Seismic Design Coefficients & Considerations When Using ASCE 7 For Seismic Retrofit

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Introduction

Although ASCE 41 is the national consensus code for seismic evaluation and retrofit of existing buildings, ASCE 7, intended for new building design, is sometimes used instead of ASCE 41 for evaluation and retrofit. The provisions in ASCE 7 are not intended to be used to mitigate deficiencies in existing structures. ASCE 7's objective is to produce reliable new structures that pose a low risk of collapse due to natural hazards like earthquakes and hurricanes. While ASCE 41 is the most appropriate tool for existing buildings, this paper provides guidance on how to use ASCE 7 to evaluate and retrofit existing buildings to address some of the critical questions and considerations that arise when using a new building design standard for existing buildings. To this end, seismic force-reduction factors are recommended for common existing building types that do not strictly meet the definition of a structural system as defined by ASCE 7.

Historical Context

The development of modern building codes and advances in computing software have allowed the earthquake design of new structures to be relatively simple, prescriptive and consistent. Today's seismic design requirements for new buildings are codified in ASCE 7 and material standards like ACI 318. These codes prohibit severe structural irregularities, require prescriptive material-specific detailing requirements intended to ensure ductility, and require chain of custody on materials and inspection during construction. These code provisions are the result of learning from past earthquake damage, decades of research, and tireless efforts of largely voluntary code writing committees. Design professionals and building officials are familiar with the design provisions for new structures like ASCE 7 and therefore often apply ASCE 7 rules to existing buildings. However, often existing buildings do not meet the prescriptive requirements for use of ASCE 7.

The predecessor to ASCE 7, ATC-3-06 (1978), recognized that significant engineering judgement is needed to effectively retrofit an existing building: "The analysis [of existing buildings] shall be based insofar as possible to the seismic design of new buildings. When these design provisions for new buildings are not applicable to existing buildings, deviations shall be permitted by the Regulatory Agency." The void implicit in this ATC-3-06 language spurred the development of FEMA 273 (1997), "[FEMA 273] contains systematic guidance enabling design professionals to formulate effective and reliable rehabilitation approaches […] applicable to all types of existing buildings and in all parts of the country that have never existed before." This effort has been further developed in FEMA 356 (2000), ASCE 31-03, ASCE 41-06, ASCE 41-13 and now ASCE 41-17, which all offer explicit guidance for an engineer to effectively retrofit an existing building.

Unfortunately, the ATC-3-06 language recognizing the difference between new design and seismic retrofit was not carried into the Uniform Building Code. The UBC (and later the IBC, IEBC and Historic Building Code) has for the most part referred to its own code provisions for new building design as the requirement when a seismic retrofit is triggered. This oversight was recognized early on by many jurisdictions, including the Federal Government, Division of the State Architect (DSA), The Office of Statewide Health Planning and Development (OSHPD) and the University of California to name a few, who have historically referred to ASCE 41 (and its predecessors) as the standard for seismic retrofit. Over the past twenty years, the majority of jurisdictions have followed suit and, it has become common practice in high seismic areas to use ASCE 41 in lieu of ASCE 7. However, it is still somewhat common practice in parts of California to use ASCE 7 as the basis for seismic retrofit. Furthermore, the recent mandatory seismic retrofit ordinances for Soft Story and Non-Ductile Concrete buildings in Los Angeles allow the use of ASCE 7 as an alternative to ASCE 41 to achieve compliance. In the wake of these ordinances, this paper offers guidance for engineers when using ASCE 7 to retrofit existing buildings to avoid blunders that produce under conservative results.

Considerations for All Seismic Force Resisting Systems

Retrofit designs based on ASCE 7 often ignore, overlook or oversimplify four fundamental aspects of seismic engineering: building irregularities, deformation compatibility of existing non-ductile elements with new structural systems, consideration of diaphragm strength, and adequacy of existing foundations. While ASCE 41 offers explicit guidance on these fundamentals, the engineer using ASCE 7 is left with minimal, conflicting or improper direction to ensure an effective retrofit in the absence of the prescriptive design and detailing requirements afforded to new buildings.

