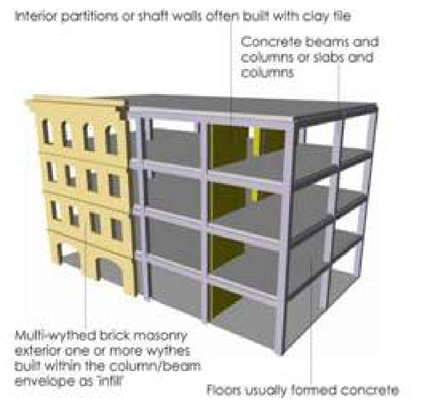
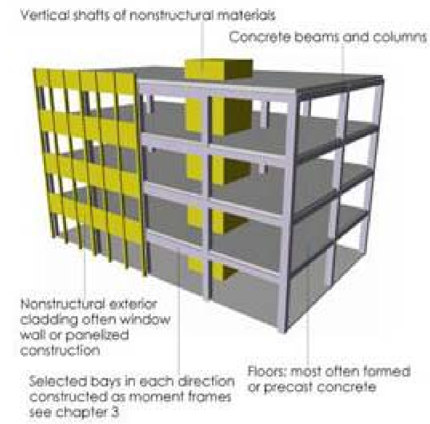
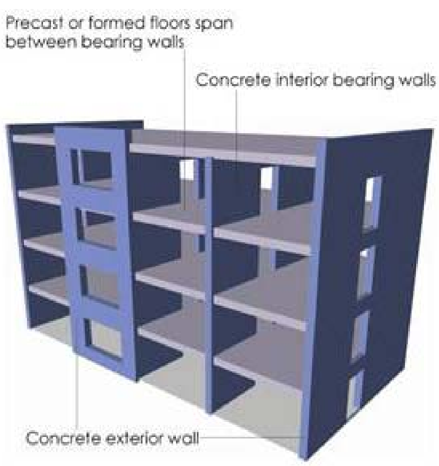
NIST GCR 10-917-6

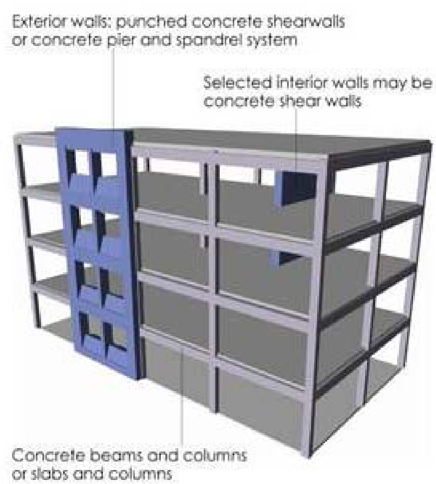
Concrete Model Building Subtypes

Recommended for Use in Collecting Inventory Data









National Institute of Standards and Technology
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Concrete Model Building Subtypes
Recommended for Use in Collecting Inventory Data

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EXECUTIVE SUMMARY

This study was conducted by the National Institute of Building Sciences' Building Seismic Safety Council (BSSC). The goal was to develop standardized categories for older concrete buildings that incorporate more detail than those included in the standard set of Federal Emergency Management Agency (FEMA) Concrete Model Building Types – namely, C1-frames, C2-shear walls, C3-concrete frames with masonry infill, and PC2-precast frames. The recommended "subtypes" generally can be identified without extensive engineering evaluation and therefore can document the inventory of older concrete buildings in an effort to better quantify how many structures might require mitigation. The identification of these subtypes also contributes to determination of the highest priority research needed to enable rapid implementation of performance-based seismic design for mitigation.

For initial collection of inventory data, building age, height, and occupancy should be documented. Data on additional attributes that affect risk of high damage levels or collapse would require engineering evaluation and cannot be collected reliably using typical inventory-collection techniques; however, additional attributes that may be important for identifying a high-risk concrete building are discussed.

The primary attribute suggested for initial classification is occupancy and 13 different occupancies are recommended. The structural systems typically, but not exclusively, used for each occupancy are described as are potential seismic deficiencies. Also described are the many variations that can affect the risk levels of each of the FEMA Concrete Model Building Types (C1, C2, C3, and PC2) including strength, stiffness, configuration irregularities, and gravity frame type. These descriptions are organized into Structural Type Families based on the four primary model building types.

