Seismic Analysis, Design, and Detailing Requirements of Special Reinforced Masonry Shear Walls According to US Codes

An Online Continuing Education Course for Engineers

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1. Introduction

The primary seismic force-resisting elements in buildings are horizontal diaphragms, vertical framing elements, and foundations. Together, these elements comprise the seismic force-resisting system (SFRS). In reinforced masonry structures, the vertical framing elements are generally structural walls. They resist out-of-plane loads from wind or earthquake and transfer those loads to diaphragms and foundations. They also resist in-plane loads received from diaphragms and convey them to foundations. Given the wide variety of masonry materials, forms, and local construction practices, many kinds of reinforced masonry structural walls are possible. **This course focuses on the design of one classification of walls for one loading case: special reinforced masonry shear walls subjected to in-plane seismic and gravity loads.** From the least to the most stringent ductility requirements, three sub-categories are defined: ordinary, intermediate, and special. Within the special classification, two fundamental types are distinguished:

- **Flexure-dominated walls**: walls whose behavior is dominated by flexure, with reliable ductility and inelastic displacement capacity

- **Shear-dominated walls**: walls whose behavior, often for reasons beyond the control of the structural designer, is dominated by shear, with limited ductility capacity

Other materials usually allow the structural designer to locate and size structural elements to achieve the desired or needed behavior, and the building is then constructed around these structural elements. Masonry, by contrast, serves simultaneously as architecture (defining a building's external or internal appearance as well as its internal functional program), enclosure (defining a building's external envelope), and structure (resisting vertical and lateral loads). The structural designer generally does not have the opportunity to choose the configuration of these wall elements; instead, the other design factors dictate their locations and proportions.

Thus, the structural designer must work with the elements that configure the space. The designer must be able to anticipate the expected behavior of those elements so that he or she can adapt the design and detailing of each element appropriately to resist all required loading combinations to meet the intent of the code for stiffness, strength, and ductility. These requirements apply to structural walls in all Seismic Design Categories (SDC) as defined in ASCE 7. However, they can be particularly challenging for special walls because the expected level of ductility implied by the "special" designation may not be available.

Although special reinforced masonry walls can be used in any building, the IBC requires them only when masonry structural walls are used to resist seismic forces in new buildings assigned to SDC D, E, or F. The design force levels are specified in ASCE 7, and the design procedures and detailing requirements are addressed in the 2013 edition of TMS 402, *Building Code Requirements for Masonry Structures* (TMS, 2013a). The masonry design requirements of these three codes or standards are generally consistent with respect to their design intent for flexure-dominated walls. In contrast, for shear-dominated walls, the assumed structural ductility associated with a particular response modification factor (*R*-factor) in ASCE 7 may not automatically result from the design and detailing requirements of TMS 402. This guide guides both conditions.

This course is intended especially for practicing structural engineers, although it will also be useful for building officials, educators, and students. Although it emphasizes code requirements and accepted approaches to their implementation, it also identifies good practices that go beyond the minimum requirements of the building code. Background information and illustrative sketches clarify the requirements and recommendations. Following the introduction, Sections 2 and 3 describe the use of structural walls in buildings and discuss the intended behavior of these walls. Section 4 provides analysis guidance. Section 5 presents the design and detailing requirements of TMS 402, along with guidance on how to apply them. Section 6 presents additional requirements that must be considered for all masonry buildings, particularly those assigned to SDC D, E, or F. Section 7 addresses detailing and constructability challenges for special structural walls. **Figure 1-1** summarizes the design process described in detail in this Guide.

