Pitfalls of Deviating from ACI 318 Slender Wall Provisions—TechNote

Introduction

The use of alternative design approaches that deviate from current ACI 318 slender wall provisions can have potential pitfalls that result in an inadequate slender wall (or tilt-up wall) design. Some of these deviations include substituting alternate equations such as an inappropriate effective moment of inertia or incorrect modulus of rupture into the approved ACI 318 methodology, using a superseded ACI 318 standard, or replacing the approved ACI 318 methodology with an inappropriate finite element model. Some of these deviations can yield particularly poor results when methods only appropriate for service level deflections are used with strength design equations for second-order P-Δ analysis.

Question

Is it appropriate to deviate from the alternate slender wall provisions in ACI 318-19, Section 11.8, when designing slender or tilt-up walls?

Answer

Modifications to the alternative slender wall provisions should be done only with great care and a thorough understanding of the underlying provisions. For this reason, they are generally not recommended because they can easily lead to pitfalls that give substantially unconservative results. Some of these pitfalls have been observed in commercially available software that incorporated these modifications.

Discussion

In most engineering firms, tilt-up wall design is accomplished using one of three methods: hand calculations, spreadsheets or similar calculation packages developed in-house, or commercially available software. Once established in an office, these methods are often used for extended periods of time without being updated to the most current code provision. There may be some reasonable justification in the mind of the engineer that various code changes seem inconsequential. Design engineers may believe they can improve upon the code provisions with newer equations from recent research or by simply using a much more involved computational process such as complex iterations or finite element modeling. While it might be tempting to deviate from the design provisions within ACI 318, it is important that it is done with a clear understanding of the ramifications, realizing slender concrete walls are, at times, very sensitive to inaccuracies that can lead to unexpected strength reductions associated with a rapid increase in deflections.

Whether the designer's intent is to be more economical or more accurate, these deviations can produce designs that either fail to agree with published full-scale experimental test data or are susceptible to sudden strength loss. It is strongly recommended that firms review their design methodology's assumptions and equations when designing slender walls, especially given that these problems are not only found in in-house-developed computational methods, but also found in some commercially available software popular in the design community.

Background

The slender wall design section in ACI 318 is a special subset of wall design provisions specifically tailored to be used for tension-controlled walls with high height-to-thickness ratios. Often referred to as the tilt-up design provisions, this section includes some basic limitations, followed by checks for minimum panel strength and minimum serviceability requirements. This section of the 318 provisions has a well-known and specific history that began with full-scale testing of slender concrete wall panels in the early 1980s by a joint venture of the Southern California Chapter of ACI (SCCACI) and the Structural Engineers Association of Southern California (SEAOSC). From these tests, design equations were developed and eventually adopted by the Uniform Building

Code (UBC) in the 1988 edition. The UBC was the prevailing model code used in the western portion of the United States at that time. When the International Building Code (IBC) created a single national model code in 2000, the slender wall provisions from the UBC were incorporated in part into ACI 318-99, which was referenced by the 2000 IBC.

This incorporation into ACI 318-99 had modifications that unfortunately resulted in provisions that failed to match the full-scale testing results. To make the slender wall design serviceability provisions fit better into ACI 318, two key parameters were changed. The modulus of rupture (f_r) was increased and the cracked moment of inertia (I_{cr}) was replaced with an effective moment of inertia (I_e), both parameters having been well established in the ACI Code. However, in the original development of the slender wall equations, the ACI-SEAOSC Task Committee on Slender Walls (1982) found that different formulations of these parameters were needed to accurately fit the test data. The changes made by ACI 318 to the original UBC serviceability design equations and parameter formulations for ACI 318-99 caused concerns and controversy. These ACI 318-99 provisions were eventually corrected in ACI 318-08 after it was verified by Ekwueme et al. (2006) that the ACI 318-99 equations created unconservative design results that did not accurately match the original test data. The slender wall serviceability provisions contained in ACI 318-19 have been carried forward since ACI 318-08, with adjustments to the formulaic expressions to be consistent with other parts of ACI 318 and maintain the fidelity of the original design provisions.

Additionally, ACI made two moment strength-check changes to the UBC provisions. Both ACI 318 and the UBC require P-Δ moments to be included due to panel bow; however, the UBC assumed using the maximum potential deflection Δ_n (using I_{cr}) unless a more comprehensive analysis is used, while ACI 318 assumes using the calculated deflection Δ_u (using I_{cr}). Both the UBC and ACI approaches allow for either an iterated or direct solution to calculate required moment strength M_u. Iteration is commonly used for second-order analysis because the calculated deflection Δ_u changes as the P-Δ moment changes. This iterative approach is within the intent of the UBC's "more comprehensive analysis" wording, but directly stated in ACI 318. ACI 318, however, also provides a direct solution equation that acknowledges that this solution is exactly equivalent to iterating when assuming a constant cracked moment of inertia I_{cr}.

The second change made to the UBC provisions was the inclusion of a 0.75 denominator stiffness factor in the equation for Δ_u introduced in ACI 318-02. The reason for this change is not discussed in this TechNote.

Because of these issues surrounding the initial ACI 318-99 adoption, substitute equations in hand calculations and computer programs to adjust for the discrepancies were often used as a work-around. Some of these substitutions and adjustments were valid only under the older ACI 318-99 or similar standards, but unfortunately are still being used by some today, modifying current ACI 318 standards and resulting in significant design consequences. Most disconcerting is the mixing of substitute equations and correction factors with the wrong provisions, which can create a potentially dangerous mixture, leading to panels that are substantially under-designed.

Another modification to ACI 318 provisions that some engineers or software developers have employed is iterating along the bilinear curve approximation for the moment-strength check using ACI's deflection serviceability check methodology. Instead of assuming a fully cracked section (I_{cr}), the moment of inertia effectively varies linearly between I_g and I_{cr} as the wall transitions from uncracked at M_{cr} to fully cracked at M_n. This approach is illustrated in two design examples published by ACI-SEAOSC Task Committee on Slender Walls (1982) but was not explicitly placed into the UBC. Some have argued that this approach might be considered an acceptable approach under the UBC language that allowed for "a more comprehensive analysis;" however, ACI 318 did not provide this explicit language for an optional approach.

While it may be true that strength design of a panel could use an iterative methodology that checks whether the panel has cracked, and, if so, iterate along the bilinear curve, this approach is potentially susceptible to unexpected behavior for theoretically uncracked wall sections that may have cracked during lifting or cracked during an overload event. Additionally, ASCE 7's out-of-plane seismic force equation $F_p = 0.4S_{DS}I_eW_p$ has an inherent response modification factor R embedded, which results in a design force less than the anticipated seismic force. As such, it is recommended that the moment strength-check avoid using an iterative procedure along the bilinear curve at this point. Future research studies would be worthwhile to determine whether this approach is acceptable in less sensitive situations, such as where panels are known to be both uncracked and the wind load is expected to control over the actual forces anticipated during a seismic event, or situations where the wall's behavior is not vulnerable to sudden changes in stiffness due to unanticipated cracking. The sensitivity to sudden and dramatic decreases in out-of-plane stiffness of this approach might also be mitigated by using stiffness reduction factors or percentage of I_g as is common with second-order P-Δ concrete moment frame drift calculations.

In short, the UBC design provisions and the ACI 318 design provisions for slender walls were developed from empirically derived full-scale experimental test data. Design engineers inclined to substitute alternative equations or design methodologies, even those found in some commercially available software, must evaluate whether

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