Structural vulnerabilities that have led to building collapse in past earthquakes have been some combination of a lack of ductility, a lack of redundancy, a lack of strength in critical elements, and major structural irregularities. Major structural irregularities tend to exacerbate seismic damage in buildings with a lack of redundancy by focusing seismic deformations in plan locations and floor levels with limited non-ductile lateral force-resisting elements. ASCE 7 prohibits the worst structural irregularities in high seismic regions and penalizes others. When approaching a retrofit using ASCE 7, the engineer should mitigate the irregularities not permitted by ASCE 7 and apply penalties associated with irregularities as applicable per ASCE 7 Table 12.3-1 and Table 12.3-2. Some structural irregularities affect building performance more than others. As such, applying ASCE 7 methodology to mitigate or penalize irregularities can result in an inefficient design.

Applying ASCE 7 methodologies could result in an ineffective retrofit as well, because ASCE 7 assumes a certain amount of inherent ductility. For example, simply applying “ordinary” R-factors to an existing structural system may greatly overestimate the ductility of that system. Consequently, the engineer is strongly urged to use either methodologies specifically developed for structural irregularities (such as the IEBC or FEMA P-807) or ASCE 41 which requires advanced analysis for certain types of irregularities rather than prohibiting them outright.

It is common practice to evaluate the lateral force-resisting system in existing buildings using R-factors of “ordinary” systems, and then retrofit using R-factors for “special” systems while often ignoring the contribution of the existing lateral force resisting system. As will be addressed in subsequent sections of this paper, the evaluation approach of using “ordinary” R-factors, which are most often too high for the building’s actual detailing, can often lead the engineer to conclude that a building’s existing lateral force resisting system is sufficient where it is actually deficient. Conversely, some engineers disregard existing non-ductile building systems not permitted by ASCE 7 Table 12.2-1 completely, as the elements would not be permitted to be used as a lateral force-resisting system in a new building. While it’s good practice to be wary of relying on a non-ductile system, it may be possible to justify the existing system provided it has a low enough ductility demand.

Where retrofit is deemed necessary, the approach of discounting the existing lateral force-resisting system can sometimes lead to overly conservative retrofits where too much strength (but sometimes not enough stiffness) has been added to the structure. Conversely, in buildings with stiff existing lateral force resisting systems, this approach can lead to retrofits where considerable softening and damage to the existing lateral force-resisting system (and sometimes the gravity system) has to occur before the new system is engaged. When apportioning a seismic retrofit, it is critical to consider the deformation compatibility of the existing lateral force-resisting system and gravity system to ensure their damage state under ultimate seismic deformations will not lead to partial collapses or global building instability. In the displacement-based design approaches of ASCE 41, deformations compatibility is considered explicitly; while in the force-based approach of ASCE 7, considerably more judgement is required because ASCE 7 assumes and is tuned for ductile detailing in the entire structure. The following procedure is therefore recommended when using ASCE 7 to conduct seismic retrofits:

- Establish an R-factor for the existing lateral force resisting system based on the least ductile characteristics in the elements expected to undergo inelastic actions.
- Establish an R-factor for the new lateral force resisting system.

- Create a building model (or mathematical representation) for the combined system.
- Run an analysis on the model with the combined system with the R-factor of the existing lateral force-resisting system to check the existing system.
- Run an analysis on the model with the combined system with the R-factor of the new lateral force resisting system to check the new system.
- Increase stiffness and/or strength of the new system until both systems are found to be sufficient[1].
- Calculate inelastic story drifts using $R = C_d$ and limit them to 1% unless it can be shown by the engineer that existing elements can sustain larger drifts. If the inelastic drifts are less than 1%, it is reasonable to assume that building collapse will not initiate with the failure of gravity elements in most cases. Still, the engineer should exercise judgement with respect to the 1% limit in cases of unique or extreme non-ductile detailing (such as compression-only lap splicing in columns). Note that gravity elements, like columns under discontinuous walls, that are directly affected by forces in the lateral force resisting system should be evaluated per the irregularity requirements of ASCE 7.
- If drifts are larger than 1%, evaluate gravity elements for forces from and analysis where $R = C_d$[2] to ensure that the elastic capacity of these elements has not been exceeded.
- Check the diaphragms and foundation per the recommendations below and strengthen as required.

