conference preview

ROAD TO RECOVERY

A look at resilience in steel buildings subjected to earthquakes or other hazards.

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MODELING THE FUNCTIONALITY RECOVERY PROCESS of a community's infrastructure after an extreme event is now at the forefront of research—and may soon be part of everyday engineering practice.

Estimating post-disaster recovery of either single or multiple infrastructure facilities in a community requires proper flow and interaction of information of the physical, economic and social components of the involved sectors. Understanding this recovery process is essential, particularly for critical infrastructure facilities, such as hospitals, whose rapid recovery is vital to a community's well-being. Luckily, hospitals and other facilities framed with steel have a head start on recovery, given steel's high level of performance in seismic events.

Stages of Recovery

We'll go through an example seismic recovery effort involving a steel building, but first let's take a look at the recovery process. A change in functionality due to an earthquake is categorized into three different stages, as shown in Figure 1(a). The first stage is the pre-disaster stage, which is the original level of functionality before the hazard, and the immediate functionality drop, which takes place at the time the hazard occurs. It can be expressed as a function of the direct losses, the efficiency of the backup systems and the interdependence between the different lifelines, as shown in Figure 1(b). The second stage is the assessment and planning stage, which takes more time compared to the immediate functionality drop stage. It can be expressed as a function of the direct losses and damage level that controls the assessment and planning process. The third stage is the recovery stage, which is mainly a function of direct losses, available resources and interdependence between the hospital and other lifelines. The duration of the recovery stage has substantial impact on indirect losses.

For the building itself, different parameters play various roles in the level of functionality restoration that can be achieved following an earthquake. This includes damage to the structural and nonstructural components as well as the building's content. The quantification of such damage requires the development of appropriate numerical models that can capture the behavior under the expected demand.

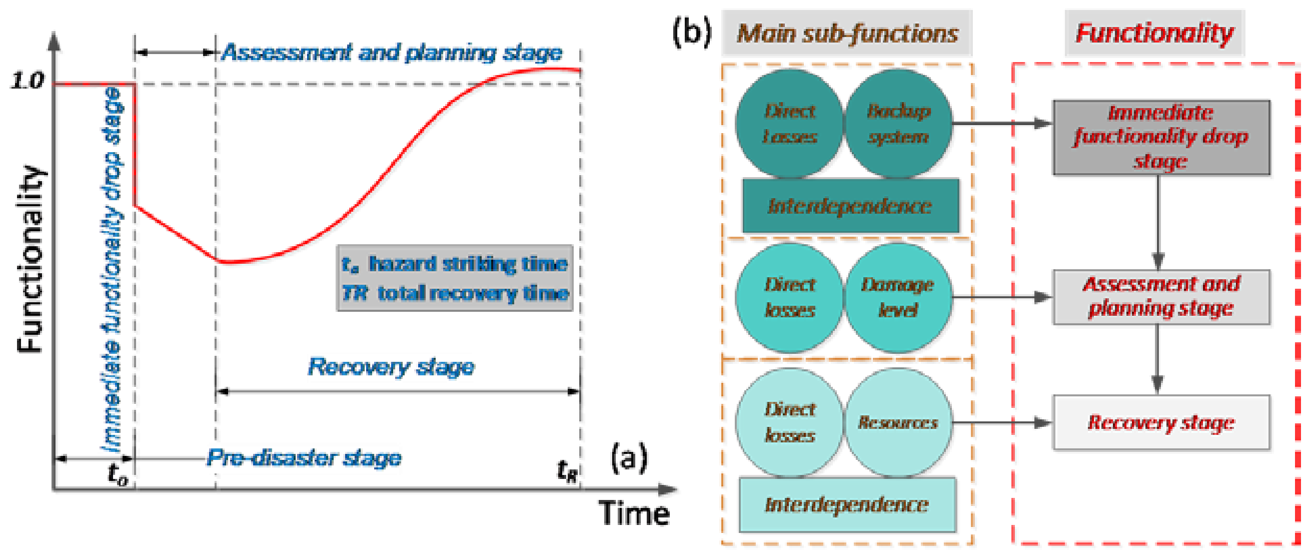

Figure 1. Functionality: (a) different stages and (b) main sub-functions.

