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Functional Recovery: A Conceptual Framework

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Why Functional Recovery?

Communities should be explicit about the time it will take to recover functionality after an earthquake. Buildings and lifeline infrastructure can be designed or retrofitted for timely restoration of service. Stating these goals and implementing regulations to support them is what it means to design for functional recovery.

Design for functional recovery does not necessarily mean an increase in construction cost or even a change in performance relative to current practice. Rather, it means making two measures of design equally important: safety *and* recovery time. With functional recovery times better understood and more clearly conveyed, higher performance goals might then be selected where needed.

Design for functional recovery is a necessary tool for assessing and improving community resilience. As such, functional recovery concepts and design provisions should be developed with the whole community in mind, considering interdependencies between buildings and lifeline infrastructure systems and accounting for existing conditions, which vary from community to community. Due to these complexities, efforts are needed by multiple stakeholder groups to develop consensus definitions, design strategies, policies, and practices regarding post-earthquake functional recovery of:

- Buildings, new and existing, serving all occupancies and uses
- Lifeline infrastructure systems, starting with those prioritized by NEHRP:
    - Water and wastewater systems
    - Energy systems
    - Communication systems
    - Transportation systems.

EERI supports such efforts and intends to contribute to them. Indeed, functional recovery is related to the topics of other EERI policy statements, including lifeline infrastructure (EERI, 2016a), building code adoption (in development), and community resilience (EERI, 2019). This paper starts this effort to reach consensus by clarifying the concept of functional recovery and describing how it relates to current practice.

In addition, EERI is also exploring public policy actions that government agencies might take to facilitate the implementation of functional recovery-based seismic design. EERI recognizes that the normal processes for developing design standards can and should be used, and that there are also interim options available to policymakers. EERI currently suggests four categories of policy options that could each encompass a suite of future policy recommendations:

- Legislation and regulations that require designing and planning for functional recovery, in addition to safety.
- Interim programs that encourage designing and planning for functional recovery.
- The development of technical consensus, specifically in the form of standards that set objective design criteria and planning strategies for achieving specified functional recovery times.
- The development of policy consensus, specifically in the form of building code provisions and infrastructure regulations that assign, with local customization, acceptable functional recovery times to buildings and lifeline infrastructure systems based on their role in supporting various community functions.

EERI expects to expand upon the ideas outlined in these categories in a future policy position statement.

Rethinking Codes for Safety

Earthquake-resistant design, especially as required by building codes, has always been primarily about safety. Over the last few years, policymakers and advocates have begun calling for "better than code" seismic design (Federal Register, 2016; San Francisco, 2016; NIST, 2017).

A productive way to think about this goal is to envision codes and standards written to achieve not only safety, but also acceptable recovery times. The recent NEHRP reauthorization, which EERI supported and helped to draft, does this. It calls for FEMA and NIST to convene experts to recommend "options for improving the built environment and critical infrastructure to reflect performance goals stated in terms of post-earthquake reoccupancy and functional recovery time" (42 U.S.C. § 7705(b); Senate Bill 1768, 2018). Where current reoccupancy or recovery times are unacceptable, higher performance goals might be set, resulting in changes to what and how we build. But in many cases, expected reoccupancy or recovery times might already be adequate, in which cases "better than code" performance would mean only that the recovery goals and expectations are better understood and more clearly conveyed.

Understanding Functional Recovery

The NEHRP reauthorization cites two milestones on the post-earthquake timeline: reoccupancy and functional recovery. For a building, the first milestone, reoccupancy, is the ability to re-enter, take shelter, and begin the recovery phase safely (SPUR, 2012). Functional recovery is the next milestone; it marks the restoration of building services as needed to support a significant measure of the building's intended pre-earthquake use (Bonowitz, 2011). Similarly, for infrastructure systems functional recovery marks the restoration of the system's services as needed to allow users to resume most of their pre-earthquake activities (Davis, 2019a).

Functional recovery is different from performance in the emergency or response phase that immediately follows a damaging earthquake. Certain buildings (designated "essential facilities" by the building code) and parts of all lifeline infrastructure systems have pre-assigned roles to play in the response phase, so for them, functional recovery will include the ability to handle those response-related demands. In general, however, functional recovery is about what's needed under normal conditions, not the performance under extreme or emergency conditions.

A consensus formal definition of functional recovery has not yet been established, though the key concepts are widely accepted (PUC, 2019). A working definition, suitable for both buildings and lifeline infrastructure, can be derived from the text of proposed California Assembly Bill 393 (2019):

Functional recovery is a post-earthquake state
in which capacity is sufficiently maintained or restored
to support pre-earthquake functionality.