After apportioning the retrofit of the lateral force resisting system, it is essential that a seismic load path be provided that allows the lateral force-resisting system to be fully engaged. It is important to remember that introducing strength and stiffness into a structure changes the building's dynamics, and that if the lateral force resisting system is inadequately tied into the building, seismic damage will concentrate in the diaphragm and critical collector connections at the lateral force-resisting system. In this manner, it's not only possible to design an ineffective retrofit, but it is possible to design a retrofit where the building's seismic performance is worse off after the retrofit is implemented than before.

ASCE 7 uses the same R-factor as the lateral force resisting system as it does for the diaphragm design, with minimum and maximum forces. It is implicit in new building design that the diaphragm design force levels in ASCE 7 §12.10.1.1 effectively impose significant ductility demands on diaphragms. In the most recent code cycle, it was recognized that the current ASCE 7 approach is unconservative[3] for diaphragms with limited ductility capacity. An alternate diaphragm design approach has been included in ASCE 7-16 which accounts for the ductility capacity of the diaphragm more explicitly, and this approach will be required for pre-cast concrete diaphragms under the 2018 IBC/2019 CBC. When using ASCE 7 to retrofit an existing building, it is recommended that the alternate procedure in ASCE 7-16 §12.10.3 be used when examining chords, diaphragm and collectors. It is noted that a diaphragm design force reduction factor for bare metal deck was not included in Table 12.10-1 of ASCE 7-16. When a bare metal deck is encountered, it is recommended that a diaphragm design force reduction factor of 1.5 be used[4].

Foundation design occurs at the intersection of the structural engineering profession and geotechnical engineering profession. Currently, foundations in most new structures are designed using the same R-Factor as the superstructure when using ASCE 7. This practice has been recognized as potentially un-conservative particularly for deep foundations and very high R-Factor lateral force resisting systems, and

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[1] ASCE 41 methodology allows more damage to the existing lateral force resisting system where it can be classified as a secondary element or when non-linear analysis is used. Because ASCE 7 uses a system approach versus a component based approach, it is not possible to reliably discount individual elements of the existing lateral force resisting system. Consequently, this approach may be unnecessarily conservative for certain types of existing lateral force resisting systems.

[2] This check will essentially ensure that gravity elements do not yield at the point where the building has reached its ultimate seismic displacement. Most gravity elements, even those without ductile detailing, have some measure of ductility capacity so this check may be overly conservative. However, without conducting a component based analysis as in ASCE 41, or providing prescriptive ductile detailing requirements of new buildings, this conservatism is warranted. ASCE 41 procedures explicitly allow for ductility demand in many types of gravity elements, and thus an ASCE 41 type approach will often lead to a more economical retrofit.

[3] See ASCE 7-16 C12.10.3.

[4] Based on the testing that was done to develop ASCE 7-16 Table 12.10-1, this is the value that would have been included. However, it was thought that this low value as compared to plywood diaphragms would discourage the use of bare metal deck, so it's inclusion in Table 12.10-1 was blocked by affected parties.

there are currently efforts underway in the ASCE 7 development process whereby undesirable foundation failure mechanisms like punching or 1-way shear failures would be prohibited. The foundation system would consequently be designed with a different R-factor than the lateral force-resisting system.

ASCE 41 currently contains provisions to assess the stability of a foundation system. However, ASCE 41 Chapter 10 currently considers concrete foundation elements as having force-controlled failure mechanisms to be evaluated for no ductility capacity. Because of the broad-brush approach on all foundation elements, ASCE 41 often classifies even ductile foundation mechanisms as force-controlled actions resulting in evaluations that conclude retrofit is necessary even though engineering judgement might determine otherwise. ASCE 41 currently allows capacity-based concepts and ultimate bearing pressures to determine the maximum forces that can be delivered to the foundation, along with using the smallest m-factor in the load path to the foundation element (when using linear procedures). ACI 369, the technical update committee for concrete provisions in ASCE 41, has a focused effort to develop foundation-specific ductility capacities to be available in future editions of ASCE 41.