Without further understanding of the collapse mechanisms of older concrete buildings, building subtypes that can reliably distinguish seismic risk levels cannot be established.

Chapter 1
INTRODUCTION

Background

As a class, older concrete buildings are likely to include a significant number of buildings at risk of significant damage and collapse in earthquake shaking. Certain combinations of configuration characteristics, coupled with the potential for brittle behavior in key elements, can produce these collapse conditions. This group of buildings generally is considered to be second only to unreinforced masonry bearing wall (URM) buildings as a high seismic risk in both the United States and worldwide.

Risk mitigation programs for older concrete buildings have lagged behind those aimed at URM buildings, possibly because this building category is less homogeneous. The variation in configuration and framing systems in older concrete buildings results in a class of buildings that presents a wide range of risk. The building type is difficult to identify. Further, methods to efficiently identify high-risk members of the type are not currently available. The cost of typical retrofit procedures and the associated disruption are perceived to be much greater than for the URM class of buildings.

Recently, however, interest in the development of risk mitigation programs for older concrete buildings has grown, spurred by their consistently poor performance in other countries and knowledge that the category includes buildings with high occupancies and/or importance in this country. The Concrete Coalition (Comartin, 2008) was formed by the Earthquake Engineering Research Institute (EERI) to promote further understanding of these buildings and to encourage mitigation programs. The National Science Foundation's NEES Research Program awarded a Grand Challenge to the Pacific Earthquake Engineering Research Center (PEER, 2006) to increase basic understanding of the building type. Interest in this building type also is demonstrated by the formation and activity of the first American Concrete Institute (ACI) committee (ACI 369) to consider older concrete buildings.

The first step in achieving mitigation of the risk from this building type is to improve understanding of the existing conditions as reflected by the total number of buildings in the class, the uses and occupancies of those buildings, and the range of configurations and structural systems employed. Accordingly, collection of inventory data is a first step for both the PEER Grand Challenge (with collection of inventory in Los Angeles) and the Concrete Coalition (with collection of inventory in California's high seismic regions for the State of California).

Insurance industry and emergency management efforts to classify buildings in order to estimate risk and losses have been under way for more than 35 years (FEMA 1989; FEMA 1994); however, more attention has been paid to this subject since the mid-1980s. A multitude of classification schemes exist but there is no agreed-upon standard. The design of classification schemes depends on available data sources, regional construction characteristics, and ultimate use of the data as well as the resources available to collect and analyze the data. Although each scheme has some distinct features and different numbers of classes, all the schemes generally are based on similar assumptions and, as such, have many commonalities.

Existing model building type schemes typically attempt to characterize the variation in performance (or damage) of different structures subjected to earthquake loading. Classification schemes include factors such as structural system, construction materials, building size or height, and the extent to which seismic loads and detailing have been included in design and construction. However, it is important to note that in all schemes the initial classification can be made without specific-building level engineering evaluation.

The Federal Emergency Management Agency (FEMA) developed the classification system currently in most widespread use as part of its overall program to mitigate the seismic risk posed by existing buildings and has been formalized in several FEMA publications (FEMA, 1992; FEMA, 1994; FEMA, 2002). This set of structural descriptions, called Model Building Types (MBT), is similar to other systems previously used. It also was adopted for use in HAZUS, FEMA's loss-estimation software (FEMA, 1994). Unfortunately, however, the system provides only a very coarse separation of concrete building types that does not adequately distinguish between levels of risk among buildings or allow a reliable categorization of individual buildings using economical inventory collection methods.

A subgrouping of older concrete buildings that both identifies relative life safety risk and allows for collection of inventory data without engineering evaluation would offer an important and efficient first step to communities that want to reduce their seismic risk. A basic assumption for this study is that the identification of concrete building subtypes should not require building-specific engineering evaluation.

A better understanding of the characteristics of the existing inventory of older concrete buildings also will inform research necessary to advance the accuracy and usefulness of performance-based design in this area.

