RESILIENCE AND EARTHQUAKE ENGINEERING

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Abstract

Achieving the "right amount" of resilience in structures and systems potentially subjected to strong earthquakes in their design life is an ideal but difficult goal, because of the inherent uncertainty of future earthquake activity and the pressure to reduce costs, especially for conventional buildings. I discuss some of the tradeoffs involved in choosing the design basis appropriate for life safety, recovery, and long-term resilience to reduce operational and business interruptions.

The paper discusses (1) the state-of-the-art in the finance, design, and construction of structures for resilience from an earthquake/structural engineering perspective, (2) existing conditions that make it difficult to achieve resilience beyond basics like life safety, and (3) approaches to achieve resilience at the right cost. The paper is based on first-hand experience and observations, over the last 45 years, with all of the professional disciplines involved in creating a more resilient built environment.

Introduction

Resilience for (1) structures and their non-structural components and (2) systems, such as lifelines, has not been adequately defined and addressed in the context of earthquake engineering. This also applies to other natural hazards and other extreme or infrequent incidents (or events), but this paper will be limited to earthquake engineering for the purposes of brevity and emphasis.

The concept of designing structures and systems to achieve a desirable and a safe level of resistance for earthquakes and other natural hazards has been around for a long time. In California and Japan, for example, the concept started developing in earnest after the 1906 San Francisco and the 1923 Tokyo earthquakes. More specifically, the response to the 1933 Long Beach, California earthquake redefined the concept of structural resilience for a specific class of buildings - school buildings. Further, the 1971 San Fernando, California earthquake and the partial collapse of the just completed Olive View Hospital redefined the concept of expected hospital performance (resilience). The replacement hospital survived the stronger 1994 Northridge earthquake without structural damage but suffered damage to critical equipment that led to the interruption of vital services. That, in turn led to the rethinking of business (operational) interruptions in hospitals and the need for enhanced system resilience. One of the outcomes was the development of the general concept of performance-based seismic design. Note, however, that the location of the 1994 earthquake, from the likelihood perspective, occurred in the least expected area of Los Angeles for the next major earthquake – close to the 1971 epicentral location. That played havoc with the concept of the return period for earthquakes but did not receive significant recognition at the time by both seismologists and the engineers who are the final users of updated seismology findings. Currently there are serious discussions and disagreements in seismology about the adequacy of the repeating earthquake model (characteristic earthquake model). For the most part, design engineers are not participants in that discussion. They should be.

Learning from Earthquakes

The pattern and development of enhanced natural hazards design following disasters, as discussed above, has relied on findings based on the failure of structures and systems after strong earthquakes. The engineering professions, till now, have consistently learned from failures during many investigations of the effects of earthquakes.

Engineers, however, have not adequately learned from successes observed in earthquakes. For example, following the 1985 M7.8 offshore Valparaiso, Chile earthquake and the success of taller shear wall buildings, design standards for taller buildings in Chile were in effect reduced due to pressure from developers to reduce "excessive" conservatism in order to reduce the cost of structures. That led to many total failures (and a few collapses) of new high-rise buildings in the M8.8 Maule, Chile earthquake, while the older taller buildings that survived the 1985 earthquake were generally not damaged. This is one of the better examples of not considering resilience in new design. It is interesting and encouraging, for Japan only, that this particular observation has not surfaced in recent major Japanese earthquakes, including the M9.0 2011 earthquake.

The M9.0 2011 Great East (Tohoku), Japan earthquake, however, also provides us with an extreme example of not learning from success - in Japan, the United States, as well as worldwide. Whereas engineers, and particularly the nuclear industry, have made use of the collected detailed information on the failure of the Fukushima Daiichi Nuclear Power Plant, they have almost completely neglected the success data from the Onagawa Nuclear Power Plant (and other infrastructure), which recorded stronger ground motion than the Fukushima plant, and was essentially undamaged.

In effect, we have made, and continue to make a fundamental omission in learning from earthquakes – we continue to miss "seeing the forest for the trees".