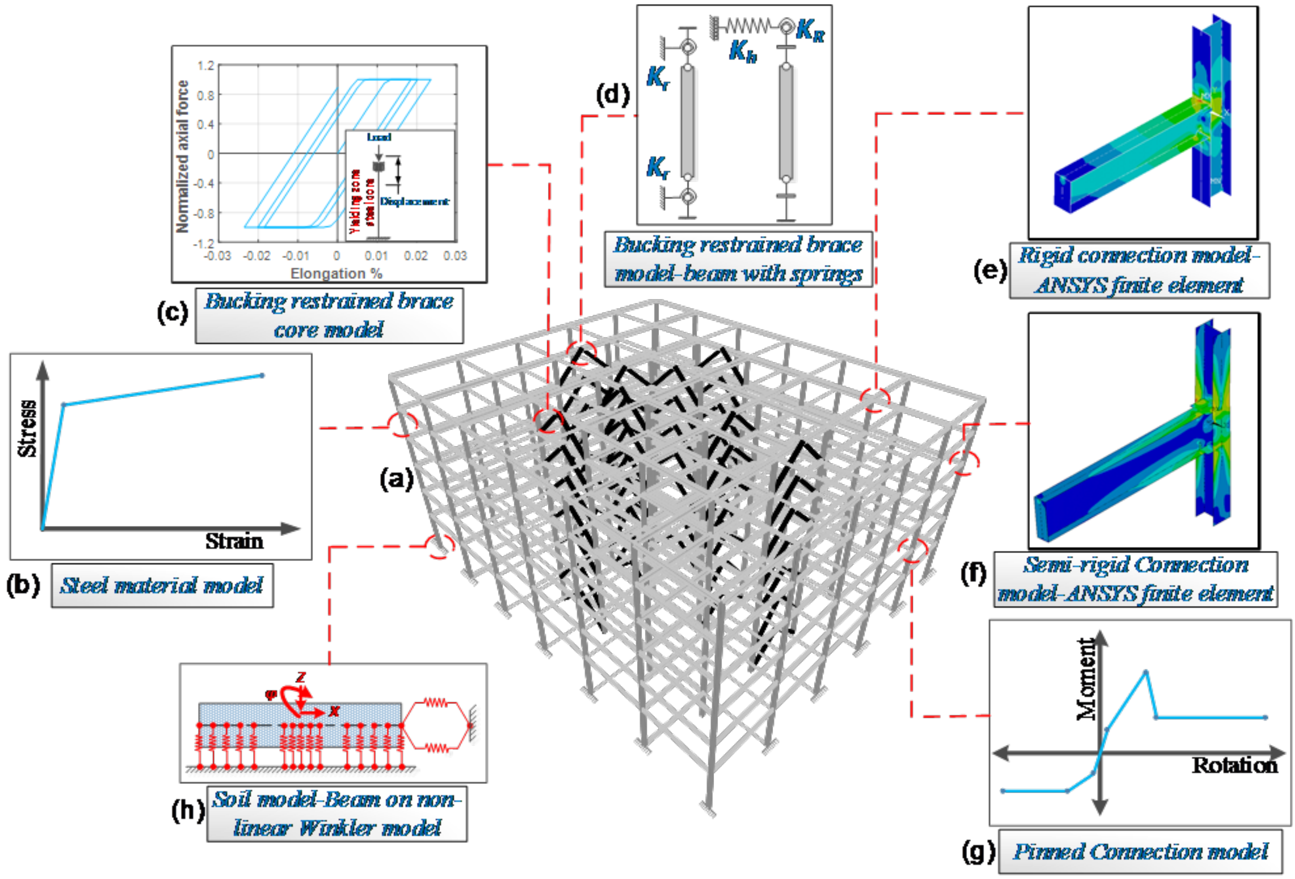

Figure 2. Hospital model: (a) building configuration, (b) steel material model, (c) BRB core model, (d) BRB connections model, (e) rigid connection model, (f) semi-rigid connection model, (g) pinned connection model and (h) soil-structure interaction model.

