functional form of the equation proposed in ASCE-41 to estimate coefficient C_1 while additional third and fourth terms account for local reductions in C_R that take place for periods close to the fundamental period of vibration of the ground motion $(T/T_g \approx 1)$ and at periods close to the second mode of vibration of the soil deposit $(T/T_g \approx 1/3)$, respectively. Parameter estimates for using (3) can be obtained through nonlinear regression analysis employing statistical results such as those presented in this study. As an example, parameter estimates for (3) employing statistical results from the Mexico City ground motion ensemble are given in Table 2. Since C_R spectra computed from the San Francisco ground motion set does not show clear influence of second mode of vibration of the soil deposit, (3) could be simplified by taking into account only the first three terms. Thus, Table 3 presents parameter estimates obtained from nonlinear regression analysis.

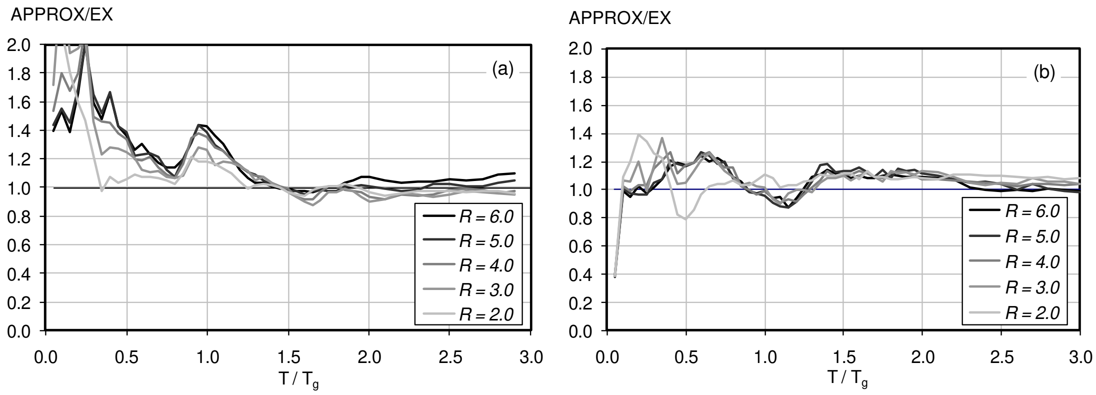

Figure 9. Mean error for computing inelastic displacement ratio provided by proposed equation of coefficient c1 for soft soil sites.

Again, to assess the accuracy of (3), mean ratio of proposed coefficient C_1 and C_R computed from the statistical study, $\bar{C}_1/C_R$, was obtained for each period of vibration, each level of relative lateral strength, and each record in both ground motion dataset. Figure 9 shows the error measure of using (3) for both soft soil sites. It can be seen that (3) significantly improves prediction of maximum inelastic displacement demand over the whole spectral region. Good improvements in prediction of maximum inelastic displacement demands are obtained for systems having periods of vibration longer than about 1.5 times the predominant period of the ground motion when using (3) and parameter estimates given in Table 3. Overestimation of maximum inelastic displacement demand for systems having periods of vibration shorter than the predominant period of the ground motion could be attributed to the record-to-record variability in this period range as well as the missing fourth term in the functional form. Improvement in the estimation of (3) could be obtained when more earthquake ground motions recorded in the San Francisco Bay Area are available.

Table 2. Parameter estimates summary for equation (3).

Parameter	R = 2.0	R = 3.0	R = 4.0	R = 5.0	R = 6.0
θ_1	1.096	1.104	1.119	1.148	1.149
θ_2	3.685	4.489	5.674	7.083	8.608
θ_3	2.0	2.0	2.0	2.0	2.0
θ_4	-0.640	-1.023	-1.197	-1.307	-1.341
θ_5	-4.5	-4.5	-4.5	-4.5	-4.5
θ_6	-0.05	-0.05	-0.05	-0.05	-0.05
θ_7	-0.589	-0.578	-0.562	-0.537	-0.522
θ_8	-14.914	-52.803	-132.146	-177.709	-211.622
θ_9	0.67	0.67	0.67	0.67	0.67

Table 3. Parameter estimates summary for equation (3).

