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EVALUATION OF EARTHQUAKE DAMAGE IN WOOD-FRAMED STRUCTURES

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ABSTRACT

The 2009 *International Building Code* (IBC) includes explicit triggers that will require seismic strengthening of an entire building when damage levels to the vertical elements of the lateral force-resisting system exceed certain quantitative thresholds. These triggers, which are defined as a function of *reduction in lateral load-carrying capacity*, are applicable to all building types and to all structural systems. The term *reduction in lateral load-carrying capacity* is a term of art that has received relatively limited attention from the structural engineering profession; for most structural systems there are no established or published procedures for physically assessing or computing this reduction. This paper reviews available literature and explores rational methods for determining strength loss and providing economical repair for wood framed buildings with gypsum-sheathed shearwalls. These buildings are of interest because of the large inventory of these buildings in states with high levels of seismic hazard.

Introduction

Breaking with decades of precedent the 2009 *International Building Code* (IBC) (ICC 2006) includes explicit triggers that will require seismic strengthening of an entire building when damage levels to that building exceed certain quantitative thresholds. These triggers, which are defined as a function of *reduction in lateral load-carrying capacity*, are applicable to all building types and to all structural systems, whether or not the damaging event was an earthquake, regardless of the intensity of the event that might have caused the damage, and regardless of any evidence that may exist about whether the system being evaluated has historically demonstrated adequate performance. To complicate matters, the term *reduction in lateral load-carrying capacity* is a term of art that has received relatively limited attention from the structural engineering profession; for most structural systems, there are no established or published procedures for physically assessing or computing this reduction. For most systems, therefore, engineers tasked with assessing *reduction in lateral load-carrying capacity* will need to first identify relevant published laboratory test data, and then interpret the data in a manner consistent with fundamental principles of earthquake engineering and structural mechanics, and with the physical evidence exhibited by the building of interest, to generate the quantitative values required by the IBC.

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Large inventories of California wood-framed structures, whose lateral force-resisting systems consist largely of shearwalls sheathed with gypsum board, have experienced earthquake ground shaking. A substantial number of these have been located in regions of strong or very strong shaking, at or exceeding code demands, especially during the 1971, 1989, and 1994 earthquakes. In spite of the high levels of ground shaking, these structures have largely escaped severe structural damage of the type that potentially threatens occupant safety, other than those exhibiting significant defects in configuration or load path. Moreover, many of these structures were not designed with any engineered lateral force resisting system until the 1970s, and even today many such structures are built using the conventional construction provisions in the code, requiring no engineering. Yet even for these structures with little definable lateral force resisting system other than gypsum- or stucco-sheathed shearwalls, documented earthquake performance has been sufficient to protect occupant safety, the implicit performance goal of the IBC.

This paper focuses on the earthquake response of the group of buildings braced by gypsum-sheathed wood framed shearwalls. This group is important because of the very large inventory of these buildings and the significant ramifications of incorrectly assessing the *reduction in lateral load-carrying capacity*. Based on their history of generally good performance in earthquakes, an overly conservative interpretation of *reduction in lateral load-carrying capacity* will create unnecessary cost and disruption to occupancy for large numbers of buildings. An unconservative approach could fail to identify the subset of significantly damaged shearwalls. This paper explores rational methods for determining *reduction in lateral load-carrying capacity* of gypsum-sheathed wood framed shearwalls and for appropriate repair of the subset of walls that sustain a significant reduction.

Literature Review

Since the 1970s there have been numerous testing programs addressing the in-plane behavior of gypsum-sheathed shearwalls, some under cyclic loading regimes but most under monotonic loading. Three of these programs are summarized below to provide background for following discussions. It should be noted that none of the experimental test programs described employed certain construction details that are common in wood-framed buildings in California, such as inclined blocking, or let-in bracing. Where present in real buildings, these elements no doubt play a role in the behavior of gypsum board sheathed shearwalls in which they reside.