Purpose of This Study

The purpose of this study is described in the project scoping statement as follows:

> Older concrete buildings are generally considered the most dangerous building type as a group, but the class includes a wide variety of structural systems and configurations, not all of which are in the high-risk category. To achieve effective and efficient mitigation, the building class must be broken down into smaller subclasses that present more consistent seismic risk and that can be more readily identified. The identification of these subclasses will also allow determination of the highest priority research to enable rapid implementation of performance-based seismic design for mitigation.
>
> The goal of this effort is to identify a sub-grouping system for older concrete buildings and to provide more robust information about the specific sub-building types that need to be researched.

Efforts to inventory older concrete buildings to date have not used any standard system to subcategorize the group and, in many cases, have not subcategorized the buildings at all.

This project seeks to balance the relatively small level of effort needed to collect basic inventory (at the lowest level, the number of buildings) with the larger effort and cost of drawing review and engineering evaluation – ranging on the lowest level from FEMA 154 (FEMA, 2002) to the highest level represented by methods in ASCE 31 (ASCE, 2003) and ASCE 41 (ASCE, 2006).

Chapter 2
DEVELOPMENT OF SUBTYPES FOR OLDER CONCRETE BUILDINGS

Definition of Older Concrete Buildings

For the purpose of this study, the age of "older concrete buildings" is defined by the "milestone" code years given in Table 3 of ASCE 31, *Seismic Evaluation of Existing Buildings* (ASCE, 2003). This table lists the editions of the various U.S. building codes that can be considered to yield seismically adequate buildings needing no further evaluation. For concrete buildings, the key provisions first appeared in the 1976 *Uniform Building Code* (ICBO) and equivalent editions of other U.S. codes used are identified in the ASCE 31 table. Thus, "older concrete buildings" in this study are taken as those that were designed to earlier codes and are referred to in this study as "pre-milestone" designs.

Concrete has been used alone in U.S. buildings in many configurations, including a wide variety of both gravity and lateral systems, as well as in combination with structural steel and wood. Characteristics of older inadequately reinforced concrete buildings that make them, as a class, high risk are:

- Brittle failure modes and/or cyclic degradation in lateral-force-resisting elements and

- Shear failures that lead to shortening and loss of capacity in a gravity-load-supporting element.

Those buildings that contain concrete but are unlikely to exhibit these failure modes should not be considered part of this class even if it is impossible to make such distinctions while collecting inventory data. In addition, tilt-up buildings (with much of their gravity load supported on independent steel columns and lateral performance typically controlled by diaphragm connections) and composite buildings (with structural steel embedded within concrete columns and beams) should not be considered part of this class.

Lift-slab buildings, although not common, are another special case. One dangerous failure mode is loss of support at the steel-column-to-flat-slab connection, which could be controlled by brittle concrete behavior. The lateral system for these buildings is typically a concrete core that, when improperly detailed, can exhibit serious degradation. Therefore, although mostly supported on steel columns, such a building is likely to suffer a brittle concrete failure and should be included in the class.

Steel framed buildings with concrete shear walls also are a special case. In pre-milestone buildings, it is expected that shear walls will be minimal and, although the initial response of the lateral system will mirror concrete behavior, the collapse potential is much different. It is recommended that these buildings not be included in an inventory of older concrete buildings; however, if local construction practices are known to produce buildings of this type that perform poorly, they can easily be included.

Process Used in This Study

A small workshop was convened with representatives from the various regions of the country with moderate to high seismicity. Each attendee described the typical types, ages, and characteristics of older concrete buildings in his/her region. Both the PEER Grand Challenge and the Concrete Coalition were represented. Characteristics of concrete buildings including occupancy, height, lateral-force-resisting system, gravity support system, and configuration deficiencies (soft story, torsional layouts) were identified and discussed. Several categorization schemes were assessed to determine their applicability to inventory collection and the potential to differentiate risk. Workshop participants agreed that the characteristics of a given concrete building that may indicate a high risk of collapse typically will not be available during collection of inventory data unless engineering evaluation to at least the level of detail of rapid visual screening (FEMA 154) is employed.

Based on the workshop discussions, the general method recommended herein was developed, proposed to the workshop participants, and discussed and refined as described in Chapter 3.