Parameter	R = 2.0	R = 3.0	R = 4.0	R = 5.0	R = 6.0
θ_1	1.0	1.0	1.0	1.0	1.0
θ_2	7.237	9.015	10.443	12.414	14.553
θ_3	2.1	2.1	2.1	2.1	2.1
θ_4	-0.227	-0.355	-0.404	-0.475	-0.531
θ_5	0.038	-0.502	-0.750	-1.421	-1.709
θ_6	-0.08	-0.08	-0.08	-0.08	-0.08

CONCLUSIONS AND FUTURE RESEARCH

The purpose of this study was to evaluate the Coefficient Method, suggested in ASCE-41 standard (2007) for the seismic assessment of existing buildings, for estimating peak roof inelastic displacement demand of typical steel office buildings built on soft soil conditions. From this investigation, the following conclusions are offered:

1. The Coefficient Method slightly underestimate median peak roof inelastic displacement demands of a 3-story frame model ($T_1 = 1.0s, c_y = 0.25$), it tends to overestimate median peak roof inelastic displacement demands of a 6-story frame ($T_1 = 1.3s, c_y = 0.20$) around 15%.
2. A careful examination of coefficient C_1 (i.e. the ratio of peak inelastic displacement demand to peak elastic displacement demand) suggested in FEMA 440 recommendations highlight that it tends to underestimate or overestimate statistical results obtained from the nonlinear response of constant-relative strength single-degree-of-freedom systems subject to earthquake ground motions recorded on very soft soil conditions. The level of underestimation or overestimation depends on the level of relative lateral strength and the fundamental period of vibration of the system.
3. It was shown that the record-to-record variability involved in the estimation of the ratio of peak inelastic displacement demand to peak elastic displacement demand can be reduced when the predominant period of the ground motion T_g is considered in the estimation of the ratio.

4. An enhanced functional form of coefficient C_1 that take into account predominant period of the ground motion T_g is proposed to be incorporated in the Displacement Method for the seismic assessment of existing buildings built on soft soil conditions.

ACKNOWLEDGEMENTS

The author would like to express their gratitude to *Universidad Michoacana de San Nicolás de Hidalgo* in México for the support provided to develop the research reported in this paper.

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Resilience Criteria for Seismic Evaluation of Existing Buildings: A Proposal to Supplement ASCE 31 for Intermediate Performance Objectives

David Bonowitz, S.E.[1]

[1] 605A Baker Street, San Francisco, CA 94117, (415) 771-3227, dbonowitz@att.net

ABSTRACT

Earthquake resilience, the ability to respond to and recover from a damaging event, is gaining currency as a performance metric even for non-“essential” facilities. Resilience can be measured as the time needed to restore basic operations. Yet our standards for seismic evaluation do not explicitly address recovery time.

This paper proposes new evaluation criteria to address questions of resilience. The proposed criteria will help distinguish and prioritize likely seismic deficiencies, grouping them by their impact on recovery time. The criteria use the standard known as ASCE 31 as a platform, building on its procedures and terminology and extending its use to resilience planning.

WHAT IS RESILIENCE?

Earthquake resilience, simply put, is the ability to recover from the effects of a defined event. While more sophisticated descriptions have been proposed (for example, by Tierney and Bruneau, 2007), this simple definition is sufficient for introducing the idea of resilience into structural engineering practice.

More resilience means the ability to recover basic operations faster, sooner, in less time. Engineers familiar with the ATC-58 project will recognize “downtime” as one of three categories of potential earthquake losses, along with casualties and direct economic costs (ATC, 2007). It is easy to imagine how the three loss types are related, but they impact a client’s mission differently. Collapse is certainly more dangerous to life than downtime, but downtime is far more common. Damage to finishes is often costly to repair, but downtime can be more disruptive. Thus, a client’s attention to resilience might result in different decisions regarding building purchase, lease, occupancy, or retrofit.

Importantly, resilience is an attribute of an organization, not a building. It requires emergency preparedness and continuity of operations planning. Still, buildings and structures play an important role, and one that is often overlooked.