Coming back to the example of the engineering response to damage at the Olive View Hospital, the professions (and particularly structural engineers) continue to miss the bigger picture. The current emphasis in hospital design on attempting to assure the operability of individual hospitals, one at a time, again misses the bigger pictures. History has shown repeatedly that complex systems, such as an individual modern hospital, fail in earthquakes from a variety of major to minor failures, particularly of equipment. The lessons from earthquakes for hospitals, through the building code, have been applied to individual hospitals rather than to a "system" of hospitals. The Fukushima example has shown that no matter the level of design, failures will occur. History clearly shows that no hospital should be expected to remain operational. That leads to the simple conclusion that hospitals in the area of strongest ground motion must rely on assistance from nearby hospitals that have experienced lower ground motion and no significant damage. In effect, the lesson from earthquakes is that at some point higher earthquake design is not the solution. The additional solution is better emergency planning and response for what happens immediately after the shaking stops. In the case of hospitals that likely means quickly transferring critical patients to other, nearby and less affected hospitals. Resilience is equally applicable to individual hospitals and to the local health system.

It is interesting to note that the above lesson from earthquakes has been learned and applied more successfully in conventional electric power systems. In those systems the ceramic components of electrical equipment, particularly in substations, have proven so damage prone that the industry has responded in two ways – (1) strengthen the components, and (2) rely on emergency response planning, undamaged substations, and quick repairs to reroute power to customers. In other words, the industry is now focusing on seeing the bigger picture, or the response and the resiliency of the entire system.

Seismology and Resilience, or the Lack of It

A major weakness in earthquake engineering is the poor understanding of seismology, and particularly the probabilistic aspects of seismology, by the design professions. In preparation for this paper, I spoke with Professor Robert Geller, Professor of Seismology at The University of Tokyo. He made the following points, with which I agree completely:

1. In many cases the final decision for ground motions for design may be more or less reasonable but the process is not. Basically (to grossly oversimplify) the consultant gives the designer a number and as long as the structure meets that number everyone is off the hook. In his opinion the mindset has to be changed so that everyone involved in the process takes part ownership of the uncertainty.
2. In the case of ordinary structures, cost-benefit analyses suggest that some relatively small probability of exceedance (the consequences of which may be enormous) have to be accepted. At the extreme, as in the case of nuclear power plants, the consequences of exceedance can be so terrible that (i) extra margins should explicitly be added and (ii) to the extent possible, "fail soft" precautions in the event of exceedance should explicitly be built in.
3. What is missing in the design process, and particularly for resilience, is the fundamental and unavoidable uncertainties of seismology and ground motions. In particular, "maximum magnitude" is frequently used as a parameter in earthquake engineering, but unfortunately there's no such thing in the earth. Some further references on this subject are Kagan (1999, 2002) and Geller et al. (2013, 2015).
4. Engineers have to understand recent (past 20 years) developments in seismology and deal with the earth as it is, not as they would like it to be. This is essential!

The Building Codes and Resilience, or the Lack of It

In the sphere of earthquake engineering, including seismology, the current system of code development and code enforcement makes it difficult to achieve resilience beyond basics like life safety.

For earthquakes, the conventional building codes are not geared towards resilience, at the right cost, but towards life safety. Conventional buildings, from individual houses to the biggest buildings and high-rises, are designed to protect lives and are expected to suffer damage. Depending on whom you believe, these buildings are expected to suffer repairable damage to major damage (and possible collapse) that may lead to tearing down and replacement of the building at a great cost (as happened in the 2010 M8.8 Chile earthquake with brand new high-rises). That is not the case for special classes of buildings, like schools and hospitals, which, because of the higher design requirements for earthquakes, are expected to be occupiable immediately after the earthquake (but may still require some repairs, as again experienced in the Chile earthquake). This additional resilience is built-in for the safety of the occupants (schools and hospitals) and the continuation of critical operations (hospitals). The increased resilience has nothing to do with financial (cost-benefit) considerations. It is, in effect incidental resilience.