Given the lack of rational guidance currently available in both ASCE 7 and ASCE 41, considerable care and judgement is necessary when evaluating and retrofitting existing foundation systems. Until specific guidance is available, when using ASCE 7 to evaluate and retrofit existing buildings, it is recommended that the foundation system be evaluated for stability using the same R-Factor as the lateral force resisting system. Similarly, it is recommended that relatively ductile foundation mechanisms like flexural hinging of fully developed reinforcement in a deep pile foundation, or flexural yielding in a shallow foundation system be evaluated using the same R-Factor as the lateral force resisting system, or an R-Factor that is appropriate for the mechanism(s) occurring in the foundation system. For non-ductile component actions such a shear failure, however, assessing foundations at overstrength level forces is recommended. Regardless of the methodology and judgement used by the engineer in assessing and retrofitting an existing foundation system, it is important that the foundation system not be ignored.

In conjunction with the considerations mentioned above, the engineer should follow prescriptive requirements of new building design when using ASCE 7 for existing structures. For example, importance factors, redundancy factors, and other force amplifications should be applied similar to new building design. Also, minimum specified material properties and strength-reduction factors (ϕ) should be applied. Where As-Built construction drawings are not available or do not contain specified material properties, lower-bound properties based on mean-minus-one-standard-deviation are recommended based on a material testing program to be consistent with minimum specified properties in the new building code.

Considerations for Structural Steel Seismic Force Resisting Systems[5]

When using ASCE 7 to conduct a seismic retrofit of an existing steel structure, the following seismic design coefficients are recommended for commonly occurring lateral force resisting systems in existing buildings:

Table 1.1 – Design Coefficients for Structural Steel Systems

LFRS	R	Ω_o	C_d
Fully Restrained Moment Frame[6,7]	2.2	2.0	2.2
Partially Restrained Moment Frame[8]	1.8	1.5	1.8
Eccentrically Braced Frame	2.4	2.0	2.4

[5] R-Factors developed from the lowest applicable ASCE 41-13 m-factor multiplied by $(f_{ye}/f_y)/\phi$ not to exceed the applicable R-Factor from ASCE 7-10 Table 12.2-1

[6] In Welded Flange Plate systems, an R-Factor of 1.0 is recommended per ASCE 41-13 Table 9-4 where it cannot be shown that the failure mechanism of the connection is not flange plate net section failure.

[7] Many types of Fully Restrained Moment Connections, even those with "Pre-Northridge" detailing, can warrant the use of higher R-Factors. It is acceptable to alternatively use 1.2* the value listed under ASCE 41-13 Table 9-4, under the column "Primary" & "LS" in lieu of 2.2. If an R-Factor higher than 2.2 is used, Cd be set equal to R, and Ωo should be taken as the minimum of R and 3.0. In no case should an R-factor taken higher than that for Steel Ordinary Moment Frames as defined in ASCE 7 unless approved by the building official.

[8] Depending on the type of Partially Restrained Moment Connection, and the limit state of the connection, the use of higher R-Factors may be warranted. It is acceptable to alternatively use 1.2* the value listed under ASCE 41-13 Table 9-4, under the column "Primary" & "LS" in lieu of 1.8. If an R-Factor higher than 1.8 is used, Cd be set to equal R, and Ωo be taken as the lower of R and 3.0.

(EBF) Link Beam[9,10]			
Concentrically Braced Frame (Including Tension-Only Bracing)[11,12]	3.5	2.0	3.5

Footnotes contained within Table 1.1 apply to recommendations.

Considerations for Reinforced Concrete Seismic Force Resisting Systems

SEAOSC published a design guide for Non-Ductile Concrete (NDC) Buildings in 2016. The user is referred to the SEAOSC design guide for more extensive recommendations for Design Coefficients and other considerations when conducting a retrofit using ASCE 7. It is not within the scope of this document to summarize all recommendations of the SEAOSC NDC Design Guide, but it is important to note there should be significant limitations for evaluating an existing reinforced concrete structure using the seismic design coefficients for "ordinary" systems from ASCE 7 Table 12.2-1. In many cases, the use of much lower R-Factors is more appropriate.