Growing interest, but no standard. More clients, from homeowners to small businesses to local governments, are thinking about recovery time. Some, especially in the public sector, have indirectly raised the issue through emergency plans that set recovery targets (with or without assessment of current capacity). Others, especially businesses, have begun to address the concern through risk management. A relative few are working toward explicit and well-defined – though unique – recovery goals. Some recent efforts from the San Francisco Bay Area:

- Community-based social service organizations need to be active in disaster response and recovery, but codes and regulations treat their facilities as typical commercial or residential buildings. Fritz Institute is working with Bay Area service providers and philanthropies to set standards for Disaster Resilient Organizations (Bonowitz, 2008).

- UC Berkeley, after working to ensure earthquake safety throughout its campus, has recognized that its mission is also at risk due to potential downtime in funded research. The University has adopted an earthquake recovery goal of 30 days (Comerio, 2006).

- On a larger scale, San Francisco Planning + Urban Research has built on the city's stated recovery goals to develop a resilience-based mitigation agenda (SPUR, 2009).

All of these efforts, however, are limited by the available engineering tools. Building codes remain focused on safety. By assigning buildings to Occupancy Categories our code presents a vague policy about post-earthquake use, requiring higher design loads for "essential" facilities (CBSC, 2007, Table 1604.5). But the provisions (especially for new construction) are prescriptive, not to mention inflexible and opaque. Besides, they merely imply which facilities should be available *immediately*. All others, presumably, should have no expectation of being usable within any prescribed time.

Our standards for existing buildings, ASCE 31 (2003) and ASCE 41 (2006), consider objectives such as Immediate Occupancy and Life Safety but still do not deal explicitly with recovery time. Most businesses can afford to close for a week for clean up, but not a month or more. Social service providers and government offices are not essential in building code terms, but people rely on them to be recovered within weeks of a damaging event. We can check a building against our Life Safety or Immediate Occupancy standards, but what about these cases in between?

So while structural engineers – and our clients – are motivated to think about downtime and recovery, we lack the tools to turn motivation into routine practice.

Solutions in concept. Despite their shortcomings, the available codes, standards, and policies offer ideas that inform our thinking on resilience.

- From building codes comes the common sense notion that not all buildings should be held to a single set of requirements.

- From our performance-based standards comes the idea of an explicit objective linking measurable quantities to a specified earthquake hazard (for example, Life Safety in a "10% in 50-year" event).

- From emergency plans that envision a phased restoration of services comes the time dimension essential to resilience.

A first-generation resilience assessment tool should combine these ideas. To start engineering for resilience, we need a tool focused on recovery time, with specific, repeatable criteria, and covering a range of user-chosen objectives.

What should the assessment tool produce? Ideally, we would like to look out over, say, the next twenty years and know with, say, 80% confidence that a given facility will not have to suspend operations for more than, say, 3 days after any event. A tool to generate or justify such a statement would be remarkably powerful.

As it happens, such a tool is in development through ATC-58, and its pieces exist in various forms today. But its promise is limited by two obstacles. First, we lack a robust database of resilience observations from past earthquakes with which to calibrate the device. Second, so many externalities affect actual recovery time that quantitative downtime predictions would be questionable in any case. Therefore, it is perhaps wise to focus less on quantitative prediction than on qualitative planning. That is, it might be more feasible to produce a tool that can find vulnerable or critical conditions, as opposed to one that can predict actual earthquake response.

So a first-generation resilience assessment tool might be valuable even if it can answer only the following question, given a facility and a resilience objective stated as the time allowed for recovery after a specified event:

> **What existing conditions are expected to prevent this facility from supporting the user's resilience objective?**

Beyond this intention, effective criteria should also:

- Adapt to a range of conditions, typical and not,
- Be prescriptive enough to yield repeatable findings
- Allow useful distinctions between facilities
- Allow quick and cost-effective assessment
- Mesh with existing guidelines, codes, and standards.

Among our available tools, ASCE 31 comes closest to offering all these features. Its Tier 1 procedure (this paper presumes a working knowledge of ASCE 31) is widely used, even if many practitioners perceive it as overly conservative. It focuses the evaluator on issue-spotting, not analysis, and it generates consistent and fairly thorough output.

