

Material Matters: A call for unified design

As one of the fastest-growing construction methods in the industry today, tilt-up construction, has witnessed a great deal of flux in its governing building codes.

By John Lawson, S.E.

Deflection limits for tilt-up wall serviceability

While contractors are accustomed to viewing building standards as static, set-in-stone guidelines, the truth is that the development of these codes is often a constantly changing process. As new technologies develop, standards must shift to reflect this—and for emerging sections of the industry, this means current guidelines may require some modifications before they can be applied universally.



As one of the fastest-growing construction methods in the industry today, tilt-up construction, has witnessed a great deal of flux in its governing building codes. Although currently more than 650 million square feet of tilt-up buildings are constructed annually in the United States, acceptance of the method has only become widespread in the past few decades. As engineers have begun to experiment with new capabilities for tilt-up, it follows logically that new standards need to be created—and often revised several times before they are truly accurate for the majority of tilt-up projects.

Slender wall panels: A history

One such example is the standards dictating provisions for slender wall panels, which have been consistently re-evaluated since their roots in the 1980s. Prior to this time, the concept of a slender wall panel was foreign. In the 1960s and 1970s, concrete-bearing walls were limited by American Concrete Institute (ACI) height/thickness (h/t) ratios that specified walls much thicker than seen today. Engineers began experimenting with new analysis techniques of second-order effects to avoid the arbitrary h/t limits prescribed by ACI. Even though very thin wall panels were being erected successfully in the 1970s, there was growing concern over the engineering fundamentals behind these walls.

It wasn't until the late 70s and early 80s—as tilt-up construction began to gain momentum—that any widely accepted standards were instituted. The Structural Engineers Association of Southern California (SEAOSC) laid the foundation with two publications that provided examples and test results to prove that h/t ratios could be increased if proper analysis of second-order effects was used. However, the large deflections demonstrated by SEAOSC's test subjects raised some serviceability concerns. Slender walls designed to meet strength requirements alone, free of h/t ratios, could be overly flexible, possibly resulting in permanent deformation. The SEAOSC tests and companion rebound study resulted in service-level deflection equations based on a bilinear load-deflection curve and a proposed $L/100$ deflection limit. That limit was eventually decreased to $L/150$ when these provisions were incorporated into the 1988 Uniform Building Code (UBC), although the equations remained nearly the same.

With the push to develop a uniform national building code in the late 1990s, ACI incorporated UBC's slender wall provisions into ACI's Building Code Requirements for Structural Concrete (ACI 318-99). Whereas the ACI equations checking strength had similar results to the UBC, the results of the service-level deflection equations were significantly altered. The most marked difference was ACI's use of Branson's equation for the effective moment of inertia, in place of the UBC's bilinear load-deflection equation. A subsequent SEAOSC task committee found that ACI's equations do not necessarily correlate well with the wall specimens' test observations.

In response to the SEAOSC task committee's findings as well as support from the Tilt-Up Concrete Association (TCA) and ACI's Tilt-Up Concrete Construction Committee (ACI 551), ACI 318 has approved revisions to the serviceability deflection check for slender walls, with results more in line with SEAOSC test data and the prior UBC approach. Prior to being incorporated into the 2008 ACI 318 document, these revisions will be open for public comment this summer.

Additional issues

The equation issue isn't the only potential problem with the current ACI standard. The calculation of service-level deflections is meaningless without useful criteria to judge it. When the limit of $L/100$ was specified by SEAOSC, it was based in part on concern about permanent residual deformation, but there may be other reasons to consider limiting service-level deflections. Other materials that interface with slender walls may be susceptible to damage due to slender wall movement. Although very limited in traditional warehouse buildings, interior drywall partitions and exterior glass facades are becoming quite common as tilt-up construction makes significant inroads into the commercial and institutional construction markets. The current $L/150$ within ACI 318 appears to be at least a middle-of-the-road value when dealing with common drywall and glass systems that interface with the slender wall. Unusual

situations may require greater restrictions, yet on the other hand, $L/150$ may be unnecessarily restrictive for bare warehouse occupancies.

The next issue to consider is how the service loads are defined. Traditionally, the term, "service loads" refers to unfactored loads from allowable stress design, also known as working stress. With today's load combinations becoming more probability based, the allowable stress load combinations now contain load factors as well. Despite the transition to strength-based structural safety checks, there is still a need to check more frequently occurring loads for serviceability. This style of performance-based design is nothing new, and is a useful tool when addressing an owner's performance expectations. The newly released ASCE 7-05 has recognized the need to establish a basis for defining these service loads and, in its Appendix C Commentary, provides load combination guidelines for a 5-percent annual probability that appropriate service loads will be exceeded.

However, one notable omission from the Appendix C Commentary is a service-load combination for seismic forces. ACI 318 Section 9.2.1c implies a simple equation of $E/1.4$ for determining service-level seismic loads, but the variable it uses is based upon the Maximum Considered Earthquake (MCE), whose probability is 2 percent every 50 years in areas where there has been limited fault documentation. However, in parts of the West Coast where the fault characteristics are well known, MCE is based instead on a deterministic approach, and in some regions between the East and West Coasts, transition zones link these approaches. This variance across the country means there is no consistent load factor divisor that can be applied to E to obtain service-level loads. The 1.4 divisor is rather conservative except in areas of high-fault concentrations (or near-source fault regions).