As noted in the design guide, the following restrictions should be made when applying the noted seismic design coefficients:

- Detailing of beams and columns should comply with ACI 318-14 chapters 9 and 10, and walls should conform to Chapter 11 unless otherwise noted below.
- Reinforcing bars must be deformed, and the deformations must conform to modern requirements (ASTM A305-49 and more recent).
- Reinforcement lap splices shorter than the ACI 318 straight development length in tension without consideration of lap-splice classification may be acceptable if it is shown that no inelastic seismic action is expected at that location based on limit-state analysis or there is sufficient capacity for overstrength (Ω_0) demands.
- Global instabilities and the consequences of failure of critical non-ductile concrete elements and connections not in conformance with current code requirements must be considered.
- Lateral systems that are not recognized by ASCE 7 default to the "Non-Ductile" systems shown in the table below. The R, Ω_0, and C_d values are consistent with historical values the City of Los Angeles has used for voluntary seismic retrofit of non-ductile concrete buildings.

Table 1.2 – Design Coefficients for Structural Concrete Systems

LFRS	R	□o	C_d
Ordinary Reinforced Concrete Moment-Resisting Frame[13,14]	3	2.5	3
Ordinary Reinforced	4	2.5	4

[9] Depending on the length of the link beam, considerably higher R-Factors may be warranted. It is acceptable to alternatively use 1.2* the value listed under ASCE 41-13 Table 9-4, under the column "Primary" & "LS" in lieu of 2.4. If an R-Factor higher than 2.4 is used, Cd be set to equal R, and Ωo be taken as the lower of R and 2.5.

[10] The capacity of the beam-outside-the-link, the brace, and the columns in the EBF frame should be checked to ensure that they can develop the capacity of the link beam. Should any of these elements fail before the link beam, an R, Cd & Ωo of 2.0 be used.

[11] Connections be checked to develop the tension capacity of the brace. If the connection cannot develop the tension capacity of the brace, an R, Cd & Ωo of 1.0 per ASCE 41-13 9.5.2.3 be used. Note that even in "ordinary" steel systems, current AISC detailing requirements protect the connection from premature failure.

[12] Beams at chevron braces be checked for the unbalanced loading condition where one brace buckles in compression simultaneously with the other brace yielding in tension per AISC requirements for "ordinary" concentrically braced systems.

[13] At least two longitudinal bars are provided continuous along both top and bottom of beams, and developed at face of support, with the continuous bottom bars not less than one-quarter of the maximum bottom bar area along the span.

[14] Column clear height is not less than 5 times its largest dimension. If less than 5 times column dimension, the columns should be shown to be flexure-controlled in accordance with ACI 318-14 section 18.3.3a or that the shear capacity is adequate for load combinations including the overstrength factor in accordance with ACI 318 Section 18.3.3b.

Concrete Shear Wall[15,16,18]			
Shear Wall-Frame Interactive System with Ordinary Reinforced Concrete Moment Frames and Ordinary Reinforced Concrete Shear Walls	4.5	2.5	4
Reinforced Concrete Moment-Resisting Frame not meeting footnotes 14 and 15	1.4	1.4	1.4
Reinforced Concrete Shear Wall not meeting footnotes 16 and 17	2	2.5	2

Footnotes contained within Table 1.2 apply to recommendations.

