Linking Next-Generation Performance-Based Seismic Design Criteria to Environmental Performance (ATC-86 and ATC-58)

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ABSTRACT

The Federal Emergency Management Association (FEMA) has sponsored a project by the Applied Technology Council (ATC) to develop next generation performance-based seismic design guidelines, FEMA P-58, that can be used to design new buildings or upgrade existing buildings to reliably and economically attain desired performance goals, and to assist stakeholders in selecting appropriate design performance goals for individual buildings (ATC, 2011). The project includes the establishment of a methodology for predicting the earthquake performance of buildings characterized in terms of probable life loss, repair costs and time out of service resulting from earthquake effects, expressed in a variety of formats useful to different stakeholders and decision makers. As part of this effort a Performance Assessment Calculation Tool (PACT) has been developed to gather and organize building information, perform loss calculations and evaluate loss information.

In the spring of 2011, the project was expanded with the initiation of the ATC 86 to develop a draft methodology to quantify the environmental impacts (in terms of carbon footprint and other measures) of seismic damage and potential environmental benefits of performance based seismic design and retrofit. The project team is currently developing strategies to link life cycle assessment data to the damage and repair estimates generated by the P-58 methodology and as of December 2011 is approximately half way through the project. This paper outlines the seismic and environmental performance measures being integrated by the ATC-86 team and identifies critical issues to address as the project moves forward.

INTRODUCTION

The FEMA P-58 Seismic Performance Assessment Methodology report developed by the Applied Technology Council under the ATC-58 project describes "a general methodology and recommended procedures to assess the probable earthquake performance of individual buildings based on their unique site, structural, nonstructural and occupancy characteristics. Performance measures include potential casualties, repair and replacement cost and schedule, and potential loss of use due to unsafe conditions. The methodology and procedures are applicable to performance-based design of new buildings, and performance assessment and seismic upgrade of existing buildings"(ATC 2011).

The purpose of the ATC-86 project is to develop a performance based environmental impact assessment methodology to integrate into the P-58 procedures and its companion Performance Assessment Calculation Tool (PACT). The ATC-86 methodology should account specifically for the environmental impacts of the probable earthquake damages and repairs predicted by the P-58 method. Life cycle assessment provides a natural framework for this purpose. Traditional life cycle assessment accounts for environmental impacts over an entire building life cycle from cradle-to-grave. It has not typically accounted for impacts due to earthquakes. P-58 provides a powerful tool for predicting earthquake damage and its consequences and offers a unique opportunity to quantify the probable earthquake impacts and add them to the full building life cycle assessment.

In the long term, a primary goal of the ATC-86 project is to help designers and their clients make more informed sustainable design decisions considering earthquake risks and the probable environmental consequences of earthquakes on buildings. The procedures and tools developed in future phases of this project should provide effective ways to measure the environmental benefits of more seismically resistant designs. They should enable comparisons between alternate designs and between retrofitted and un-retrofitted buildings. They should provide tools to evaluate the potential environmental benefits of rehabilitating older or earthquake-damaged buildings rather than demolishing and reconstructing them. They should eventually help green building rating systems, such as LEED and Green Globes, recognize and reward seismic designs in new buildings and structural rehabilitations that minimize environmental impact considering the building life cycle.

The target audience for this project includes practicing engineers and their clients, sustainable design practitioners, policy makers, standards developers, and academic researchers. The interim audience includes FEMA, practicing engineers, researchers and developers of the P-58 methodology who may wish to begin testing the potential effectiveness of the recommended procedures or who will implement the methodology to incorporate environmental impacts into P-58 and its companion computational tools.

CONCEPTUAL FRAMEWORK OVERVIEW

Environmental life cycle assessment procedures provide a framework for adding the impacts of probable seismic damage and repairs to traditional cradle-to-grave assessments. In order to add seismic impacts, an estimate of the probable earthquake intensities expected over the considered building life, a prediction of the probable seismic damage, and an estimate of the environmental consequences of the damage cleanup and repair are needed.

The P-58 assessment methodology provides tools for predicting the probable seismic damage and related consequences to individual buildings at specific sites with known seismic hazard. The P-58 methodology enables users to estimate the material damage to a building of a specific design and to predict the improvements in seismic performance and reductions in damage that can be expected from an improved seismic design. The P-58 tools predict the probabilities of a building suffering various quantities and dollar values of damages for given intensity, scenario or probabilistic earthquake events. The tools categorize the losses according to various structural and non-structural building component groups.

With a life cycle assessment approach, users can assess the environmental impacts of a building's initial design and construction. They can add to that the impacts of its operations over its life and the impacts of its end of service disposition. Then utilizing the P-58 methodology, users can consider the probabilities of earthquake shaking and the resulting damage. They can estimate the environmental impacts of the probable damage and repair and add those impacts to complete a whole building life cycle assessment. They can then repeat the process for alternate designs to compare the overall impacts and select an appropriate seismic design to reduce life cycle environmental consequences. Similarly, in the case of a seismic retrofit and building rehabilitation, users can assess the environmental impacts of the proposed retrofit and rehabilitation construction and compare that to the reduction in impacts achieved with better seismic performance.