Freeman, 1971

One early example of a cyclic testing program is found in Freeman (1971, 1977), where fifty-four wall panels with metal or wood studs, thirty-four of which were sheathed with gypsum wallboard on both sides, were subjected to in-plane cyclic loading. The goal of the testing program was to characterize damping, stiffness and strength contributions of partitions in high-rise buildings, so the test setup was designed to simulate shear deformation of the panels only, with pinned links between the guide beam at the top and the base plate. With the general exception noted above, the details of the tested assemblies are largely consistent with the details of typical gypsum board sheathed shearwalls in service throughout California. Freeman found that the partition walls added considerable damping and measureable strength and stiffness to buildings, that these effects could be considered in analysis, and that the onset of damage requiring repair occurs at drifts between 0.5% and 0.75%, with minor separations commencing at 0.25% drift. Figure 1 illustrates hysteretic behavior of a gypsum-sheathed shearwall from this testing program.

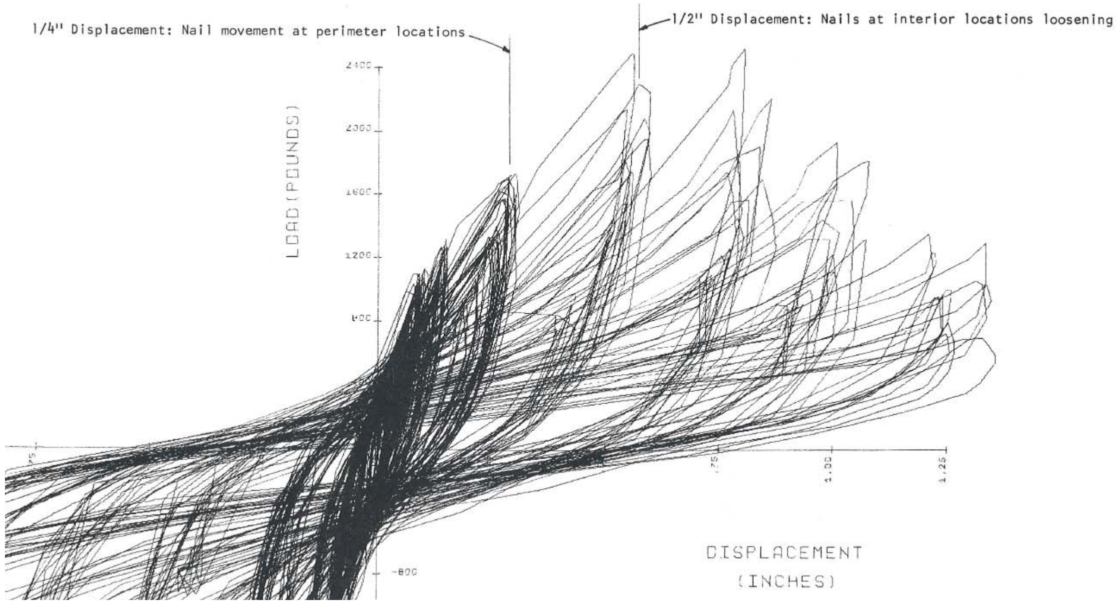

Figure 1. Hysteretic load-deflection behavior of gypsum-sheathed wall tested (Freeman 1971).

CoLA-UCI, 2001

Following the 1994 Northridge, California Earthquake, the Structural Engineers Association of Southern California (SEAOSC) Research Committee formed a subcommittee known as the *CoLA-UCI Light Frame Test Committee*, in conjunction with the University of California at Irvine, and funded by the City of Los Angeles. The CoLA-UCI committee developed a testing program for wood-sheathed light-frame shearwalls, following observation of damage to these walls during the 1994 Northridge earthquake (CoLA-UCI 2001). The testing program employed a version of the Sequential Phased Displacement (SPD) loading protocol, and incorporated new construction requirements that the LADBS had been enforcing following the Northridge Earthquake. The research program included testing of just two panel types with gypsum-only sheathing, that are relevant to this paper.

Loading Protocol - The SPD-based loading protocol's displacement history is based on the First Major Event (FME), defined as the point at which the "load resistance of the wall, upon recycling to the same wall displacement, first drops noticeably from the original load resistance at the same displacement." The FME was estimated prior to start of loading, based on earlier tests. At the completion of testing, the Yield Limit State (YLS) was derived based on the test load at which a 5% drop in load occurred when recycled to the same displacement. By these definitions, both the YLS and the FME are clearly stiffness-based parameters (as opposed to strength or capacity-based parameters). The SPD protocol involves cycling through levels of displacement which are 25% increments of the FME. Because the FME is itself a small increment of the displacement, this protocol results in the test specimens undergoing scores of cycles of loading at very small increments of displacement. Although the test specimen failure modes were not provided in the CoLA-UCI report, later studies observed that the SPD protocol can result in low-cycle nail fatigue failure, which has rarely been observed in real earthquake damage, due to the large energy demands created in the loading regimen. (Cobeen *et al.* 2004) The results of tests employing SPD should therefore be viewed with caution, and may not be particularly useful in studying the effects of real earthquakes on real structures.