Determine Design Criteria and Actions on Wall Elements

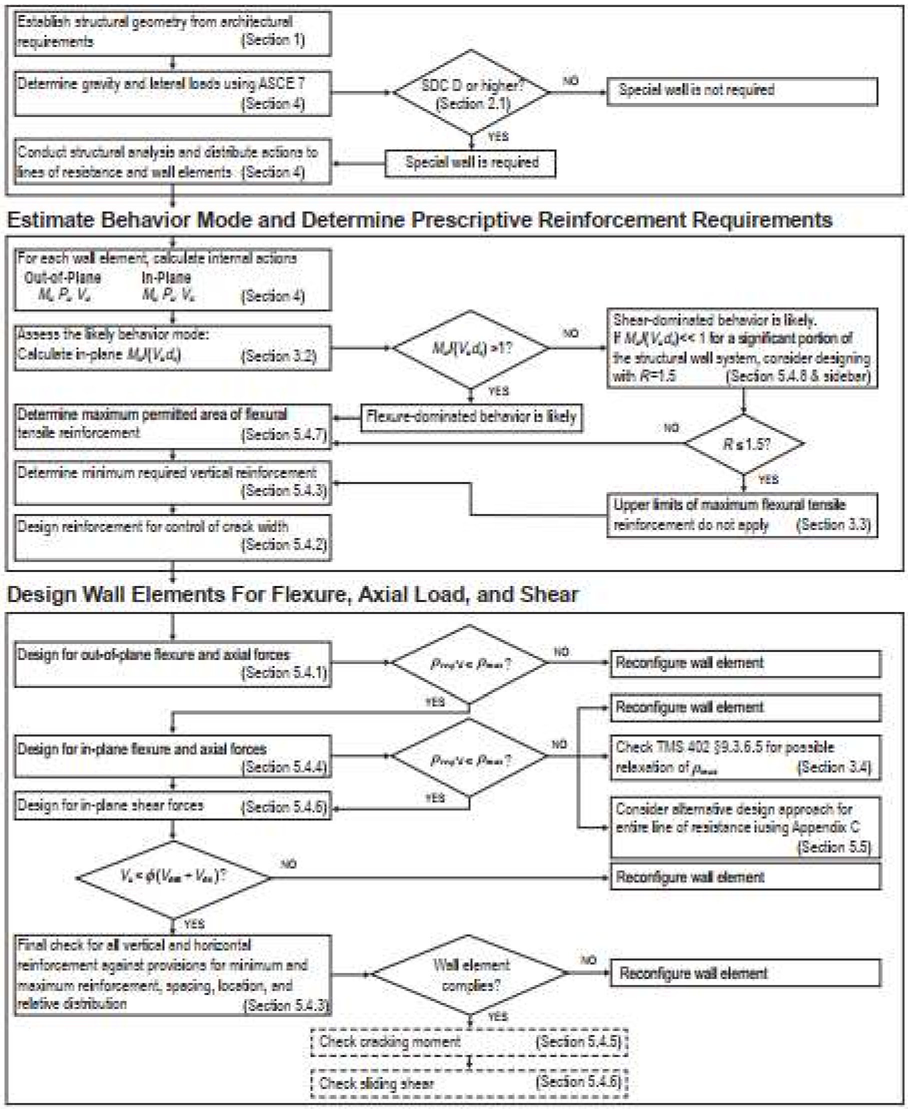

Figure 1-1. *Flow chart of steps in the design of special reinforced masonry shear walls. Numbers in parenthesis cross-reference the sections in this Course.*

2. The Use of Reinforced Masonry Structural Walls in Buildings

This section focuses on the global behavior of groups of masonry walls acting together to form a vertical and lateral load-resisting system. It categorizes typical configurations of masonry structural walls in elevation and plan and identifies structure and building types that are likely to have configurations that have significant structural consequences. Issues related to individual element design are deferred to Section 3.

2.1 Use of Special Reinforced Masonry Shear Walls

Masonry walls proportioned to resist a combination of shear, flexural, and axial forces are referred to as structural walls. When the primary function of structural walls is to resist in-plane loads conveyed from diaphragms down to the foundation, they are generally referred to as shear walls. **ASCE 7 recognizes eight categories of masonry walls, and TMS 402 distinguishes among twelve shear wall categories. Within the category of reinforced masonry shear walls, three subcategories are recognized: ordinary, intermediate, and special. This Guide considers only special reinforced masonry shear walls.**

Special reinforced masonry shear walls ("special walls") are required to meet the most restrictive material and prescriptive detailing requirements. Accordingly, they are permitted by ASCE 7 to be used in any SDC per the judgment of the structural designer. Special walls are required to be used for reinforced masonry walls in SDC D, E, or F.

