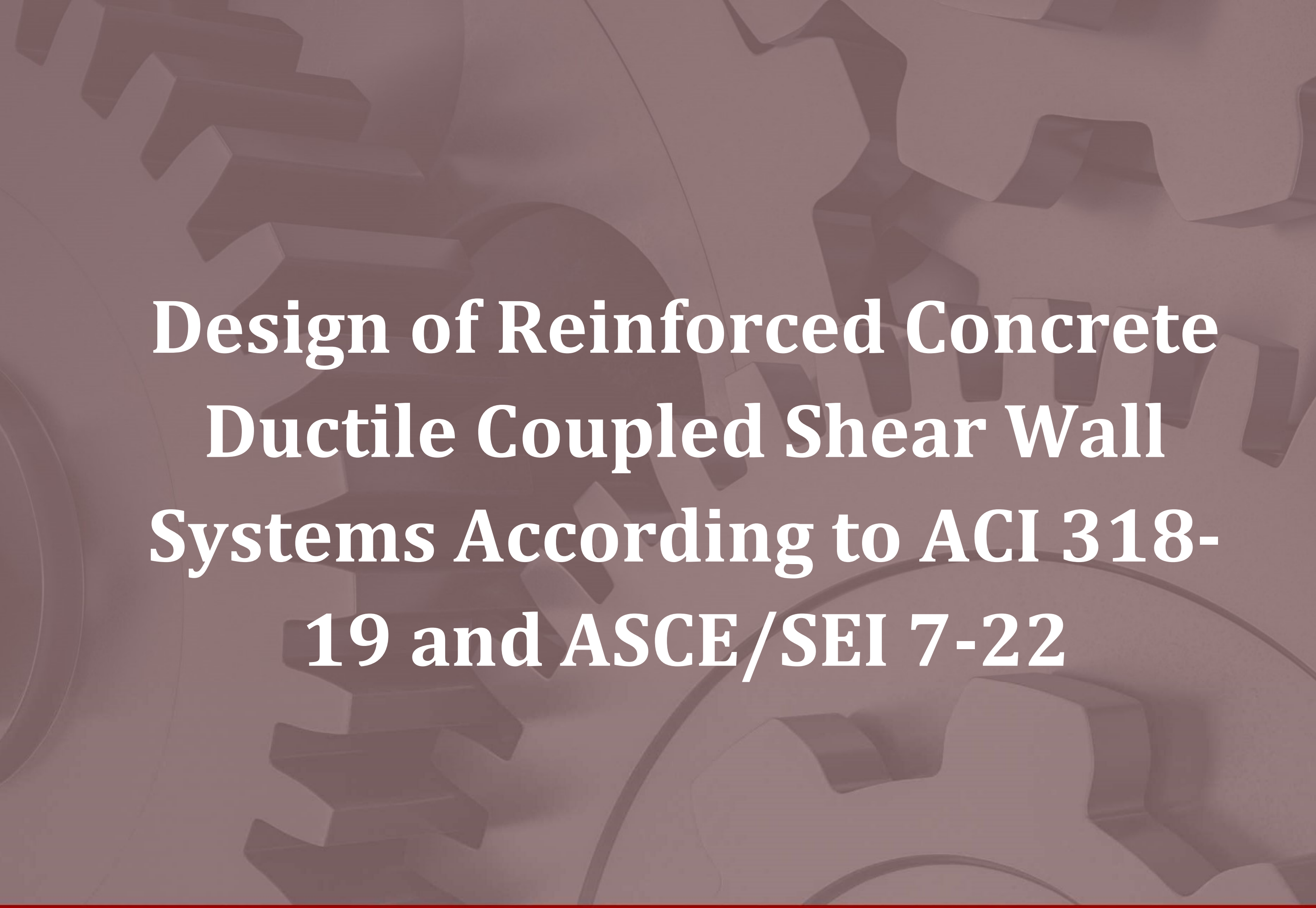

Design of Reinforced Concrete Ductile Coupled Shear Wall Systems According to ACI 318-19 and ASCE/SEI 7-22

An Online Continuing Education Course for Engineers

Course Number: S-3026

Credit: 3 Hours / 3 PDH / 3 CPD

Design of Reinforced Concrete Ductile Coupled Shear Wall Systems According to ACI 318-19 and ASCE/SEI 7-22