Test Specimens - The CoLA test specimens lacked "floor system" framing, either at the specimen base or top, and included no cross walls or flange walls such as those typically present in constructed buildings. Thus, the specimen boundary conditions are not representative of actual conditions of most in-service gypsum board sheathed shearwalls. Of principal interest, the tests employed tie-downs at the end of the walls built for the tests. The tie-downs were designed to be extraordinarily stiff and were constructed of ¼-inch steel plates as compared to the lighter steel used for fabrication of typical steel tie-downs. This created uplift restraint much stiffer that used in most gypsum-sheathed shearwall tests. This configuration forces the specimens to deform with only shear-related displacements neglecting flexural and uplift contributions due to flexibility at the wall ends. The rigidity of the tie-down connection was such that the test report warns that the results of the tests are not applicable to walls constructed without similar restraints. For the two groups of gypsum-sheathed walls, nailed at four and seven inches on center, the mean drifts reached at YLS were 0.108 and 0.087 inches respectively, and the strength limit states (peak capacities) were reached at 0.559 and 0.356 inches. The very low displacements determined by the tests appear to have been influenced by the extraordinary stiffness of the tie-downs, which prevented the base of each specimen from globally rotating and/or uplifting under load, as well as the large number of loading cycles. Later CUREE testing by Gatto and Uang (2002) illustrated the impact of CoLA protocol in reducing peak strength and displacement at peak strength.

CUREE-Caltech Woodframe Project, 2001-2004

Two experimental programs were undertaken as part of the CUREE-Caltech Woodframe Project (Pardoen *et al.* 2003, McMullin & Merrick 2002). The first program tested 28 walls, just two of which were gypsum sheathed on both sides. McMullin & Merrick (2002) tested seventeen walls, all of which were gypsum sheathed on both sides, with either nail or screw fasteners. Both of these experimental programs used a cyclic loading protocol developed as part of the CUREE program (Krawinkler *et al.* 2001). The CUREE loading protocol was developed specifically for wood-framed shearwalls to more accurately represent the energy associated with seismic loading corresponding roughly to a 10% probability of exceedance in 50 year California-style earthquake, and thus promote failure modes consistent with those observed after earthquakes in California. In McMullin & Merrick (2002), no tie-downs were used in the test setup and instead, a pair of 1⅜-inch diameter bolts was installed at each end of the wall, next to a 4x6 post designed to simulate the resistance provided by intersecting partition walls. According to the report, a gypsum sheathed shearwall will experience no damage up to a drift level of 0.24% and be able to sustain a maximum drift level of around 2.5%, corresponding to a usable ductility of perhaps 5 or 6. These values (both the drift level at which damage begins to occur, and the ultimate drift level that can be sustained by the walls) far exceed those identified by the CoLA-UCI testing program. The differences appear to be attributable to the efforts of the CUREE to configure the specimens with more realistic boundary conditions and more representative loading protocols.

Other Studies

Deierlein et al. 2003 - As a compliment to the CUREE test program, an analytical investigation was carried out to predict damage to gypsum board sheathed shearwalls. The analyses concluded that cracking in gypsum wall board initiates at the corners of window and door openings, reach 1 inch in length at drifts between 0.05% and 0.1%, and grow to 12 inches at 0.3 to 0.7% drifts. It should be noted that these are the very areas also most likely to experience cracking due to shrinkage, thermal, and settlement effects.