Considerations for Reinforced Masonry Seismic Force Resisting Systems

When using ASCE 7 to conduct a seismic retrofit of an existing reinforced masonry structure, the following seismic design coefficients are recommended for commonly occurring lateral force resisting systems in existing buildings:

Table 1.3 – Design Coefficients for Masonry Systems

LFRS	R	Ω_o	C_d
Ordinary Reinforced Masonry Shear Walls[17]	2	2.5	1.75
Unreinforced Masonry Shear Walls[18]	See Footnote	See Footnote	See Footnote
Prestressed Masonry Shear Walls	1.5	2.5	1.75
Reinforced AAC Masonry Shear Walls	1.5	2.5	1.5

Considerations for Wood and Cold Form Light-Framed Seismic Force Resisting Systems

When using ASCE 7 to conduct a seismic retrofit of an existing wood or cold-form light framed building, the following seismic design coefficients are recommended for commonly occurring lateral force resisting systems in existing buildings:

Table 1.4 – Design Coefficients for Light-Frame Systems

LFRS	R	Ω_o	C_d
Wood or Cold-Form Walls with Wood Structural Panel Sheathing or Siding[19,20]	6.5	2.5	6.5
Gypsum Wallboard[20]	2	2.5	2
Stucco Plaster on Lath[20]	2	2.5	2
Sheathing (Straight or Diagonal) or Siding[20]	2	2.5	2

[15]Minimum wall reinforcement ratios, vertical $\rho = 0.0015$ and horizontal $\rho = 0.0020$.

[16]Wall reinforcement must be hooked at wall ends/openings and doweled into the boundary framing and foundation.

[18] The wall R-factor was selected for "Bearing Wall Systems" given the variable axial load and more appropriate R-factor for walls with unconfined boundaries and/or shear failure modes, as represented in experimental testing and ASCE 41.

[17] If $P_u < 0.10\ A_g f'_m$, an R-Factor of 1.5 be used. If the reinforced masonry shear wall meets all requirements of a special reinforced masonry shear wall, the R-Factors from ASCE 7-10 Table 12.2-1 may be used.

[18] Unreinforced masonry shear walls of all types should be evaluated using other standards like ASCE 41, IEBC, FEMA 547 etc. that deal specifically with Unreinforced Masonry evaluation and retrofit.

[19] Wall piers with height-to-width aspect ratios greater than 3.5 be neglected in the evaluation and retrofit.

[20] To justify using this high of an R-Factor, hold downs or another means of transferring overturning between floors and between the sill plate and the foundation should be present.

Cold-Form Walls with Diagonal Gauge Metal Straps[21]	4.0	2.0	3.5

Consideration of the diaphragm capacity and the capacity of connectors that complete the load path between the diaphragm and the lateral force resisting system are very important for light-framed systems. These elements should be evaluated using the alternate diaphragm design procedure of ASCE 7-16 §12.10.3. Alternatively, ASCE 41 should be considered as it often will result in a more efficient retrofit than using an ASCE 7 approach[22]. Unbraced cripple walls should be sheathed and unanchored sill plates should be anchored when encountered. Cripple walls can be retrofitted with prescriptive methodologies that produce effective and inexpensive retrofits.

Conclusion

The reality of retrofitting an existing structure is that it will be more complicated than designing a new structure because the existing structure is not afforded prescriptive provisions that allow for a simplified new design approach. If ASCE 7 is chosen as a means to retrofit a structure, the retrofitted structure must meet the intent of the document in its entirety. Restrictions in ASCE 7 are put in place to ensure the performance claimed by the code, and omitting a code requirement therefore voids the performance objectives of ASCE 7. However, because no existing building (even a retrofitted one) will meet every provision in ASCE 7, considerable judgement and considerations including those outlined in this paper will be necessary to produce an effective retrofit. Consequently, despite the imperfections of ASCE 41, considerably more engineering judgement is needed to effectively retrofit an existing structure using ASCE 7 than using ASCE 41. This paper is not intended to be an exhaustive list of issues encountered when using ASCE 7 to retrofit existing buildings. However, the authors intend for this paper to have identified and lent some clarity to major issues that have historically led to ineffective evaluations and retrofits of existing buildings.

[21] Connections be checked to develop the expected tension capacity of the brace. If the connection cannot develop the expected tension capacity of the brace, an R, Cd & □o of 1.0 per AISI S213 5.2.1.1 be used.

[22] ASCE 41 explicitly considers the ductility of individual connector types and diaphragms in a more rational and less conservative way than the alternate design provisions in ASCE 7-16. Consequently, a more efficient retrofit is often achieved using ASCE 41 in lieu of a new building code type approach.