In these procedures, the environmental impacts assessed can be limited to global warming potential (GWP) measured in CO_2 equivalent units, or can be expanded to include embodied energy, natural resource consumption, waste streams, and other measures of interest. The ATC 86 project proposes a methodology to integrate a broad spectrum of environmental impacts into seismic performance assessments in a rigorous and practical manner.

LIFE CYCLE ASSESSMENT

Life cycle assessment is a procedure for measuring the environmental impacts of products or processes over their full life cycles from cradle-to-grave. Environmental impact metrics typically include global warming potential, embodied and operational energy, natural resource consumption, waste generation and a broad range of environmental pollutant impacts.

The International Standards Organization in its ISO 14040 series (ISO 2006b,c) provides life cycle assessment guidelines. Buildings are considered products, albeit large products with long and uncertain lives, and are currently being assessed using these ISO standard life cycle assessment procedures. Significant effort is currently underway (ASTM, CEN, ISO) to develop standardized methods to use life cycle assessment specifically to evaluate the environmental impacts of buildings. The ISO 14044 standard defines four components of life cycle assessment relevant to buildings: goal and scope definition, life-cycle inventory, life-cycle impact assessment and interpretation.

Goal and Scope definition sets the goals and boundaries of the life cycle assessment by defining questions to be answered, alternatives to be compared, intended uses of the results, quality of data and peer review requirements, and the acceptable levels of uncertainty in the input and output. The goals statement addresses why the assessment is being performed, what is to be learned, who is the audience and what is the functional unit for comparison. The scope statement addresses what is included in the assessment, what is excluded, what are the boundaries and what are the environmental impact data sources. For the purposes of the P-58 and ATC-86 methodologies, the goal will typically be to assess the impacts of probable earthquake damage and to compare different seismic resistant designs or retrofitted versus un-retrofitted structures, considering functionally equivalent buildings.

Life-cycle Inventory lists all the energy and material flows associated with the material components during its life cycle. This inventory includes the input flows from nature and the output flows back to nature throughout the stages of the building life. . Life Cycle Inventory (LCI) databases exist that quantify average emissions for different material processes. In the context of the P-58 methodology, this inventory includes an input and output bill of materials (e.g., pounds of steel) and processes (welding) associated with earthquake damage clean-up and repair and the emissions related to each of these processes. The U.S. Life Cycle Inventory Database has limited LCI reports available for free download (NREL)

Life-cycle Impact Assessment combines interrelated emissions to report total potential of causing an environmental impact. For example, the Intergovernmental Panel on Climate Change publishes standard methods of reporting Global Warming Potential (GWP) by multiplying quantities of different greenhouse gas emissions (e.g. carbon dioxide, methane, etc.) by different factors to determine an equivalent carbon emission (CO_2e). This permits end users of LCA data to focus on relative potential impacts without understanding the details of relationship between different emissions and their potential environmental impact.

Interpretation involves evaluating the results of the life cycle assessment. That evaluation should include identifying major contributing processes and materials, assessing environmental impact data quality and uncertainty, and comparing results between alternate designs. Part of the challenge for the ATC-86 implementation will be to assure that the appropriate supporting information is provided to enable P-58 methodology users to interpret the data effectively so that it can be used in the design decision process.

INTEGRATING SEISMICITY INTO LIFE CYCLE STAGES

For the purposes of life cycle assessment, a building life cycle can be viewed as including several distinct stages in the cradle-to-grave spectrum. These stages can be identified as the material production stage, initial construction stage, the building use stage, and the end of life stage. They include the raw material extraction, transport, manufacture, construction, building operations, maintenance, repair, remodel, demolition, waste processing and disposal activities. Each of these stages and activities has environmental impacts that need to be accounted for in a life cycle assessment. Of these, only the impacts related to earthquake damage and repair will be addressed in the P-58 and ATC 86 methodologies. These earthquake consequences can be seen as a part of the repair and maintenance activity or as a separate repair activity occurring during the use stage of buildings. Design or retrofit of buildings for better seismic performance could thus reduce the damage related impacts.

The probability of damaging earthquakes occurring during a building's service life significantly influences the life cycle assessment of environmental impacts. The probability can range from very high to very low. In seismically active areas, the earthquake probability is relatively high over a 50 year to 100 year building service life; in less seismically active areas, the probability can be very low. If a significantly longer service life is expected, perhaps several hundred years in the case of a monumental structure, then the probability of damage occurring over the service life increases accordingly; whereas, if the structure is a temporary structure with a very short life span, the probabilities decrease significantly. Given these conditional probabilities, either an annualized probability or a cumulative probability of a damaging earthquake occurring over the life of a building becomes a useful way to evaluate the probable earthquake impacts.

