for the structural system.

Building Materials and Technologies

New and improved building materials and technologies can offer improved options to prevent, detect, and mitigate building damage and expedite post-hazard recovery times. Research is needed to develop materials, technologies, and strategies that can decrease the likelihood of damage, lessen potential repair costs, and reduce potential recovery timeframes. Recommended research and implementation activities to achieve these goals are summarized below.

***Lower-cost materials*:** High materials costs can hinder decisions to repair damaged buildings and to retrofit buildings that are vulnerable to damage. The development of lower cost materials, both for the construction of new buildings and retrofit of existing buildings, must accompany the development of IO objectives.

***Performance of new materials*:** Research is needed to evaluate the performance of new materials when subjected to various hazards and environmental conditions. Research that investigates the economic impacts of using various building materials throughout a building's lifecycle, including post-hazard repairs, should be conducted to evaluate the potential long-term benefits of using new materials.

***Materials for modular, standardized construction and repair*:** Research is needed to develop new repair methods and modular building construction and modification techniques, particularly for non-structural systems, to facilitate rapid repairs and replacements. Both laboratory and in-situ testing of these new materials and building systems should be conducted.

Smart buildings**:** Smart buildings that integrate a network of sensors that communicate the condition of a building's various systems can assist in making decisions for evacuation and reoccupation, and can expedite the post-hazard repair process. Research for such smart buildings is needed at both the material level and system level. At the material level, research should prioritize the development of technologies that can communicate material damage and repair needs, as well as materials that can self-repair or adapt to changing conditions. System level research should include the development of new sensors and technologies that can communicate building functionality and identify the systems that are hindering functionality.

Damage-tolerant, rapidly-repairable building systems**:** An important advancement for the implementation of IO objectives will be the development of new materials and technologies that are either capable of sustaining minimal damage or being rapidly repaired in the aftermath of a hazard event. Material level research is needed to develop new damage-resistant materials (e.g., mold-resistant materials) and increase the accessibility of such materials to the building industry. System level research needs include developing new low-damage technologies, developing systems in which damage is concentrated to a small number of easily-repairable components, introducing new rapid-repair methods to minimize post-hazard downtime, and developing new damage-resistant building envelopes.

Adoption of new materials and technologies**:** The use of new materials and technologies in the construction industry has been hindered due to a variety of issues including high initial costs, lack of workforce expertise, lack of adequate design guidelines, and liability concerns. Research is needed to better understand how the building industry responds to advances in materials and technologies and what steps are needed to encourage their adoption. Design guidelines and standards should be adapted to provide guidance on new materials and technologies. Additionally, the U.S. should study international communities that have successfully adopted these new materials and technologies in the construction industry.

Maintenance, Repair, and Retrofit Methods

Damage and degradation to a building can reduce the building's structural capacity and ultimately its ability to meet its intended safety and functionality objectives. To improve and optimize building maintenance, research is needed to quantify the impacts of environmental factors on the degradation of building materials and how such degradation affects the performance of building components. The development of low cost, rapid repair technologies is needed to enable timely repair of damaged building components such that buildings designed for IO are able to meet their functionality goals. The development of effective retrofit technologies for existing buildings is also needed to enable the implementation of IO performance objectives. Additionally, research is needed to understand the decision-making processes that influence whether a building owner will choose to invest in maintenance, repair, and retrofit. Recommended research and implementation activities to achieve these goals are summarized below.

Inventory of existing building stock**:** Data identifying the physical systems and conditions of a community's buildings are needed to inform a number of different studies. Data collection needs include architectural drawings, land use, maintenance and repair records, and information about any building modifications. This information is needed in order to prioritize buildings that might require retrofits or repairs prior to and following a hazard event. In addition, there is a need to collect data about the costs and methods used for repairs and retrofits so that communities and building-owners can make informed decisions to undertake these efforts.

Decreasing cost and improving methods to repair and retrofit buildings**:** Identifying ways to decrease the costs of repairs and retrofits, as well as ways to expedite repair and retrofit processes, can enable more rapid implementation of IO objectives. Lower repair costs may come as a result of more affordable materials and the development of new rapid repair techniques. In new buildings, both direct and indirect repair costs may be reduced by integrating predefined components designed to sustain the majority of damage and which are easily accessed and repaired. In addition, smart materials that communicate repair needs or are able to self-repair could aid maintenance and repair processes.

Behavioral research**:** Behavioral research is needed to understand current decision-making processes concerning how building owners choose to invest in maintenance and repair. This research should prioritize understanding when a building owner chooses to upgrade a building, and for what purposes. In addition, research is needed to understand the extent to which building owners value retrofits and repairs to improve hazard resilience.

Understanding and enhancing repair effectiveness**:** Research is needed to identify and evaluate repair and retrofit techniques for various building types, including the repair or retrofit of building envelopes and the nonstructural systems of the buildings. The effectiveness of these repair and retrofit methods in restoring and enhancing the strength, safety, and functionality of a building should be studied.