Proposed revisions

Two separate studies in Australia and Canada have attempted to address the discrepancies between the ACI 318 provisions and the reality of lightly reinforced, slender flexural members. Based on test data of deflecting flat slabs, Ian Gilbert, Ph.D., of the University of New South Wales in Australia identified internal concrete shrinkage stresses as a significant contributor to reducing the cracking moment. Normally, modulus of rupture test specimens are unreinforced and have little restraint, allowing free shrinkage. Once reinforcement is added, shrinkage is partially restrained as the reinforcing goes into compression, causing surface-tension stresses to develop in the concrete. These pre-existing tension stresses cause reinforced members to crack earlier than expected. To address this issue, Gilbert developed an equation for the cracking moment that reduces the surface stress necessary to initiate cracking, see Figure 1. This was the basis of the equation adopted in 2000 by the Australian Standard for Concrete Structures AS3600 and correlates well with the SEAOSC test data.

However, this equation still doesn't assist in explaining why the bilinear curve once used by the UBC seems to be a better fit than the ACI-favored Branson's equation, see Figure 2. In his studies of concrete reinforced with both steel- and fiber-reinforced polymer bars, Peter Bischoff, Ph.D., of the University of New Brunswick discovered that similar issues persist among other thin, lightly reinforced concrete members. The problem, he found, is that Branson's equation was based on more heavily reinforced beams where the ratio of gross/cracked moment of inertia was set at 2.2. When the ratio exceeded 3, Branson's equation became a poor predictor of deflection—and the slender concrete walls of today far exceed this ratio, with common values ranging from 15 to 25 for single-layer reinforced walls and 6 to 12 for double-layer reinforced walls. The alternative equation proposed by Bischoff matches well with both heavily and lightly reinforced flexural beams and slender walls, effectively transitioning seamlessly to an abrupt, bilinear load-deflection curve at high moments of inertia ratios.

Conclusion

Although they still have a ways to go, the codes governing slender wall design have come a long way since the early days of h/t ratios, and the ability to design efficient concrete wall systems with greater predictability has been an important advancement in the industry. The slender wall design of tilt-up construction is here to stay, and it's time now to move toward a unified equation capable of handling a wide range of flexural members, ranging from deep beams to flat slabs, thick walls to slender walls.

Sidebar: Tilt-Up Concrete Association's seismic design task group

The Tilt-Up Concrete Association (TCA)—a non-profit international organization that serves to expand and improve the use of site-cast, tilt-up as the preferred construction method—formed a seismic design task group in 2005.

According to Jim Baty, technical director of the TCA, the task group was formed as a proactive measure to involve the experts in the tilt-up industry. Responding to concerns regarding the performance of tilt-up structures during earthquakes in high-seismic regions, largely due to incomplete information on both design and performance characteristics, this group is charged with identifying the current state-of-the-art, tilt-up design procedures and standards for seismic performance and developing modifications to the current building code provisions based on these current state-of-the-art procedures and standards. The task group has begun to develop models for current design practice as well as solutions for dynamic modeling through the National Earthquake Hazard Reduction Program (NEHRP) and proposed detailing through the American Concrete Institute (ACI).

"The task group concentrates on understanding the dynamic behavior unique to tilt-up buildings with flexible diaphragms and its impact on seismic loads applied to panels, details for connections, design of the panels, and adjustments to the current code," said Baty. "Additional studies will be undertaken on complex façade perimeters and irregularly shaped buildings, recognizing the increasing number of tilt-up buildings with these trends."

For more information on the committee, contact Jim Baty at 319-895-6911 or jbaty@tilt-up.org.

The Tilt-Up Concrete Association (TCA) was founded in 1986 to improve the quality and acceptance of site-cast, tilt-up construction, a construction method in which concrete wall panels are cast on-site and tilted into place. Tilt-up construction is one of the fastest-growing industries in the United States, combining the advantages of reasonable cost with low maintenance, durability, speed of construction, and minimal capital investment. For more information about the TCA, visit www.tilt-up.org.

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AS3600 – Australian Code, 2009 amendments

$$M_{cr} = 517.23 \sqrt{f'_c} - f_c + P(1.8) - P\gamma$$

where

$$f_c = \left(\frac{1.5p}{1 + 0.8p} \right) f'_c \quad (f_c \text{ is the concrete design age stress})$$

Bischoff – Journal of Structural Engineering, ASCE, May 2005

$$l_e = \frac{l_u}{1 - \left(\frac{M_2}{M_1} \right) \left[1 - \frac{l_u}{l_c} \right]} \leq l_u$$

Figure 1: The Australian concrete code AS3600 contains new equations to more accurately predict service-level cracking moment M_{cr} . In addition, Peter Bischoff, Ph.D., has proposed a new equation to replace the current Branson's equation for l_e . These two equations applied together provide a powerful new tool to accurately estimate service-level deflections for a wide range of concrete members, and especially tilt-up panels.

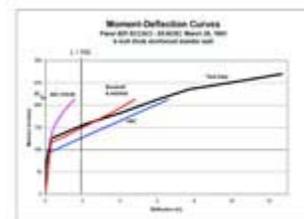


Figure 2: Tilt-up wall panels are typically designed as concrete slender walls under ACI 318 Sec. A comparison of the original SEAOSC test data with current ACI 318 reveals an underestimation of deflection. Both the UBC and the proposed Bischoff/AS3600 equations provide a more accurate estimation of service-level deflections for slender wall panels.