Background of Use of Model Building Types and Other Inventory Classification Systems

FEMA Model Building Types (MBT)

Several sets of standard structural types have been created to describe the building inventory of the United States. These model building type classification systems initially were developed for the purposes of assigning fragility relationships to inventories of buildings for loss estimation in ATC 13 (ATC, 1985). Studies of the existing U. S. inventory during development of ATC 14, *Evaluating the Seismic Resistance of Existing Buildings* (ATC, 1987) identified a large variety of construction types and subtypes, but identified 15 primary lateral-force-resisting systems that could be used to group evaluation considerations.

This classification system included only five types of concrete building:

C1 – Concrete moment-resisting frame buildings
C2 – Concrete shear wall buildings
C3 – Concrete frame buildings with unreinforced masonry infill walls
PC1 – Tilt-up buildings (primarily West Coast style tilt-ups with exterior bearing walls)
PC2 – Precast concrete frame buildings

ATC 14 was later adapted for use in the FEMA series as FEMA 178, *NEHRP Handbook for Seismic Evaluation of Buildings* (FEMA, 1992a). This set of building types has subsequently been used extensively in other FEMA documents related to existing buildings (FEMA 154, 1988; FEMA 227, 1992b; FEMA 156, 1995) and has become known as the FEMA Model Building Types.

Recently, the concrete group of buildings was expanded in FEMA 547, *Techniques for Seismic Rehabilitation of Existing Buildings* (FEMA, 2007), to better differentiate between buildings that are primarily composed of bearing walls and those that have a few walls within a gravity frame structure. Specifically, concrete shear wall buildings (Building Type C2) were split into two groups, those with essentially complete gravity frames (Building Type C2f**)** and those primarily using bearing walls (Building Type C2b).

FEMA 154, Rapid Visual Screening

The importance of quickly and efficiently identifying high-risk buildings was formally recognized in FEMA's original action plan to mitigate risks from existing buildings developed in 1985 (FEMA, 1985). Implementation of that portion of FEMA's plan resulted in *Rapid Visual Screening of Buildings for Potential Seismic Hazards* in 1988, updated in 2002 (FEMA, 2002). The method is based on a first-level categorization of a building into a FEMA Model Building Type and a second-level identification of risk characteristics such as age (to determine design code), height, configuration irregularities, and site soil type. The final result is a numerical score intended to be used to rank buildings by relative risk.

Although it was originally intended as a screening method that could be completed in the field, the data judged to be minimally necessary for estimation of relative risk for most engineered structures could not be recognized at the site. Except for wood (W1 and W2), tilt-up (PC1) and URM buildings, the identification of model building type, which is dependent on the material and type of lateral-force-resisting system in the building, typically requires review of construction drawings. In addition, vertical and plan configuration irregularities identified in the field often prove to be structurally insignificant.

The FEMA 154 process also collects occupancy data that are potentially useful to community planners and risk managers. Occupancy data often are related to structural types, and guidance for these relationships is given in Tables D4 through D7 of the document. The occupancy classes included are assembly, commercial, government, historic, industrial, office, residential, and school. In addition, the tables estimate the number of occupants and notes apparent exterior falling hazards.

FEMA 154 has been used extensively both with and without a drawing review but most commonly to collect general inventory information and to gauge a community's overall risk rather than to identify high-risk individual buildings.

The FEMA 154 developers concluded that subcategorization beyond the MBT should be dependent on several variables, the weighting and combining of which required numerical scoring. The need to combine characteristics to identify risk, even on the rapid visual screening level, indicates that the number of subcategories needed to represent all the combinations of significant characteristics and deficiencies of concrete buildings would be large and impractical. Further, experience with rapid visual screening indicates that even the most basic structural characteristics of buildings can seldom be identified without a level of effort approaching evaluation (engineering review of drawings and/or detailed field review of each building).

HAZUS

Emergency operations planners at the local, state, and federal levels use the HAZUS earthquake loss estimation methodology to estimate building damage, casualties, and monetary losses, thus making the HAZUS model building types one of the more widely used classification schemes. Unfortunately, this doesn't provide any additional insight into the ideal classification scheme for this study because, as indicated in the HAZUS Technical Manual (2003), the HAZUS model building types are based on the FEMA model building types that were described in the previous section. The HAZUS scheme includes the same five concrete classes as the standard FEMA set described above.