For a building, "capacity" traditionally refers to the structural and nonstructural systems whose design is regulated by building codes. When considering a building's "functionality," one should also consider building contents and even the ground itself, as well as the availability of certain external services delivered by lifeline infrastructure systems. For lifeline infrastructure systems, functional recovery is likely to be measured as the maintenance or restoration of some substantial percentage of pre-earthquake network capacity.

But which functions are necessary, how much of each are needed, and how soon must they be restored? These are among the obvious next questions (discussed in four categories below), and they anticipate the development of a functional recovery-based code or standard. Assembly Bill 393 envisions such a document, defining a "functional recovery standard" as:

> [A] set of enforceable building code provisions and regulations that provide specific design and construction requirements intended to result in a building for which post-earthquake structural and nonstructural capacity are maintained or can be restored to support the basic intended functions of the building's pre-earthquake use within an acceptable time, where the maximum acceptable time may differ for various uses or occupancies.

This definition presumes the working definition of functional recovery as a measurable state, then adds the element of time. Functional recovery need not be immediate, but it should be achieved "within [the] acceptable time" established by policy. By linking functional recovery to a "set of enforceable ... regulations," the definition also suggests that certain design strategies might or might not be needed depending on the desired recovery time (Bonowitz, 2018; PUC, 2019). Traditional design strategies to ensure the damage resistance of physical components are likely to be supplemented by planning strategies as needed to meet the prescribed recovery time. Planning strategies might include land-use planning, business resumption and continuity planning, pre-planned inspection or repair protocols, infrastructure substitutions or back-ups, strategies to reduce impeding factors, or other risk reduction, restorative or adaptive strategies (Almufti, 2013).

A functional recovery code or standard would have benefits even if the substantive design criteria, and the resulting buildings, do not change. Just the explicit assignment of buildings and infrastructure systems to expected or acceptable functional recovery times would inform stakeholders and support broader planning efforts.

Relation to Community Resilience

Functional recovery concepts can be applied to the design or retrofit of individual buildings and infrastructure systems. From the perspective of public policy, however, functional recovery-based design is also a tool for achieving community-wide goals. With the NEHRP reauthorization, increasing community resilience is now a stated purpose of the program (42 U.S.C. § 7702), and NIST is charged with conducting research "to improve community resilience through building codes and standards" (42 U.S.C. § 7704(b)(5)).

NEHRP, like other government and non-government groups, defines community resilience largely in terms of the capacity of a community to recover from natural hazards effects (42 U.S.C. § 7703; PUC, 2019). The emphasis is on the community as an organization of people, not just physical objects. Yet the services people rely on – housing, education, commerce, government – are in the modern world closely related to the built environment.

The NIST *Community Resilience Planning Guide* (2016a) describes community resilience as a set of recovery time goals for these various community services. For a community-wide service to recover in an acceptable time, the buildings and lifeline infrastructure that support it must recover their own basic functionality in time as well. Thus, functional recovery is the link between design provisions – which are technical and applied to individual buildings or lifeline infrastructure components – and community resilience – which is holistic and measured at a broader scale.

Because a community's built environment can contain both new and old buildings and infrastructure, its potential resilience is a function of more than just the regulations adopted for new construction. For example, housing as a community-wide service comprises recent buildings, non-conforming buildings, and possibly even collapse-prone buildings of every size and construction type. Therefore, in setting recovery goals, it is rational that communities with an older or more vulnerable housing stock might set more aggressive goals for its new housing to ensure a larger portion will provide reliable fast recovery (SPUR, 2009a; SPUR, 2019c; Mieler, et al., 2015). This might pose a challenge where communities within a state or region are committed to using a uniform model code. Retrofit programs serve community-wide resilience goals if they close gaps between current and desired recovery times for a given community service (SPUR, 2009b; City and County of San Francisco, 2016). Even if a retrofit cannot achieve the same functional recovery time as new construction, the aggregate effect of a citywide program might effectively close the resilience gap. From a community resilience perspective, functional recovery concepts and design provisions should be developed with the whole community in mind.

System Interdependencies

Functional recovery is closely related to community resilience in part because of the unavoidable interdependencies between buildings and lifeline infrastructure systems. Individual buildings are often dependent on other buildings due to geographic proximity, or commonality of functional purpose (e.g. a university campus, or buildings within a community that support healthcare delivery). Additionally, buildings are connected to dispersed and overlapping infrastructure networks. Water and wastewater systems rely on the energy system, communication systems need water and energy, all rely on goods and services delivered over transportation networks and, increasingly, on wireless communications, and each infrastructure system includes building structures among its physical components (San Francisco, 2014). Earthquake damage or slow recovery of one system is likely to affect the others. In effect, the modern built environment is a system of systems.