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A ductile coupled wall system of reinforced concrete is now defined in ACI 318-19 (ACI, 2019), and it is recognized as a distinct seismic force-resisting system in ASCE/SEI 7-22 Table 12.2-1, Design Coefficients and Factors for Seismic Force-Resisting Systems. Three line items have been added to the table, featuring the ductile coupled wall system of reinforced concrete. The line items are under:

A. Bearing Wall Systems,
B. Building Frame Systems, and
D. Dual Systems with Special Moment Frames.

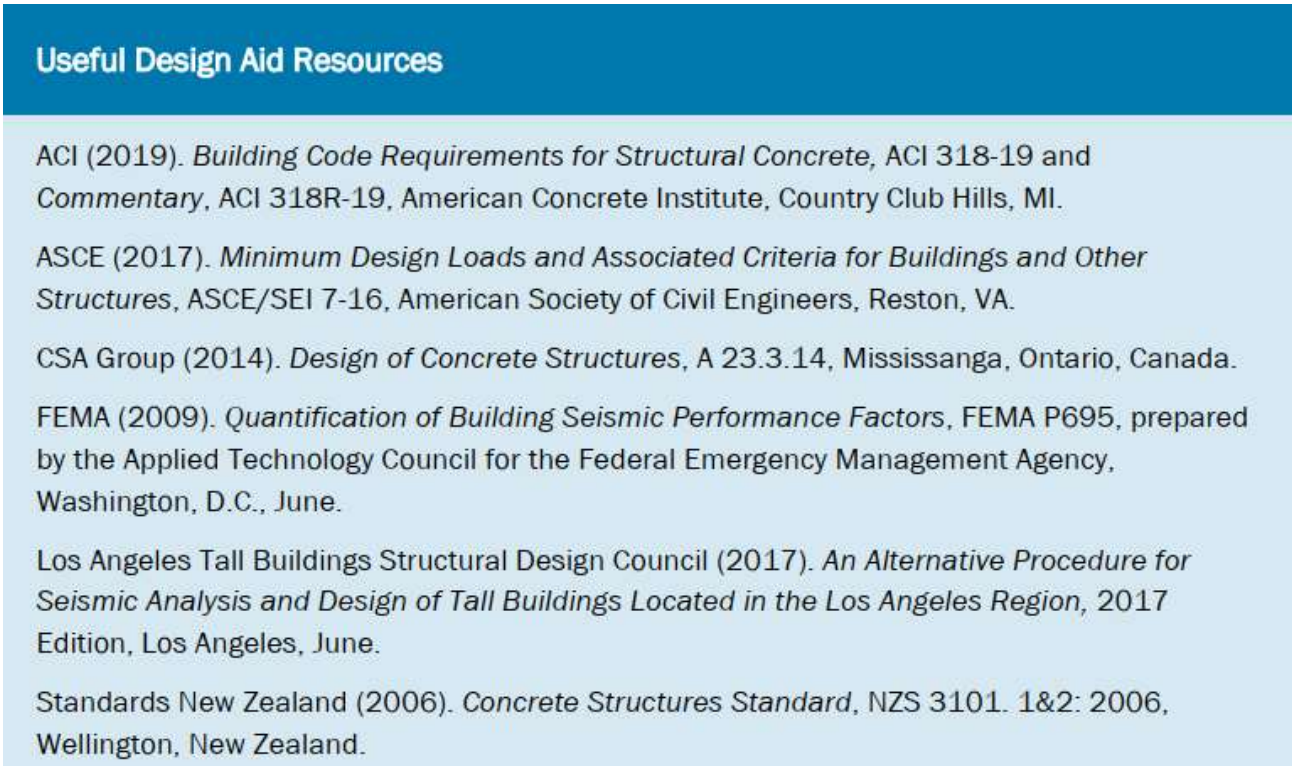
R **= 8**, ***Cd*** **= 8, and Ω0 = 2.5** are the design coefficients in all the line items. The height limits are the same as for corresponding uncoupled isolated wall systems. Several important changes made in ACI 318-19 for the design and detailing of special structural walls were implemented in the design of prototypes for the FEMA P695 study supporting the above values.

A few words about terminology may be in order here. “Reinforced Concrete Ductile Coupled Shear Wall System” is the terminology used in the title of this course. An effort has been made to use this terminology consistently throughout the course, except that “reinforced concrete” is typically dropped as being redundant or understood. The whole chapter, after all, is about a reinforced concrete system. There are, however, a few obstacles to attaining total consistency. The system discussed in this chapter is defined in ACI 318-19 Section 2.3 as follows: “structural wall, ductile coupled – a seismic-force resisting-system complying with 18.10.9.” Several aspects of this definition ought to be noted.