The structural response of a building to an earthquake can be characterized by a set of peak response parameters occurring at different points throughout a structure, most typically acceleration and inter-story drift which can be calculated using traditional seismic analysis procedures. The P-58 methodology takes the values of these response parameters from structural analysis and probabilistically convolves them with fragility, consequence and hazard functions to form probability distributions for various earthquake impacts including repair cost, repair time, casualties and unsafe postings. The fragility relationships express the probability of specified levels of damage occurring at a given value of a response parameter (e.g., the probability of a joint failure occurring in a moment frame connection at a story drift ratio of 2%). The consequence functions project the probable amount of repair cost and time, and similar consequences, given that certain damage has occurred. The hazard function indicates the probability of different earthquake shaking intensities occurring in a time period. The FEMA P-58 report includes a companion computational tool, PACT, to assist in performing these probabilistic calculations.

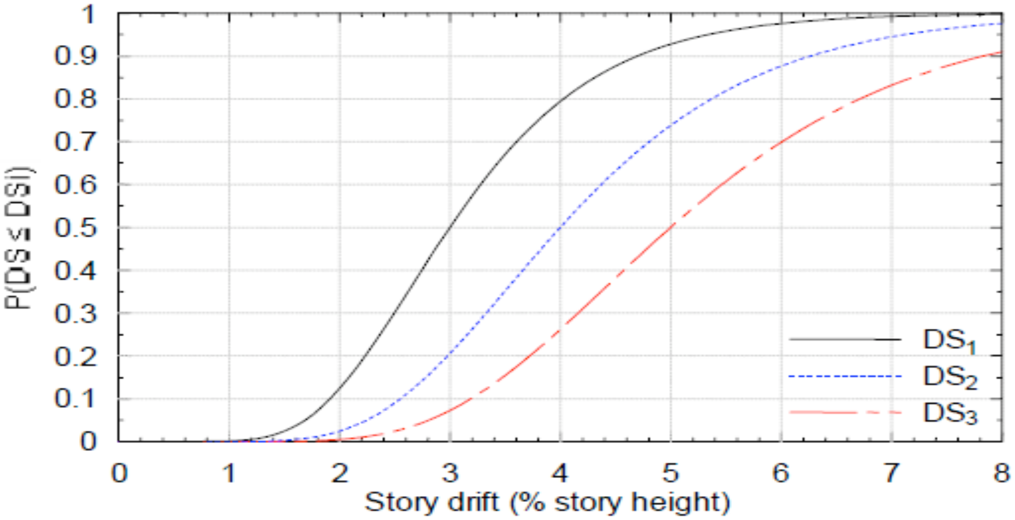

Figure 1: Fragility Relationship expressing the probability of incurring either of three component damage states (DS1, DS2, DS3) as a function of a response parameter, story drift ratio.

CURRENT STATUS

As of December 2011, a 50% draft of ATC 86 has been developed to outline methodologies to integrate life cycle assessment data and methods into FEMA P-58. In the process of developing the draft the following issues have been identified as worthy of further study and refinement:

1. Generating a bill of materials (BOM): Ideally the P-58 methodology will

generate a repair bill of materials giving estimated ranges of material and labor quantities needed for seismic repair. Databases that link the BOM to cost and environmental impact could thus be regionally customized, updated easily and transparent for user verification and customization.

2. Industry average LCI data: Use of national average LCI data seems appropriate for quantifying the environmental impacts of materials and products. Regional differences could be accounted for by using regional multiplication factors.
3. Characterizing Uncertainty: P-58 uses probabilistic methods to capture uncertainties in generating repair impacts. Uncertainty and variability in LCI data should also be captured to help users understand the statistical relevance when comparing differences between alternates.
4. State of Practice: LCA is not used in common practice in the building industry necessitating more background information and documentation to enable users to interpret results effectively.
5. Transparency: The lack of familiarity with LCA data requires that the analysis be more transparent than is necessary with more common metrics such as cost. While the PACT tool utilizes itemized cost estimates, the details of the estimates are not presented to the user. Users who have a sense of relative magnitudes of costs can be comfortable using data that intuitively seems to be in the right order of magnitude. Few users understand relative magnitudes of environmental impact and thus will likely require additional transparency on data documentation and calculation methodology to have confidence in the results.
6. Unique Post-Disaster Conditions: Average assumptions may be less relevant post disaster (materials and workers may travel farther, waste/recycling methods altered etc). Final methods should permit user to modify results to test sensitivity to these measures

LIMITATIONS

The ATC-86 project is not complete and thus the methodology and recommendations noted within this paper are preliminary and will be refined throughout the course of the coming year.

Assessment of a building's probable performance in future earthquakes involves significant uncertainty related to earthquake ground motions, structural response, and damage consequences. Assessment of environmental impacts due to earthquakes involves significant uncertainty related to the scope and extent of damage and repair, the means and methods of repair, and the measurement of the environmental impacts of the damage and repair. Assessment results are consequently uncertain. The selection and prioritization of the environmental metrics used to characterize the impacts can be done in different ways and should be adapted to the evolving current standards and to project circumstances and requirements.

Neither the Federal Emergency Management Agency, nor the Applied Technology Council, their employees, directors nor consultants present any warranty expressed or implied as to the methods and procedures proposed or the accuracy of the environmental performance assessments made based on the recommendations herein.

ACKNOWLEDGEMENTS

The authors are members of the ATC-86 project team and are greatly appreciative of the significant work that the FEMA P-58 team developed over the past ten years which serves as the basis of the ATC-86 project.

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