Development of functional recovery as a meaningful and robust concept will obviously need to acknowledge these interdependencies. Even so, any near term development will just as obviously need to start from existing conditions recognizing that each system is already organized around its own stakeholder groups, its own policies and procedures, its own terminology and knowledge base, its own body of law, and even its own history and culture. Independent development within each system is inevitable, but it can perhaps be better coordinated through adoption of common ideas, vocabulary, and goals. Coordination and collaboration among the leading stakeholder groups could be facilitated by the establishment of regional "lifelines councils," as previously recommended by EERI (EERI, 2016a; NZLC, 2016).

Developing the Concept of Functional Recovery

In the short term, recovery-based design is likely to draw on existing tools and policies already applied to essential facilities and infrastructure systems (NIST, 2017; Bonowitz, 2018; PUC, 2019). As the concept develops, these tools will be enhanced by research and practice in four issue areas: Definitional, Policy, Technical, and Implementation. The issue areas necessarily overlap, but they are distinct enough that EERI recommends using them as a way of framing efforts to develop the concept of functional recovery.

Progress within each issue area can be – and is likely to be – largely independent of the others, with some issues reaching consensus while others are still being debated. EERI advises that this reality should be embraced as essential. Speculation about implementation or policy feasibility should not rule out technical options, and the lack of a technical standard should not inhibit interim policies and experimental implementations.

Definitional

For a given building or lifeline infrastructure system, what needs to be functional to achieve "functional recovery"? Which internal components or external resources are needed to ensure functionality? This question is addressed by analytical research (NIST, 2018; Center for Risk-Based Community Resilience Planning; Soga et al, 2019; Davis, 2008) and by new approaches to earthquake reconnaissance that reveal recovery-critical issues (Davis, 2014a; Davis, 2014b; EERI, 2016b; Tremayne et al, 2017).

Policy

For a given building or lifeline infrastructure system, considering its use and the needs of its users, what is an acceptable functional recovery time? This question is addressed by established policy-making practices informed, ideally, by scientific research to quantify the benefits and costs to communities. This will require data, models and other evidence to understand community preferences and benefit-cost considerations (NIST, 2016a).

Technical

For a given building or lifeline infrastructure system, what strategies and criteria will provide high probability that functional recovery will be achieved within the acceptable time? In what cases will planning strategies be needed to supplement design strategies? These questions are addressed by analytical research and testing, together with established practices for developing consensus-based codes and standards (RRMC, 2019; PUC, 2019; NIST, 2014).

Implementation

What aspects of our current practices might need to change in order to apply the technical standards to achieve the policy goals? How will interdependency effects be coordinated between responsible stakeholders? If planning strategies are needed to supplement traditional design strategies, who will be responsible for setting criteria and implementing them? These questions can be anticipated by the same groups that address the other three issue areas, but progress is generally made only through experiment by innovative stakeholders, followed by promotion by professional organizations (including EERI), and in some cases by eventual codification or regulation.

State of Practice

To develop the concept of functional recovery, and to identify options for implementing functional recovery-based design and improving community resilience, it is useful to review the state of practice regarding each of the five systems identified above: How do current practices and leading documents in each field think about post-earthquake functional recovery?

For the purposes of this discussion, it is acknowledged that the infrastructure systems described consist of buildings to support their functions, non-building structures, and many other subsystems and components, that are explicitly stated in each section. In most cases, building structures that serve these systems are designed to the building codes described in the buildings sections, while other non-building structures are designed to standards described in each specific section.

Buildings

Current building codes already acknowledge that some facilities, like hospitals and fire stations, are "essential" for public safety and need to be functional immediately after a damaging earthquake. The code therefore assigns these buildings to the highest of four "risk categories" and sets design criteria to ensure quick recovery. Buildings that are components of lifeline infrastructure systems that serve essential facilities (such as water pump enclosures, power generating stations, or emergency communications offices) are also assigned to the highest risk category. For other buildings – including schools, housing, workplaces, and public accommodations – the code focuses on safety. Nearly all well-designed but non-essential buildings are expected to recover functionality over time, but the code states no specific goals and makes no specific requirements.