The codes are not yet driven by resilience. Worse, code development is often driven by compromises over political (i.e., material or manufacturer) special interests, rather than purely engineering concerns. That impedes our ability to improve resilience. Codes are also not driven by long-term and societal cost-benefit considerations and concerns with longevity. We, engineers, have learned that a higher level of design provides additional resilience, but we have not quantified the benefits. In the current environment, engineers are not expected to do that. The problem is that no one is expected to quantify the cost-benefit and apply it in a reasonable or optimal way to conventional buildings. In effect, no one is in charge of providing the optimal resilience for earthquakes.

Conventional buildings, again from houses to high-rises, are typically built to code and with the intent to sell in the short term. There is little, if any, incentive for a developer or a Real Estate Investment Trust (REIT), for example, to increase the level of design and the resilience because of the associated higher cost. The developer will not design and build beyond code, and the REIT will not acquire such buildings, unless everyone else does it. In other words, resilience will not happen because it is desirable. It will only happen if it is required or the public demands it. Increased earthquake resilience will only happen if it is quantified and found to be cost effective in the long run and to the benefit of society (as has been generally the case with life safety).

This is where the earthquake engineering profession has failed. We have not made an adequate public case that increased seismic resilience beyond the code and life safety is worth the price. We have learned again and again, following major earthquakes, that we can provide resilience at a minor to a reasonable cost. But we have not made the case public, and worse, we have not even convinced architects, the developers, and the owners or buyers, that we have a strong case.

My own experience is that when I presented in person the case for additional resilience to senior management of corporations and other large organizations, they usually agreed to accept the additional cost. I would summarize the engineering case in non-technical, business oriented language and keep it simple. Often, the main impediment for convincing senior management was their own engineering staff that was unwilling or unable to change.

Building a Better Case for Additional Resilience and Quantifying It

To build a better case for increased resilience, we must go beyond engineering and present a business case. We must do the following:

1. Determine the acceptable damage. Do we want the building to be immediately occupiable after the likely strongest expected earthquake? Do we want any acceptable damage to be repairable in one week, one month, more?
2. Determine the additional cost of increasing the capacity of the building to meet the selected criteria (beyond the current code requirements).
3. Determine the cost-benefit of the increased design criteria and the reduced damage. The cost-benefit analysis must include all possible benefits over the life span of the building, including:
    - Reduced direct damage,
    - Reduced down-time (reduced business interruption),
    - Reduced injuries or life-loss,
    - Reduced cost of property and casualty insurance and earthquake insurance (direct damage and business interruption),
    - Reduced reputational damage,
    - Reduced security costs,
    - Reduced litigation costs, etc.

Communicate the results to decision makers and the public in the appropriate technical and non-technical language. Typically, technical terms such as “ 2,500-year return period” completely defeat the case for additional resilience to non-engineers. In the public view taking a 2,500-year view is comparable to questioning the building design techniques of the Roman Empire. Keep it simple and relevant.

Engineers are typically not involved in making the above analyses. But the problem is broader than that. No one conducts these analyses. The insurance industry makes an attempt to do the analyses, primarily for the purpose of protecting their bottom line. These insurance analyses are based on generic assumptions and software, and are mostly aimed at the broader picture – the risk to the overall portfolio of insured risks, rather than the details of a specific building. Such analyses may or may not be adequate for specific risks and are not useful to an owner, or to the public in general. Often the analyses are counter-productive, as they provide the appearance of deep understanding of the risks and a security blanket to laymen and the public who do not understand the risks.

Speaking from personal experience, engineers are perfectly capable of doing the analyses needed to build better cases for resilience. With a few exceptions, they have not done it.

What Can Engineers Do Now?

As this paper follows the lead paper of this workshop entitled "Engineers: The Forgotten Stakeholder in the Resilience Conversation" by Jon A. Heintz of the Applied Technology Council of the USA, I will conclude with Jon Heintz's conclusion in his paper, with which I agree completely:

"As community leaders seek to develop long-term resilience plans that satisfy all interest groups, and researchers continue to advance our analysis and design technologies, engineers should use engineering principles (although not necessarily engineering language) to simplify the design challenges and help implement near-term steps leading to resilience. Since we know the desired outcome, it is time for engineers to take a leadership role, and once again make decisions on behalf of society to help it achieve what we know it wants."

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