Special walls are assigned the highest response modification factor, *R*, of any of the masonry shear wall types. For bearing wall systems, as defined by ASCE 7, special reinforced masonry shear walls are assigned an *R* factor of 5; for special reinforced masonry wall building frame systems, $R = 5.5$ (see bottom bar). Inherent in the use of an *R* factor of 5 or greater is the presumption of ductile behavior associated with the development of plastic hinges with stable inelastic rotation capacity. The development of strains characterizes stable plastic hinges well past yield in the flexural reinforcement before the occurrence of flexural strength degradation or shear failure occurs in the wall. Prescriptive requirements found in TMS 402 intend to provide reinforcement configurations that ensure ductility. The prescriptive requirements of TMS 402 have been developed over many years. However, given the wide variety of masonry wall types and configurations and the lack of control of the structural designer over these configurations in many cases, the designer should not assume that following the prescriptive requirements alone will necessarily ensure ductile, flexure-dominated behavior.

Building Frame versus Bearing Wall Systems

Masonry shear walls appear in two places in ASCE 7 Table 12.2-1, where building response modification factors are defined. They appear under "A Bearing Wall Systems" and "B. Building Frame Systems." The distinction between the two building systems, documented in the NEHRP 2003 Commentary (FEMA, 2009), is that in Building Frame Systems, the walls resist in-plane shear loads but only "a relatively small percentage" of gravity loads. This distinction may be interpreted differently by different jurisdictions. Generally, the intent of the original NEHRP definition of Building Frame Systems cannot be met unless the walls are specifically detailed to resist in-plane shear loads but not gravity loads. This Guide recommends the use of a Bearing Wall System unless specific measures are taken to minimize the portion of gravity loads carried by walls relative to frames.

2.2 Shear Wall Configurations in Buildings

A typical lateral load path through a masonry building is illustrated in **Figure 2-1**. Because masonry walls configure architectural space, they often perform as part of the building envelope or as fire or acoustic separation walls, in addition to their multiple structural roles. Walls often serve to resist both in-plane and out-of-plane forces from wind or seismic loads or both. In fact, once shear walls have been designed for out-of-plane forces, prescriptive reinforcement requirements, and shrinkage and thermal movements, walls often meet or exceed in-plane strength requirements.

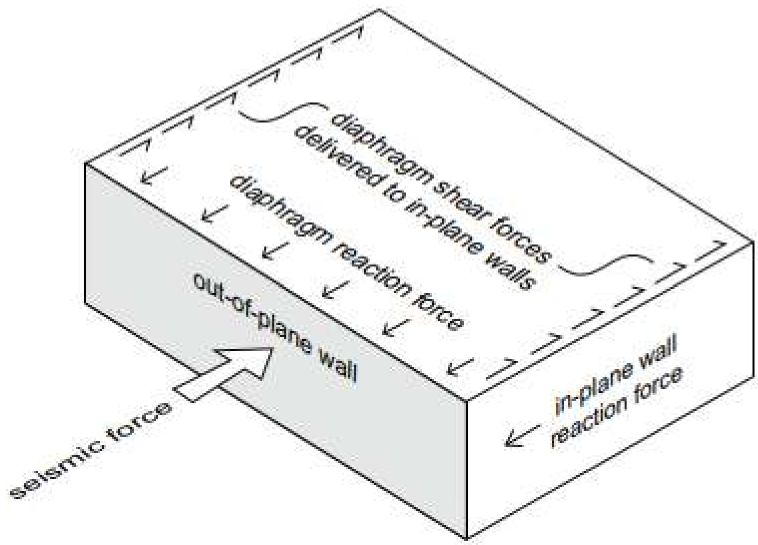

Figure 2-1. *Typical load path through a masonry building.*

Masonry walls can have a variety of plan configurations (**Figure 2-2**). Most reinforced masonry codes and design guides provide rules for the design of simple, planar wall elements, as in **Figure 2-2(a)**, but in practice, such walls can be part of complex structural elements and systems that affect their behavior, as illustrated in **Figures 2-2(b)** through **2-2(f)**. The designer can choose to design and detail such walls to have an integral cross-section, with the wall segment aligned parallel to the lateral shear force acting as a web and the perpendicular wall segments acting as tension or compression flanges, as in **Figure 2-2(g)**. Alternatively, the designer can choose to treat groups of intersecting walls as individual planar elements, provided that they are sufficiently separated so that shear cannot be transferred between them either through the masonry or through stiff horizontal diaphragms. Depending on the nature of the diaphragm, small gaps between wall segments, as in **Figure 2-2(h),** may not be sufficient to decouple the walls, and some separation may be required, as in **Figure 2-2(i)**.