Building code provisions for essential facilities assigned to the highest risk category thus offer a basic version of a functional recovery-based code. These provisions address the definitional question by setting the scope of design to ensure the desired building use will be maintained (including both the basic structural elements and nonstructural components), and identifying, for example, which nonstructural components must be braced or have their ruggedness verified by testing. They address the technical question by providing enforceable design and acceptability criteria. They address the implementation question by ensuring quality of construction through robust inspection and enforcement, and clearly delineating jurisdictional lines of authority and responsibility. And they address the policy question by specifying which building uses are assigned to the highest risk category in the first place.

Design criteria are provided in a separate standard known as ASCE 7 (ASCE, 2016). ASCE 7 expects buildings assigned to the highest risk category, Risk Category IV, to perform in ways that "would not prevent function of the facility immediately following" a design-level earthquake. The ASCE 7 commentary adds that a Risk Category IV facility should be "operational" immediately following a more frequent event. The term "operational" is defined in the performance-based ASCE standard for seismic retrofit to mean "[t]he building is suitable for its normal occupancy and use, although possibly in a slightly impaired mode, with power, water, and other required utilities provided from emergency sources, and possibly with some non essential systems not functioning" (ASCE, 2017).

The terminology of ASCE 7 and ASCE 41 is very close to the definition of functional recovery suggested above, but neither of these standards accommodates the idea that different building uses should have different acceptable recovery times. A relatively new document, FEMA P-58 (ATC, 2012), covers a full time range, but it only addresses *repair* time and impeding factors (e.g. forcible closure and long procurement times), which are easier to calculate but different from functional recovery. In any case, each of these performance-based documents represents a step toward an eventual functional recovery standard.

A more complete functional recovery code would address all building uses, not just those deemed essential. It could then extend the current Risk Category IV concepts in two ways. First, addressing the policy question, a functional recovery code would set acceptable functional recovery times for each intended building use. As suggested by NIST (2018), these could reasonably be on the order of days, weeks, or even months. Second, addressing the definitional and technical questions, this new code would provide the scope and criteria necessary to achieve the specified functional recovery time with high reliability. Such a code would be consistent with the definition of functional recovery standard discussed above.

Water and Wastewater Systems

Water and wastewater systems comprise water supply, treatment, transmission and distribution subsystems and wastewater collection, conveyance, treatment and disposal subsystems. Major operating components include treatment plants, pipes, tunnels, dams, reservoirs, tanks, and pumping stations. These subsystems and components suggest the functions necessary for functional recovery, and serve as a starting point to address the definitional question.

Performance objectives for water and wastewater systems focus on safety, public health, and fire protection (AWWA, 1994; ALA, 2004, 2005a, 2005b; ASCE, 1999, 2002; NIST, 1997). NIST (2016b) and ASCE's Risk and Resilience Measurement Committee (RRMC, 2019) summarize the existing guidelines, standards, and codes applicable to the design of water and wastewater systems. Most do not address seismic design, though some address particular components, such as ductile piping.

A relatively new voluntary standard by the American Water Works Association, AWWA J100, addresses recovery time (AWWA, 2010). For the most part, however, the industry does not address the policy question with recommended restoration times. ASCE is currently developing a manual of practice for the seismic design of water and wastewater pipelines which incorporates four performance levels, but it does not address functional recovery times (ASCE, 2019).

Work by the Los Angeles Department of Water and Power might lead to a functional recovery standard or policy of greater applicability. LADWP implemented a performance-based seismic design procedure for its Water System addressing the hierarchy of system, subsystem, and component design with a focus on providing post-earthquake services (LADWP, 2019). The procedure estimates the time needed to restore operability in a way that could accommodate functional recovery goals as described here (Davis, 2014a; 2014b; 2019a; 2019b).

Energy Systems

Energy systems comprise power plants, transmission, and distribution systems for electricity, oil, and natural gas. Non-petroleum systems include dams and hydro-electric plants, solar plants, and individual solar systems, wind farms, and nuclear reactors.

The electricity, oil, and gas industries are highly regulated, with emphasis on "low consumer costs, safe delivery and use, and reliable service" (NIST, 2016a). None of the federal regulatory bodies, including the Federal Energy Regulatory Commission (FERC) and the Nuclear Regulatory Commission (NRC), or state regulatory commissions adopt specific seismic design criteria that establish desired or acceptable post-earthquake recovery times, and in general the performance goals are not well defined. At the state and local levels, regulators may adopt codes or standards for design and construction, but "there is wide variation in the level of design guidance" (NIST, 2016a).

Communication Systems

Communication systems comprise landlines, satellite, and wireless transmission systems, as well as the internet network, for both emergency and non-emergency uses. Current emergency and non-emergency systems overlap, using the same network nodes and links, as well as the same hardware and software.