After the Quake

As an example, let's consider a study performed on a steel-framed hospital in a high-seismic region that was subjected to an earthquake. (The study was conducted as part of a cooperative agreement between the National Institute of Standards and Technology/NIST and Colorado State University.) First, the resilience (functionality) reduction and recovery is quantified and assessed. A detailed finite element model with soil-structure interaction is used to estimate damage. The results of the finite element analysis of the hospital are used in the hospital recovery framework that accounts not only for damage to the structural components, nonstructural components and other content, but also to other lifelines while considering the reliance of all lifelines on each other. This recovery process requires the inclusion of the constraints to repair each lifeline.

The sample hospital is six stories high in addition to a basement, as shown in Figure 2(a). The full design of the hospital was performed for an area with high seismicity under the direction of the National Earthquake Hazard Reduction Program (NEHRP) in accordance with American Society of Civil Engineers/ASCE 7-10: *Minimum Design Loads for Buildings and Other Structures*. The building relies on buckling restrained

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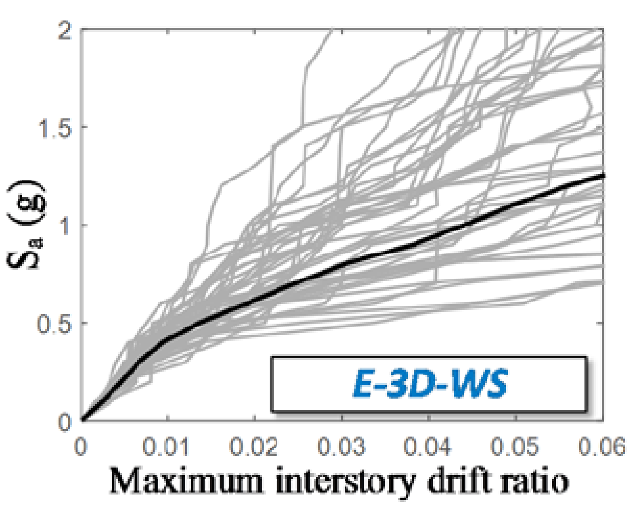
braces (BRBs) as the main lateral load-resisting elements. The beams and columns are connected using rigid, semi-rigid and pinned connections. Isolated footings are used to transfer the loads to the underneath soil, and reinforced concrete walls are used to support the outer steel columns at the basement level. The *Specification for Structural Steel Buildings* (ANSI/AISC 360) and *Seismic Provisions for Structural Steel Buildings* (ANSI/AISC 341), both available at **www.aisc.org/specifications**, were used to design the members and connections.

For the structural analysis, a 3D finite element model was used in a nonlinear dynamic analysis; a more simplified 2D model, assuming it can properly capture the behavior, could also be used. The 3D finite element model of the hospital was developed while accounting for various behavioral features including: 1) bilinear material behavior, as shown in Figure 2(b); 2) BRB core material behavior, as shown in Figure 2(c); 3) BRB connections—which are modeled using a group of springs to simulate the in-plane and out-of-plane behavior of each connection based on literature—as shown in Figure 2(d); 4) Rigid and the semi-rigid connections—which were modeled using springs based on 3D finite element models—as shown in Figure 2(e) and Figure 2(f), respectively; 5) Pinned connections, modeled using a multi-linear behavior based on literature, as shown in Figure 2(g); and 6) Soil-structure interaction, modeled using a beam-on-nonlinear-Winkler foundation (BNWF) model, as shown in Figure 2(h). In this study, the earthquake was assumed to strike the building in 2017, five years after its assumed construction date. The structural analysis of the hospital was performed using nonlinear incremental dynamic time-history analysis. The results of the analysis were then used to develop fragility functions for the hospital for the structural and non-structural components. Figure 3 shows the results of the incremental dynamic analysis and the nonstructural components drift-sensitive fragility functions.