HAZUS refines the FEMA MBTs by accounting for the effect of building height on structural capacity and response by subdividing buildings into low-rise (1 to 3 stories), mid-rise (4 to 7 stories), and high-rise (8+ stories). The PC1 type (tilt-ups), however, includes only one height class (low-rise). In addition, using year built and location as a proxy for seismic design level, four code levels are defined: pre-code, low-code, moderate-code, and high-code. The fragility curves used to estimate the probability of experiencing or exceeding a specified level of damage are assigned to groups of buildings according to designated MBT, height, and code level. Thus, HAZUS theoretically separates concrete buildings into 60 groups (5 MBTs x 3 heights x 4 code levels) of different risk levels (as measured by expected losses). For older concrete buildings, only 2 of the 4 code levels would apply so the groupings would be reduced to 30. However, the parameters associated with each of these 30 "bins" are intended to apply to the average of a large number of buildings and cannot be automatically considered applicable to any individual building that falls in the bin.

Estimation of damage to the structural system does not fully capture the contributors to losses in an earthquake. Casualties, for example, depend not only on damage to the building but also on how many people occupy the building and, to some extent, the demographic characteristics of that population. Building contents damage and business interruption depend heavily on occupancy. The contents of an apartment building have a different character and value than those of a hospital. After an earthquake, an office might be able to move into temporary space and reopen immediately whereas a factory might be unable to operate until all damage was repaired. To take these things into account, HAZUS includes a building occupancy classification system that characterizes the inventory.

The HAZUS occupancy classification scheme comprises seven general classes: residential, commercial, industrial, agricultural, religion/nonprofit, government, and education. Each general class is further divided into specific occupancy classes. For example, the commercial class consists of 10 specific occupancies ranging from retail trade to banks to parking. An advantage of classifying inventory according to occupancy is that several available databases (county assessment rolls, the Dun and Bradstreet Business Population Report, and the U. S. Census) report certain relevant statistical data (nonbuilding specific) as a function of occupancy.

Developing a regional inventory is challenging because, except for a few rare specialized studies, detailed inventories that include structural information, particularly information about the lateral-load-resisting system, do not exist. Assessor records can serve as a source of systematically collected data that may be used as a proxy for the structural and occupancy information needed to estimate losses. Assessor records typically identify construction date, square footage, number of stories, and occupancy and provide a simplified indicator of structural type that is often tied to the fire code.

Assessor records, however, have limitations, the most evident being that they include only *taxable* properties. Publicly owned facilities such as hospitals, government offices, schools, universities, airports, and utilities are not captured in the assessment roll. Buildings owned by nonprofits such as churches and museums may also be missing. Since assessor records are collected for tax purposes, much of the structural information can be inaccurate. Because property taxes often are based on size of the building, the height and square footage data are more reliable. In California, property taxes are based on the purchase price of the property; therefore, some jurisdictions devote few resources to accurately maintaining some of the key data fields needed for loss estimation. A recent effort to inventory nonductile concrete buildings in the City of Los Angeles (Anagnos et al., 2008) found that up to five buildings could be represented by a single record. In the same study, the researchers found that a single building could be represented by multiple records. Perhaps the most challenging example is a high-rise condominium building that might have 50 records, one for each individually owned unit. Other challenges include multiple addresses for the same building or buildings for which the address changes over time. While assessor files can be used as a first step in creating a regional inventory, extensive cleaning of the data needs to occur using additional sources such as sidewalk surveys, zoning maps, aerial photos, and input from local engineers (Anagnos et al. 2008).

Relevant Concrete Building Attributes

Given current procedures, each of the attributes listed in Table 1 is sometimes used to determine the relative collapse risk of individual older concrete buildings but not all of the other key characteristics may be considered. Current standards or practice do not currently define unacceptable risk of collapse or provide an importance weighting of individual or combinations of attributes or even identified deficiencies. The approximate level of effort needed to collect the various data, based on current experience, is described to provide a better understanding of the possibilities for improving the usefulness of inventory data. The darker shading in Table 1 indicates the minimum process judged to be necessary to reliably determine the attribute. Any more complete process (columns to the right) also can determine the attribute. The lighter shading indicates the potential to determine the attribute based on the judgment of the data collector. The approximate level of effort is designated by equating to the following processes:

- Inventory – Information from Assessor files, Sanborn maps, socio-economic studies of the community, or "walk-bys."
- Rapid Visual Screening (RVS) – Procedures generally described in FEMA 154 including pre-field review of construction documents.
- Abbreviated Engineering Evaluation (AEE) – Process generally equal to Tier 1 of ASCE 31 but with investigation focused on deficiencies in older concrete buildings. Targeted calculations are assumed.
- Engineering Evaluation (EE) – Process generally equal to Tier 2 of ASCE 31.