First, “reinforced concrete” is not mentioned; it is understood. Second, shear walls are called structural walls in ACI 318-19. Third and most importantly, a wall, which is a structural member or element, is defined as a system; this is a lax usage of terms.

Finally, the “seismic-force-resisting-system” in the definition is “seismic force-resisting system” in ASCE/SEI 7-22 as well as in this chapter. In ASCE/SEI 7-22 Section 18.10.9 itself, the terminology used is Ductile Coupled Walls. Where ACI 318-19 is referenced directly, the terminology used here is the Ductile Coupled Structural (Shear) Wall System. Where ACI 318-19 text is essentially reproduced (with or without quotation marks), terminology used by ACI Committee 318 is left alone. Finally, in ASCE/SEI 7-22 Table 12.2-1, the walls providing seismic force resistance as part of the structural system under discussion here are called Reinforced Concrete Walls. In portions of the table reproduced in this chapter, “shear” has not been inserted before “walls.”

In addition to the *2020 Provisions*, the following documents are either referred to directly or may serve as useful design aids.



Useful Design Aid Resources

ACI (2019). *Building Code Requirements for Structural Concrete,* ACI 318-19 and *Commentary*, ACI 318R-19, American Concrete Institute, Country Club Hills, MI.

ASCE (2017). *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*, ASCE/SEI 7-16, American Society of Civil Engineers, Reston, VA.

CSA Group (2014). *Design of Concrete Structures*, A 23.3.14, Mississanga, Ontario, Canada.

FEMA (2009). *Quantification of Building Seismic Performance Factors*, FEMA P695, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C., June.

Los Angeles Tall Buildings Structural Design Council (2017). *An Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region,* 2017 Edition, Los Angeles, June.

Standards New Zealand (2006). *Concrete Structures Standard*, NZS 3101. 1&2: 2006, Wellington, New Zealand.

1. Introduction

Functional and often structural requirements make the use of shear walls desirable in many buildings. Functionally, shear walls are useful in buildings because they serve as partitions between spaces. Structurally, they make buildings laterally stiff, particularly when used interactively with moment frames, thereby helping to keep lateral deflections within tolerable limits. Often, such walls are pierced by numerous openings for windows, doors, and other purposes. Two or more walls separated by vertical rows of openings, with beams at every floor level between the vertically arranged openings, are referred to as coupled shear walls. When a coupled shear wall system is subject to lateral loads due to wind or earthquake forces, shear forces generated at the ends of the coupling beams accumulate into a tensile force in one of the coupled wall piers and into a compression force in the other wall pier. The couple, due to these tension and compression forces, resists a part of the overturning moment at the base of the wall system, with the remainder of the overturning moment being resisted by the wall piers themselves (Figure 1).

The ratio of the overturning moment resisted by the tension-compression couple to the total overturning moment at the base of the coupled wall system is often referred to as the degree of coupling. The shorter and deeper the coupling beams, the higher the degree of coupling. When the degree of coupling is very low (25% or lower), the two wall piers tend to behave like isolated walls, and when the degree of coupling is very high (75% or higher), the entire coupled wall system tends to behave like a shear wall with openings. It should be noted, however, that as inelastic displacements develop in the coupling beams, the degree of coupling tends to lose its significance.

A coupled shear wall system can be designed such that a considerable amount of earthquake energy is dissipated by shear yielding in coupling beams with low span-to-depth ratios or flexural yielding at the ends of coupling beams with higher span-to-depth ratios before flexural hinges form (typically) at the bases of the wall piers (assuming they are slender, with height-to-length ratios larger than or equal to two). Although such coupled wall systems are highly suitable as the seismic force-resisting systems of multistory buildings, they were not recognized as distinct entities in Table 12.2-1 of ASCE/SEI 7-16. Therefore, such systems need to be designed using *R*-values that essentially ignore the considerable benefits of having coupling beams, which can dissipate much of the energy generated by earthquake excitation. This course reports on a successful effort to address this situation.