Framework and Recovery Assessment

A discrete Markov chain process was used to estimate recovery for the various hospital building components such as corridors, elevators, stairs and structural and nonstructural components, through separating the functionality to different independent sub-levels. Since there are typical limitations in available resources following an extreme event, the resources are distributed to different lifelines based on their importance and significance to community recovery. The community resources, in the form of repair crews, are distributed among the previously mentioned lifelines to repair and return them back to the required functionality level. The distribution of the repair resources can be affected by several factors such as funding availability, the type of required repair and access to the damaged lifelines, among others. In this study, the factor influencing the repair sequence of the lifelines is their expected economic return for the whole community. This is a commonly used factor by decision-makers. The repair sequence starts with the structural components followed by the stairs, the elevators and the exterior elements such as partitions and claddings. The latter can be performed simultaneously with interior repairs to the piping, HVAC elements, partitions, ceilings, mechanical equipment and electrical systems. Since the focus of this research is on functionality of the hospital, an assumption is made that all repair sequences are the same for all lifelines.

The results for the hospital and supportive infrastructure repair recovery indicate that the assessment and planning stages for transportation, telecommunications and hospital were the lowest priority while for electricity, water and wastewater lifelines were the highest. The first lifeline to reach total repair recovery was transportation followed by electricity. Even though the electric network had the highest level of damage, it achieved full recovery quickly because of its importance to the



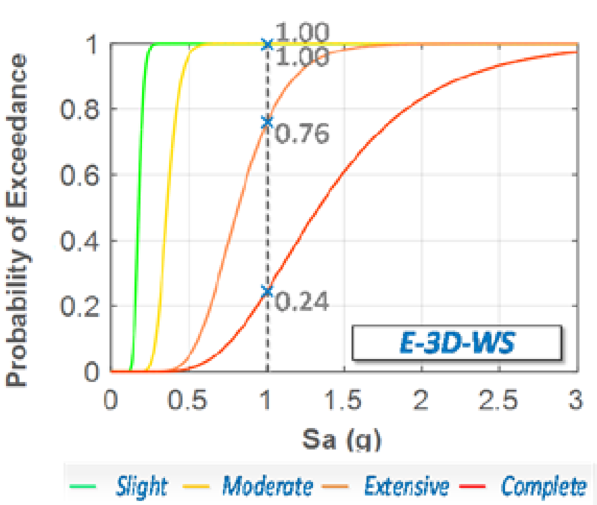


Figure 3. Hospital model: (a) incremental dynamic analysis and (b) nonstructural components displacement-sensitive fragility functions for various levels of damage.

repair of other lifelines. In addition, it's important to note that the functionality recovery rate for different lifelines depends on the assigned repair resources, which was determined using an optimization process.

Undoubtedly, reducing the recovery time of the hospital is a key design objective. From a structural standpoint, this can be achieved through collaboration between structural engineers and architects to reduce the structural and nonstructural damages as a result of the seismic event—i.e., the right shift in fragility reduces the probability of failures associated with structural and nonstructural components. Achieving this will require reduction of floor displacements and accelerations so that losses can be minimized, or by isolating damage to sacrificial components that can be easily replaced or repaired. For steel buildings, this might be realized through alternatives like using larger BRBs so as to stiffen the structure and shift its fundamental period from that of the expected earthquake records, which is typically marked by the ground motion and soil condition characteristics in the area.

Reparability

Steel buildings have historically performed well in seismic events, though every significant earthquake reminds engineers and researcher that there will always be room for improvement. While a return to functionality is of paramount concern when considering resiliency, a building owner may have an interest in the ability of a structure to withstand future events. In other words, how can the structural system be returned to its pre-event state?

Most mainstream structural seismic force-resisting systems currently in use in the U.S. accommodate the drifts associated a seismic event through inelastic deformation in primary structural components. While steel may not exhibit the obvious signs of degradation found in other materials, such as cracking and spalling, the cumulative inelastic strain capacity of steel elements is reduced once inelastic action resulting from a seismic event occurs. Quantifying the reduction in inelastic life is difficult at best in the absence of direct monitoring, which often leaves decision-makers with no choice but to remove and replace potentially damaged areas of a structure.

Removing and replacing portions of primary elements, particularly that have been welded into place, is an extremely costly prospect. Conversely, the idea of isolating damage to components that can be easily removed and replaced—e.g., the replaceable fuse concept—has been gaining more traction recently. We'll discuss this concept, as well as the results of the study, in further detail in our presentation. ■

This article is a preview of Session N1 "Resiliency and Reparability of Steel Systems" at NASCC: The Steel Conference, taking place April 11-13 in Baltimore. Learn more about the conference at ***www.aisc.org/nascc****.*