A STRAWMAN PROPOSAL

A first-generation resilience assessment tool can be built on the platform provided by ASCE 31's Tier 1 procedure. From the foregoing discussion it's clear that ASCE 31 and its Tier 1 Evaluation Statements will need to be adapted in several ways:

- New resilience objectives, stated in terms of recovery time, will need to be defined and coordinated with the Life Safety (LS) and Immediate Occupancy (IO) terminology. In particular, Tier 1 scope distinctions based on seismicity and performance objective will need to be reviewed.

- Each Evaluation Statement will need to be reviewed, and possibly reformulated, to focus on recovery and continuity of operations.

- Each Evaluation Statement will need to be categorized with respect to the proposed time-based resilience objectives.

- More attention will need to be given to building contents (which are distinct from nonstructural components).

New resilience objectives should take the established form of a performance "level" paired with a defined hazard. With ASCE 31 as a platform, the hazard is already defined, since ASCE 31 applies only one level of shaking (the ASCE 41 BSE-1, but with differences on the capacity side). The resilience level to be paired with this shaking must incorporate time as a measurable quantity.

Time is not a familiar metric to structural engineers. The temptation is to measure time as precisely as we might calculate stress or deflection, but as discussed above, such an emphasis is fraught with uncertainty and ignorance. My proposal is to begin developing resilience criteria with these somewhat fuzzy "levels" of recovery time:

Hours (H), Days (D), Weeks (W), Months (M)

If a client's recovery objective is more aggressive than Hours, then the Immediate Occupancy criteria (or probably something even more conservative) should apply. If the desired recovery time is longer than Months, then the Life Safety criteria, which already capture the kinds of damage that take that much time to repair, should be sufficient.

The proposed resilience levels can thus be thought of as intermediate ASCE 31 performance levels – states between LS and IO. More properly, recovery time should be considered a dimension semi-independent of safety or economy (as ATC-58 and others suggest), but the notion of intermediate performance levels is acknowledged as fair and useful at this stage, if only to preserve coordination with the ASCE 31 standard.

Modifying the ASCE 31 Evaluation Statements for resilience assessment means understanding them in terms of their implied impact on downtime and recovery. Each Statement suggests a damage pattern that would be expected in non-compliant cases. These damage patterns can have varying effects on recovery. If the implied effect is small, the damage pattern and the Evaluation Statement in question can be considered relevant only if the resilience objective is aggressive, such as Hours. If the implied effect is large, the Statement might be relevant even if the resilience objective is more relaxed, such as Weeks or Months.

In other words, if you don't need to recover for Weeks, then any effect that takes only hours or days to assess, clean, and repair is acceptable. If you need to restore basic operations in Hours, then almost any damage other than nominal clean-up might be critical.

So the criteria development process involves the following syllogism for each ASCE 31 Evaluation Statement:

> **How long will it take to recover from the damage implied by this Evaluation Statement? Is the expected recovery time longer than the resilience objective? If so, this Evaluation Statement is critical.**

Table 1 lists considerations that might be applied judgmentally to ASCE 31 Tier 1 Evaluation Statements to determine the objectives for which they are critical.

Table 1. Recovery issues critical to different resilience objectives

Recovery issues presented by various damage patterns	Resilience objectives for which the issues are likely to be critical
Cosmetic damage, especially in unused areas Loss of expendable items Light clean-up or non-hazardous debris removal	Moot (ignore)
Substantial clean-up not requiring outside crews Blocked egress due to contents damage	Hours
Extensive clean-up or non-hazardous debris removal Remaining falling hazard, removable Special repair required	Hours, Days
Heavy or hazardous clean-up Replacement or repair by specialty contractors Other damage requiring vacancy to effect repair	Hours, Days, Weeks
Structural or geotechnical damage making building unsafe to occupy Irreparable nonstructural damage Remaining hazard requiring specialty inspection & repair	Hours, Days, Weeks, Months

This way of thinking leads to an interesting observation about Life Safety as defined by ASCE 31, and the relative significance of structural and nonstructural damage. Certain structural deficiencies that ASCE 31 tags as critical for LS performance might not threaten recovery at all. For example, some conditions that would lead to cracking or fracture but would not render a building unsafe to occupy during repair would be moot in resilience terms. Meanwhile, many nonstructural conditions that can be ignored for safety are critical in terms of downtime. Thus, for some resilience objectives, reasonable criteria might ask for less than structural Life Safety but more than nonstructural Life Safety.