Hart et al. 2008 - In addition to testing programs described above, a summary paper was recently published that attempts to interpret the significance of the experimental data in the CoLA-UCI and CUREE tests (Hart *et al.* 2008). This summary paper re-examines the data compiled by the earlier studies and the purports to provide an "extension" of those studies. In the paper, the authors scrutinize individual test specimen hysteretic curves prior to attainment of the maximum load. They tabulate loads corresponding to the first, second and third excursion to a specified top of wall displacement, and then characterize the decrease in load for second and third excursions as a loss in strength. In fact, what they are identifying is instead a loss in *stiffness* in the re-loading curve. This loss in re-loading stiffness is an inherent characteristic of hysteretic behavior, seen in testing of virtually all seismic force-resisting systems, across all construction materials. This reduction in reloading stiffness should not be confused with a reduction in peak capacity. In addition, descriptions of physical damage seen in testing of gypsum sheathed walls are quoted, and it is suggested that the transient drift experienced by buildings be estimated based on observed damage. It is further suggested that loss of strength and stiffness can be derived from the estimated peak transient drift.

What is "Structural Capacity"?

The technical meaning of the term "capacity" has obvious import, given the 2009 IBC requirement that a value for reduction in lateral force-resisting capacity be computed in order to determine whether global seismic strengthening is required in the course of repairing a damaged building. Employment of an invalid technical definition of the term will necessarily result in an incorrect computation of "reduction in lateral-load carrying capacity" and an incorrect application of the IBC trigger. A clear definition of the technical meaning of the term is therefore essential.

Within the fields of structural mechanics and structural engineering, the term "capacity," when used with respect to a force or a moment (as opposed to a deformation), is synonymous with the term "strength", such as in the underlying physical significance of the concepts of compressive strength, tensile strength, and shear strength (Gere and Timoshenko 1997). These terms necessarily signify the *peak* (meaning maximum) load on the load-displacement curve, or some arithmetic estimate of that peak. There can only be one peak capacity defined per curve (ignoring the occasional second order effects strain hardening and geometric stiffness). While the term "strength" can be preceded by a modifier intended to define some other point on a load-displacement curve, such as yield strength, unless it is preceded by a modifier, "strength" or "capacity" will always signify the *peak* load on a load-displacement curve.

Defining Reduction in Structural Capacity

One of the seismic strengthening triggers contained the 2009 IBC is invoked when *reduction in lateral load-carrying capacity* of a building exceeds 20%. This trigger is in the process of being increased to 33% for the 2012 IBC in part due to the fact that the 20% trigger was deemed by the structural engineering community as being too low and thus too easily exceeded. In order to determine a reasonable trigger, a method of determining capacity reduction has to be defined. Because these triggers are articulated as a percentage, evaluation of whether or not the triggers have been exceeded requires that the total pre-damage lateral load-carrying capacity of the building be computed. For buildings with gypsum-sheathed shearwalls, calculation of *reduction in lateral load-carrying capacity* will therefore necessarily involve estimation not only of the contribution to lateral capacity of the gypsum wallboard sheathed walls, but also of any plywood and stucco sheathed walls that also contribute to the strength of the building. Thus, calculation of *reduction in lateral load-carrying capacity* is not properly assessed on a wall-by-wall or line-of-lateral-resistance basis; instead the effect of damage on the global capacity within each affected story of the structure must be assessed.

The intent of seismic design provisions in the IBC is to minimize earthquake-related risk to life. This is found in the NEHRP Provisions (FEMA 2003) from which the seismic design provisions are drawn. To meet this intent, the seismic design provisions focus on minimizing probability of building collapse at the maximum considered earthquake. Attention is inherently focused on the peak capacity of the lateral force-resisting system, along with displacement capacity and ductility. Loading protocols that have been developed to evaluate the seismic resistance of lateral force-resisting elements (Krawinkler *et al.* 2001), have acknowledged that structures may be subjected to a number of loading cycles due to smaller earthquakes prior to the design-level or maximum considered earthquake. The loading protocols incorporate this concept by including a number of loading cycles to smaller displacements, prior to reaching peak capacity cycles. As discussed previously in this paper, displacement cycles may also be driven by other long-term load types such as structural deflection or foundation movement. When subject to the design level or maximum considered earthquake, it is anticipated that vertical elements of the lateral force-resisting system will be pushed to near peak capacity, or perhaps beyond, as per FEMA P-750, Part 3, Technical Paper 11 (FEMA 2009). Most seismic force-resisting elements are intended to have some post-peak residual capacity, however once pushed near or past peak capacity, the element should be evaluated for possible major repair or replacement.