Typical wall configurations are shown in elevation in **Figure 2-3**. Squat wall elements like those in **Figures 2-3(a)** and **2-3(b)** with aspect ratios (height /plan length) of one or less are quite common, and they are often much stronger than required.

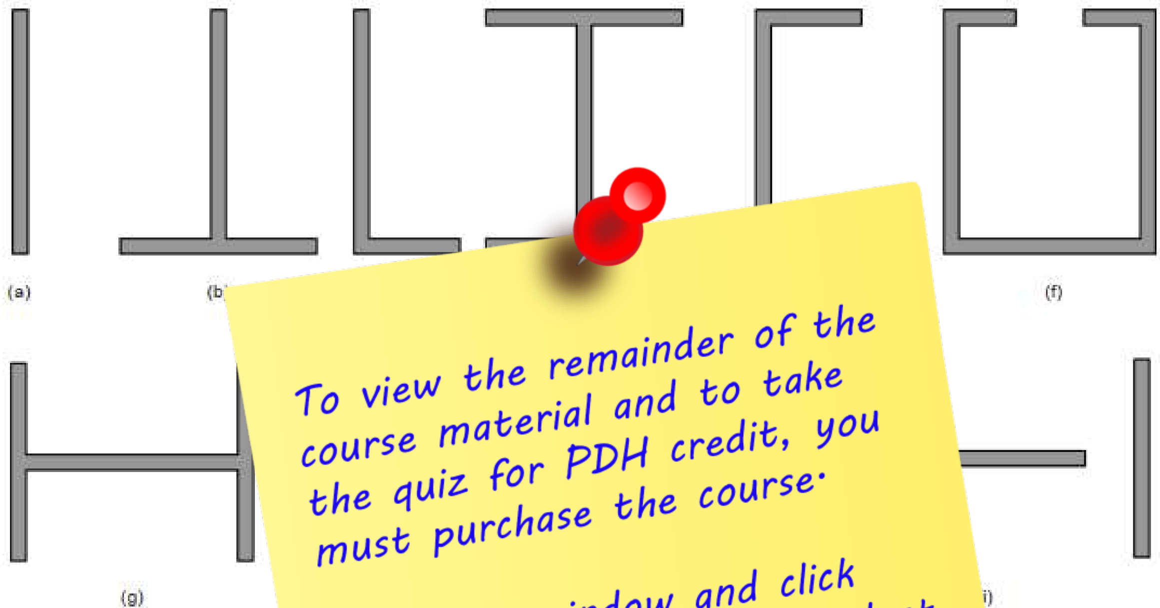

Figure 2-2. *Plan configuratio… …haped flanged wall, (d) I-shaped flanged wall, (e) … g, (g) I-shaped wall with full continuity betwee… …langes and stiff coupling …*

Another common wall type is the perforated wall (**Figures 2-3(c)** and **2-3(d)**). These exhibit more complex behavior, depending on the governing behavior mode of individual pier and beam elements (vertically and horizontally oriented wall segments, respectively). Tall cantilever walls or cores (**Figure 2-3(e)**) are the configurations most likely to display the flexure-dominated behavior that meets the intent of the code for special walls. Multiple tall walls may be coupled by masonry beam elements (**Figure 2-3(g)**), which are introduced for architectural reasons such as fire separation. When the walls are subjected to significant lateral displacement, it is unlikely that these coupling beams can meet the demand for deformation without first failing in shear. In a more common configuration, walls are coupled only by concrete slabs (**Figure 2-3(f)**). Although the coupling effect of these slabs is often ignored in design, it can significantly increase the axial forces and moments generated in some walls. These issues are discussed in detail in Sections 3 and 4.