Why is this? Primarily, it's because recovery is only partly about completing repairs. More often it's about resuming the basic or normal operations of the tenants. Thus, to be recovered, the building's structure merely has to stand stable, but its nonstructural systems have to function. This is the same reason why post-earthquake safety inspections will often "green tag" a house with pronounced stucco cracks, but "red tag" a house with a broken sewer line.

EXAMPLE RESILIENCE CRITERIA

The proposed process for criteria development will have different implications for different categories of Evaluation Statements. These are discussed below. First, however, it might be useful to see an example of how the proposed process would work generally.

Table 2 shows how a sample of ASCE 31 Evaluation Statements might be reviewed and developed into resilience criteria. The first column shows all six Evaluation Statements given in ASCE 31 for ceiling systems. The second column describes the damage pattern apparently contemplated by ASCE 31. The third column makes a judgmental assessment of the work needed before the damaged space could be reoccupied for normal tenant functions. The final column then shows which resilience objectives, if any, would be affected by such recovery measures.

In this example, three of the Statements – the ones associated with light damage, easily cleaned up – are probably irrelevant to resilience. These Evaluation Statements could then be ignored by a resilience assessment.

The other three – regarding Support, Integrated Ceilings, and Suspended Lath and Plaster – are judged to result in perhaps weeks of downtime. Therefore, they would only be unacceptable to a client with a resilience objective of Hours or Days. For clients with less urgent objectives, these Statements could be ignored or exempted by the assessment.

Table 2. Derivation of resilience criteria for ceiling systems from ASCE 31 Evaluation Statements

ASCE 31 Evaluation Statement	Implied Damage Pattern	Recovery Issues	Resilience Objectives Affected
SUPPORT: The integrated suspended ceiling system shall not be used to laterally support the tops of gypsum board, masonry, or hollow clay tile partitions.	Partition damage due to inadequately supported top edge. Localized ceiling damage unlikely to affect occupancy.	Partition repair, debris removal. Removal of remaining falling or egress hazard posed by damaged partitions, likely doable in weeks.	Hours Days
LAY-IN TILES: Lay-in tiles used in ceiling panels located at exits and corridors shall be secured with clips.	Loose or fallen ceiling tiles at exits and elsewhere. Possible egress hazard pending clean-up.	Light clean-up, likely doable by building staff in hours.	Moot
INTEGRATED CEILINGS: Integrated suspended ceilings at exits and corridors or weighing more than 2 pounds per square foot shall be laterally restrained with a minimum of four diagonal wires or rigid members attached to the structure above at a spacing of equal to or less than 12 ft.	Loose or fallen ceiling pieces, HVAC ducts, or integrated light fixtures, at exits and elsewhere. Possible egress hazard pending clean-up.	Clean-up, likely by outside crews. Investigation and removal or repair of remaining falling hazards. Likely doable in weeks.	Hours Days
SUSPENDED LATH AND PLASTER: Ceilings consisting of suspended lath and plaster or gypsum board shall be attached to resist seismic forces for every 12 square feet of area.	Loose or fallen ceiling, often over assembly areas. Damage to historic finishes. Egress and falling hazard.	Clean-up, likely by outside crews, possibly with hazmat concern. Dust and noise. Removal of remaining falling hazard. Likely doable in weeks, if not hazmat.	Hours Days
EDGES: The edges of integrated suspended ceilings shall be separated from enclosing walls by a minimum of ½ inch.	Localized ceiling damage. Loose or fallen ceiling pieces.	Light clean-up, likely doable by building staff in hours.	Moot
SEISMIC JOINT: The ceiling system shall not extend continuously across any seismic joint.	Localized ceiling damage. Loose or fallen ceiling pieces.	Light clean-up, likely doable by building staff in hours.	Moot