Based on this understanding of intent, the Hart *et al.* tabulated reductions in load at second and third excursions to the same displacement are not relevant to the determination of reduction in structural capacity, and should not be considered. The Hart study attempts to embellish the concept of strength by essentially suggesting that cyclic load-displacement curves define an infinite number of "strengths," at all displacement amplitudes represented on the curve. These embellishments, however, fundamentally obfuscate the fundamental and well established differences between strength and stiffness, which are quite distinct and ought not be confused in engineering practice. Take the example of the cyclic loading curve for a gypsum-sheathed shearwall in Figure 1. At successive crossings of any particular displacement amplitude (for amplitudes less than that associated with the peak load for the wall), the load being resisted by the element at that displacement decreases slightly. Hart suggests that any such reduction is tantamount to a "reduction in strength" or a *reduction in lateral load-carrying capacity* of the element. This characterization, however, incorrectly conflates terms with long-established distinct technical meanings; in fact, the noted reductions reflect only changes in stiffness at small displacements of the element in response to cyclic loading, and do not affect the "strength" or "capacity" of the element, much as cracking of reinforced concrete elements on the way up the loading curve has no effect on their strength. Note also in Figure 1 that after a series of cycles to a given displacement, when displacements are progressively increased, the load being resisted by the element increases progressively until the maximum capacity (i.e. strength) is reached.

Hart suggests that the amount of drift of a wall element at which the second cycle of deformation does not generate the same load as the first cycle is the threshold for structural damage requiring repair. Hart fails to acknowledge that the response of most structural systems to relatively small loads and displacements involves some reduction of stiffness, such as when minor cracking of a concrete system occurs; this in no way affects the global performance or maximum capacity of the element or system and has been long been accepted by the structural engineering community as not of structural significance and explicitly considered in structural stiffness calculations. Contrary to Hart's suggestion, for appropriate application the IBC trigger, reduction in capacity must be related to reduction in peak capacity that would affect the earthquake-related risk to life in future events.

Identifying Reduction in Structural Capacity

As discussed above, laboratory studies that employed realistic boundary conditions and loading protocols indicate that the peak capacity of gypsum wallboard sheathed wood framed walls develop peak capacity (strength) at a drift in the range of 0.5 to 0.7%. As the wall element is deformed beyond this range the load developed decreases, declining to about 70% of the peak at a drift of approximately 1%. Thus IBC triggers correspond to a peak drift of between 0.7% and 1%. With a sufficiently robust and accurate model of a specific building and recorded site-specific ground motions, combined with some invasive field observations, it would certainly be possible to determine the peak drift sustained by that building. Under laboratory conditions, numerical models can be calibrated to experimental results. The state of the practice has not advanced to the point where numerical analysis can be used to economically and reliably determine the peak drift sustained by a specific building. Nor will there be sufficient resources available following a major earthquake to perform such analyses on 100,000 or more buildings.

As a practical matter, the peak drift and any corresponding loss of strength can be reasonably determined by visual examination of damage patterns and comparison of those damage patterns with patterns recorded in laboratory tests of similar walls (McMullin and Merrick 2002, Arnold *et al*. 2003 & 2005); to effectively do this, however, significant attention must be paid to differentiating pre-earthquake damage to the panels. The CUREE publication *General Guidelines for the Assessment and Repair of Earthquake Damaged Structures* (CUREE 2007) presents a set of criteria based on visual inspection of wall finish damage that can be used without aid of a technical consultant to determine whether the observed damage is clearly non-structural or the observed damage indicates the potential for structurally significant damage. In the event of the latter, it is recommended that the services of a suitably qualified engineer be retained to assess the structural significance of the damage and determine if the IBC trigger has been exceeded. The CUREE thresholds for recommending assessment by an engineer have been intentionally set quite low, to ensure that structurally significant damage is not overlooked. It is expected that many, if not most, of the buildings evaluated by engineers will have little or no damage of structural significance.

Hart *et al* (2008) proposed to use damage descriptions by Deierlein *et al*. (2003) to estimate peak transient drifts due to an earthquake ground motion, and therefore postulate reduction in strength and stiffness. Hart notes that the analyses concluded that cracking in gypsum wall board initiates at the corners of window and door openings, and reaches 1 inch in length at drifts between 0.05% and 0.1%, and grows to 12 inches in length at 0.3 to 0.7% drifts. Hart then juxtaposes these analytical predictions with the CoLA-UCI tests, from which the YLS was found to occur at equivalent drifts. According to the CoLA-UCI definition of the YLS, buildings that commonly experience tiny 1-inch long cracks shortly after construction due to shrinkage of lumber, or due to settlement effects, have already experienced a 5% loss in strength.