Emergency call service (9-1-1) is a mandatory function supported by all service providers. Dedicated sites and circuits with redundancy and interoperability are installed to handle the high volumes expected immediately after an earthquake. FirstNet, the First Responder Network Authority, is expected to improve the emergency communication system as states implement it (FirstNet, 2019).

Power is the most critical element of a functioning communication system. Most systems use an uninterruptible power supply (UPS) with backup batteries, but newer technologies are also available. After the 1971 San Fernando earthquake, Bell Communications Research created the Network Equipment Building System (NEBS), which called for at least eight hours of backup power for communication equipment. NEBS GR-63 (2017) remains the only guideline for earthquake protection of communication equipment.

Most wireless service providers have chosen not to follow NEBS. In 2014, the FCC attempted to establish a standard for backup power to cell sites but was unsuccessful. Backup power equipment can sometimes be infeasible to install for cell sites on building roofs, so these sites typically have no backup power. In some cases, a small solar panel and rechargeable battery is sufficient. In any case, functional recovery of cell sites installed on or within buildings can be limited by damage to the building itself. Planning strategies, as opposed to design strategies, are therefore likely to be part of a functional recovery standard for communication systems. Strategies already in use for routine outages within wireless systems include substitute services (landline or internet) and mobile units.

An earthquake recovery issue perhaps unique to communication systems involves the expected demand surge that can result in a lack of service even when the system components are undamaged. Demand after the 2011 Canterbury Earthquake Sequence was ten times normal (ASCE/TCLEE, 2013); demand after Hurricane Sandy in 2012 was 13 times normal. Communication systems are designed assuming only a fraction of all potential users will be active at any time, so a demand surge exceeds the system's capacity even in the absence of damage. This demand surge is perhaps analogous to traffic jams during a pre-hurricane evacuation or planned power shutdowns during heatwaves. While perceived as a loss of function by the end user, these situations are more a result of under-design for rare conditions than a failure to return to normal.

Transportation Systems

Transportation systems comprise highways and roads (with associated bridges, tubes and tunnels), mass transit (with control facilities and stations), ports, and airports. Intermodal transportation systems, combining individual systems with often complicated transitions and intersections, are increasingly a feature of the modern built environment.

Performance-based seismic design criteria have been developed for highways, railways, ports, and airports. These address the policy question by classifying system components in terms of the importance of the facility. Typically, the criteria are intended to protect the structures and accept damage to roadways, runways, and rails on the assumption that these components can be quickly repaired.

The following discussion provides examples of existing design guidelines, illustrating the variety of transportation systems and established design approaches.

The California Department of Transportation's Seismic Design Criteria (Caltrans, 2019) are explicit about expected recovery times for two classes of bridge structures. Presuming a 975-year earthquake hazard, "Important" bridges are expected to provide limited service within days of the event, and "Recovery" bridges are expected to provide limited service within weeks. For a third class, "Ordinary" bridges, no post-earthquake recovery expectations are stated.

Outside of California, some other states also have their own criteria for bridge design, but some adopt the basic criteria developed by AASHTO (2014). Even for areas of high seismicity, the AASHTO criteria use safety-based objectives only, similar to the Caltrans criteria for Ordinary bridges. Operational objectives are left to the discretion of the bridge owner.

Seismic design criteria by the American Railway Engineering and Maintenance-of-Way Association (AREMA) specify a three-point performance objective intended to provide for train safety, "structural integrity," and collapse prevention at three different hazard levels. The specified hazard levels vary with the importance of the bridge, a classification based on damage implications, commercial value, replacement value, occupancy factors, and hazardous material factors. Any consideration of functional recovery time is merely implicit in the importance classification.

For ports, ASCE (2014) provides seismic design criteria for three categories of pile-supported piers and wharves, with the categories related to the structure's importance. As with the AREMA criteria, consideration of functional loss is implicit in the importance classification. The Port of Long Beach (2009) has developed its own criteria that are more explicit about functional recovery time, intending no interruption in service following a 72-year shaking, and perhaps a few months to recover function after a 475-year event.

The Federal Aviation Administration (FAA) has written a number of documents for airport design, but they say little about expected seismic performance, referring instead to ASCE 7, the standard for design of new building structures. Airports in areas of high seismicity often write their own design criteria. For example, San Francisco International Airport developed criteria for its new air traffic control tower intended to keep the tower fully operational through a code-level design earthquake (Structure, 2017). This is consistent with performance expectations for new buildings assigned to Risk Category IV, discussed above.

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