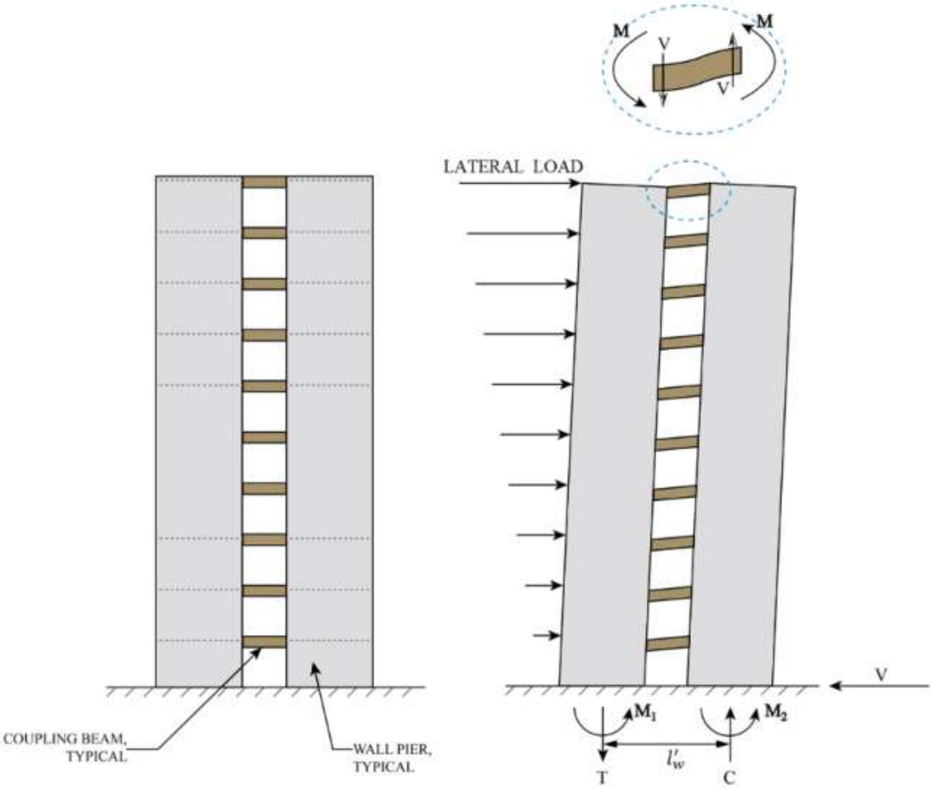


Figure 1. A Coupled Shear Wall System

2. Ductile Coupled Structural (Shear) Wall System of ACI 318-19

To quote Bertero (1977), “Use of coupled walls in seismic-resistant design seems to have great potential. To realize this potential, it would be necessary to prove that it is possible to design and construct “ductile coupling girders” and “ductile walls” that can SUPPLY the required strength, stiffness, and stability and dissipate significant amounts of energy through stable hysteretic behavior of their critical regions.”

Thus, the discussion in this course needs to focus not on just coupled walls but ductile coupled walls consisting of ductile shear walls and **ductile coupling beams**.

In the 2019 edition of ACI 318, a new system definition has been created to recognize the Ductile Coupled Structural (Shear) Wall (DCSW) system. The shear walls in such a system must be special structural walls in conformance with ACI 318-19 Section 18.10, including the proportioning requirements of Section 18.10.9, and the coupling beams must comply with the detailing requirements in ACI 318-19 Section 18.10.7.

The objective of the ductile coupled shear wall system is for the majority of energy dissipation to occur in the coupling beams. This is analogous to strong column weak beam behavior in the moment frames. Studies were conducted at Magnusson Klemencic Associates (MKA) to identify system characteristics that lead to coupling beam energy dissipation of no less than 80% of the total system energy dissipation under MCE ground motions. In these studies, nonlinear response history analyses were conducted using spectrally matched ground motion records on a variety of coupled shear wall archetypes. Archetypes ranged from 5 to 50 stories in height and considered a range of longitudinal reinforcement ratios in the coupling beams as well as the shear walls. The results of these analyses are presented in Figure 2. The x-axis represents the aspect ratio (clear span-to-total depth) of the coupling beams, with D designating a diagonally reinforced beam design and M designating a special moment frame beam design. For example, D4 is a diagonally reinforced coupling beam with an aspect ratio of 4 and M4 is a coupling beam detailed as a special moment frame beam with an aspect ratio of 4. The y-axis is the percentage of total system energy dissipation that occurs in the coupling beams alone. The resulting trend shows an energy “dome” with coupling beams dissipating the majority of system energy between aspect ratios of 2 and 5.