Since cracking of this type can be found in nearly every new wood-framed building before it is even punch-listed, the definition of YLS would appear to be meaningless in a practical sense because construction of these types of walls literally cannot occur without the concomitant occurrence of such cracking. The same can be said of 12-inch long cracks, which occur fairly regularly in new multi-story wood-framed construction, although not as frequently as 1-inch long cracks. According to the definition postulated by CoLA-UCI, walls exhibiting cracks of this sort even prior to occupancy and in the absence of any earthquake have already experienced a double-digit loss of strength. Even if the definition of YLS and FME were to be consistent with long-established engineering theory and practice, the definitions would have no practical application because of the "loss of strength" they would postulate for nearly every such wall under everyday loading conditions.

Repair of Damaged Gypsum-Sheathed Shearwalls

According to the 2009 IBC (and the 2012 IBC), a building whose *reduction in lateral load-carrying capacity* does not exceed the specified thresholds may be repaired without seismic strengthening, which means that the building may be repaired "in-kind." After repairs are completed, the building is permitted to have the same level of seismic resistance that it had prior to the damaging event, and engineering calculations of seismic demand and resistance are not required to design the repairs. If the IBC thresholds are not met, the provisions of the 2009 IBC permit seismic strengthening to achieve greater seismic resistance, however such improvements are considered to be voluntary. Methods of construction that are appropriate to the goal of simply returning the building to its pre-damage lateral resistance are therefore relevant to discuss.

Various types of earthquake damage that may be exhibited by gypsum-sheathed shearwalls were well-documented (McMullin & Merrick 2002, Deierlein & Kanvinde 2003) (CUREE 2007). Damage to gypsum-sheathed shearwalls resulting from other types of loads such as foundation settlement, framing deflection, etc. are generally similar to those catalogued therein. Generally, damage involves either cracking of panel joints or corner beads, cracking of wallboard panels, “popping” of fasteners, or some combination of these.

CUREE (2007) provides guidance on the type of damage patterns and repairs that can be undertaken without involving a technical consultant for the evaluation of damage. Damage included in this category includes cracks up to 1/8-inch wide, through the gypsum board, and nail pops.

The following recommendations are drawn primarily from Table 5-1 of the CUREE guidelines, with some additional comments and suggestions from the authors of this paper. Short cracks up to 1/64-inch wide should be repaired by patching and refinishing. Cracks following taped joints and corner beads should have the tape and joint compound removed and replaced. Because the cracking of the joint may also be associated with very localized damage to the wallboard at the fastener attachments adjacent to the joint, it is both reasonable and cost-effective to re-fasten the edge of the panel along that joint at the same time the repair is being made. If sufficient shifting of the adjacent panels has occurred such that the gap between the panels had widened by more than 1/16-inch to its pre-damage condition, it is prudent to re-fasten the entire panel.

Cracks up to 1/8-inch through the gypsum board should be repaired by removing and replacing the gypsum board to nearest studs beyond the crack (32 x 48 inches minimum). When small sections are replaced, they should be blocked and adequately fastened. If evidence exists that the fasteners for the damaged panel have been “worked”, re-fastening the sheet can be incorporated into the repair. Fastener “pops” can be repaired by replacing or re-setting the existing fastener.

When earthquake damage is beyond that described above, the CUREE guidelines recommend involvement of a technical consultant to evaluate the level of damage and recommend repair methods. Such evaluation and repair are based on the objective of the code in minimizing earthquake-related risk to life, as discussed previously in this paper.

Conclusions

The determination of *reduction in lateral load-carrying capacity* for use with the 2009 IBC triggers will be pivotal to those involved in the repair of damaged buildings. It is important that rational and uniform interpretations of this term be made in order to provide appropriate safety to repaired buildings, without imposing overly conservative requirements that will be very costly and significantly delay re-occupancy of buildings. This paper has explored available information, discussed inappropriate interpretations, and suggested directions for more appropriate interpretations and repair approaches. Continued development of appropriate damage assessment and repair criteria across all lateral force-resisting systems is very much needed.

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