***Understanding resources needed for repairs and retrofits*:** Detailed analytical studies are needed to investigate the financial and social impacts associated with repairing various building types damaged under a variety of hazards scenarios. The costs associated with retrofitting these buildings prior to the occurrence of various hazard scenarios should also be studied. A comparison of the direct mitigation costs to the potential socioeconomic costs over a building's lifecycle can help inform decision makers during the building design, repair, and retrofit decision-making processes.

***Improving availability of tools, parts, and labor*:** In the aftermath of a hazard event causing widespread damage, demand is often high for skilled labor, specialty equipment, and custom manufactured parts. This demand is often unable to be met immediately following a hazard event, leading to long recovery timeframe for impacted communities. Understanding and improving the availability of tools, parts, and skilled labor for recovery could help reduce the amount of time required for building repairs, decreasing the disruption on the community, building owners, and occupants.

***Methods to strategically implement retrofits*:** Due to the high costs associated with retrofitting a community's vulnerable building stock, a retrofit prioritization scheme may be necessary to determine which buildings should be retrofitted first, and how those retrofits should take place to minimize interruptions to building owners and occupants. Building rating systems should be explored to determine if any existing or new systems could be implemented to prioritize which buildings should be repaired and retrofitted.

Developing periodic inspection protocols: Buildings designed to immediate occupancy performance objectives should be maintained and inspected periodically to ensure that the buildings continue to meet IO objectives. This is not part of current practice, and therefore would likely require research to determine cost-effective techniques for implementation.

Monitoring and Assessment

The state of an IO building should be monitored periodically to determine how aging, environmental factors, and hazards affect the building's ability to meet IO performance objectives. Moreover, assessing the building's performance after a natural hazard event is essential to evaluate whether the building is safe to occupy and to determine the post-hazard functionality level of the building. The main challenge in monitoring building performance is developing new cost-effective monitoring techniques. Timely assessment of buildings after a hazard is also a key challenge, as it needs to be completed prior to reoccupying the building and returning to function. Recommended research and implementation activities to achieve these goals are summarized below.

Technology and sensors to assess building performance: Research is needed to identify effective technologies and methods for conducting rapid assessments of building condition. This effort includes developing cost-effective sensors and built-in monitoring systems for collecting data, as well as developing performance assessment procedures to analyze the collected data and identify the observed damage. One of the main needs in improving data collection technologies is the development of instrumentation that can monitor the response of nonstructural systems. Research is also needed to develop sensors that can monitor the degradation of material properties due to environmental impacts.

New data collection methods: Research is needed to investigate the use of new data collection methods, such as crowdsourcing, social media, and use of drones for collecting information for monitoring and assessment of buildings after natural hazards.

Linking damage measurement to the performance assessment: Data collected from sensors or similar technologies need to be processed either by an engineer or through an automated process to quantify building damage after a hazard event. Research is needed to relate recorded data to observed building damage, post-hazard functionality, and recovery time. This research effort includes benchmarking/validating the linkage between the collected data and observed damage using available data from instrumented buildings. This research is an important step toward developing a remote assessment system for buildings, where collected data is automatically sent to and analyzed by an assessment tool to identify the extent of damage. Moreover, research is needed to help develop methods to use recorded data to assist with the decision-making processes after a hazard event.

Improving inspection techniques: Currently, post-event evaluation of a building is conducted primarily through visual inspection, which may be adequate to assess collapse likelihood in a general sense but may not be sufficient to identify the safety and functionality of a building designed for IO. Research is needed to develop new post-hazard evaluation criteria, specifically for IO buildings, and to develop an IO building tagging process. One of the key issues is to identify who is responsible for tagging of IO buildings and what improvements need to be made to the current tagging process to shorten the inspection period.

Developing guidelines/protocols for inspection of the buildings for immediate occupancy: To quantify the preserved level of occupancy and functionality of a building throughout its lifecycle, guidelines and protocols on implementing inspection requirements and methods should be developed.

CONCLUSIONS

This paper articulates research needs and implementation activities concerning the design of individual buildings that are necessary to support development of IO performance objectives. These include: defining acceptable level of functionality for IO buildings; quantifying damage levels that are appropriate for the distinct functionality levels; developing new building materials and construction techniques for IO buildings; maintaining and retrofitting buildings to meet IO objectives; and monitoring and assessing the state of a building throughout its lifecycle. Unlike current building code objectives, the new IO performance objective prioritizes maintaining an appropriate level of building functionality, including retaining functionality, following a hazard event. Therefore, the research needs and activities described in this paper will require a fundamental change to the current state of practice. In addition, current practice for retrofitting and monitoring existing buildings will require substantial change. Research under the topics identified in this paper could lead to the development of new design guidelines and analytical tools to assist developers, architects, engineers, and researchers in designing and assessing buildings to achieve IO performance objectives. Development and adoption of guidelines and tools to implement IO objectives would advance current standards of practice and lead to buildings that are more resilient to natural hazards, providing a greater level of safety and minimizing disruptions for building occupants.

While this paper focuses on the technical aspect of design of individual buildings to meet IO objectives, the successful development and adoption of IO objective requires a broader perspective that considers the interactions between individual buildings and the surrounding community, the social and economic impacts of IO buildings on different stakeholders, and methods to garner public support to ensure successful adoption of IO objectives. These diverse issues demand multidisciplinary perspectives and engagement from all levels of society.

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