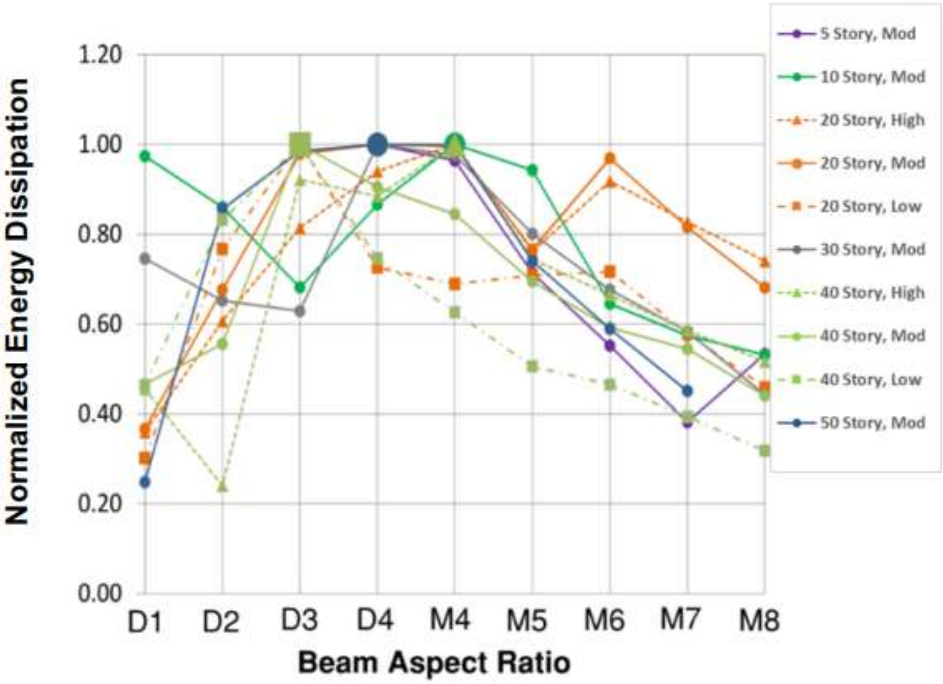


Figure 2. Energy Dissipation in Coupling Beams

The primary characteristics of such a system were found to be governed by geometry. Squat walls were found to be too stiff to allow sufficient story drift for coupling beams to become inelastic. For this reason, shear walls in the Ductile Coupled Shear Wall (DCSW) system need to have a total height-to-length aspect ratio of no less than 2.0. Squat coupling beams were found to over-couple the seismic force-resisting system and lead to significant energy dissipation in the shear walls. As such, coupling beams in DCSW systems need to have a clear span-to-total depth aspect ratio of no less than 2.0 in all cases. Very slender coupling beams, designated as having an aspect ratio greater than 5.0, are not stiff enough to contribute sufficient hysteretic energy dissipation and are allowed in no more than 10% of the levels of the building. Lastly, coupling beams conforming to these geometric constraints are required to be present at all levels in order to dissipate the intended amount of energy. It has been clarified in ACI 318-19 that longitudinal reinforcement in coupling beams detailed as special moment frame beams and diagonal reinforcement in diagonally reinforced coupling beams must develop 1.25 times *fy* of the reinforcement at each end. This last requirement is intended to preclude the use of fixed-pinned coupling beams that are the outcome where insufficient length exists to adequately develop the coupling beam reinforcement into the adjacent shear wall.

Plotted along the y-axis of Figure 2 is energy normalized with respect to the energy dissipated in a 40-story building. In Figure 2 le nd 50%, respectively, of the amount e ACI 318-19 Equation 18.10.7.4). For igh," "Mod," and "Low" mean 100%, 75 hat would generate an Mpr for which 2

As noted earlier, t system are in addition to those required f anguage of the DCSW definition in ACI 31 ilding Seismic Safety Council (BSSC) PUC

Also, as noted earlie ll, ductile coupled as a seismic force-resi

18.10.9 *Ductile couplec*

18.10.9.1 Ductile couple satisfy the requirements of this section.

18.10.9.2 Individual walls shall satisfy $hwcs/\ell w \geq 2$ and the applicable provisions of 18.10 for special structural walls.

18.10.9.3 Coupling beams shall satisfy 18.10.7 and (a) through (c) in the direction considered.

(a) Coupling beams shall have $\ell n/h \geq 2$ *at all levels of the building.*
(b) All coupling beams at a floor level shall have $\ell n/h \leq 5$ *in at least 90 percent of the levels of the building.*
(c) The requirements of 18.10.2.5 shall be satisfied at both ends of all coupling beams.