Table 1 Level of Effort to Obtain Relevant Concrete Building Attributes

Attribute	Approximate Level of Effort			
	Inventory	RVS	AEE	EE
Occupancy				
Height				
Construction material				
Age				
FEMA Model Building Type				
Structural gravity framing				
Visual torsional shape				
Visual short columns				
Visual weak, soft, or tall story				
Confirmed configuration deficiencies				
Shear critical columns (short or otherwise)				
Heavily loaded columns				
Discontinuous walls				
Inadequate load path				
Adequacy of precast connections				
Inadequate strength of lateral system				

Key:

Minimum process judged necessary to reliably determine the attribute.
Potential to determine the attribute based on the judgment of the data collector.

Chapter 3
CONCLUSIONS AND RECOMMENDATIONS

General

The level of effort available to collect concrete building inventory data in a community will vary considerably depending on funding or the availability of local volunteers. Seldom, however, will the level of effort available be equal to the effort needed to completely understand the overall risk from these buildings or to single out individual buildings as collapse risks. Currently, the reliable identification of high-risk individual buildings that require retrofit as a matter of public policy (e.g., a mandatory retrofit program) requires detailed engineering evaluation. It is clear that a more inexpensive and efficient method to identify these buildings is needed. A useful first step will be to identify attributes or combinations of attributes that can be identified with little or no engineering analysis that would separate older concrete buildings into two groups:

- Those that do not represent significantly higher risk than “average” pre-milestone buildings and

- Those that represent a higher risk than average buildings to the extent that retrofit may be justified, either mandated by the community, or voluntarily by the owner.

However, even prior to development of efficient ranking or evaluation tools, there is consensus in the engineering community that knowledge of the local inventory of older concrete buildings is useful for emergency response and mitigation planning. The recommendations of this study therefore include collection of attributes at different levels of effort and detail.

Basic Inventory Data

Basic inventory data are defined here as the results of the typical first steps comprising analysis of assessor records and sidewalk observation. Review of drawings is not included; in fact, drawings often are not available or are inaccessible.

Of the attributes listed in Table 1 for this level of effort (occupancy, height, construction material, and age), construction material and age (at least with respect to the milestone year) must be known or estimated since this information is needed to qualify the building for inclusion in an inventory of older concrete buildings. That leaves occupancy and height within the overall category. It is recommended that all four attributes form the basic inventory when possible, with occupancy being the first priority due to its importance to planners for understanding the potential risk to the community from older concrete buildings. See Chapter 4 for a general discussion of the seismic performance characteristics that might be associated with each occupancy.

Enhanced Inventory

If additional resources are available to enhance the basic information and determine attributes of individual buildings, it is recommended that the next priority be identification of the structural system type. The set of FEMA Model Building Types is not particularly useful for older concrete buildings. The primary classification attribute is the lateral-force-resisting system (C1-frame, C2-shear wall, etc.), which often is not well defined in older concrete buildings; further, the risk posed by these buildings often is more dependent on the characteristics of the gravity load system. It is therefore recommended that, if structural systems are identified, both the gravity system and the effective lateral-force-resisting system be included. As discussed in Chapter 5 of this report, a large number of separate and distinct combinations of effective lateral system and gravity systems make up the broad category of older concrete buildings in the nation, but the number of structural types in any one community typically will be more limited. It is recommended that the structural system types that are present in a local community be established by knowledgeable local structural engineers, contractors, and building officials. Descriptions of structural types are given in Chapter 5 where they are organized by "family" using the FEMA Model Building Types as a starting point.

Other attributes that could be collected with an enhanced level of effort include visual clues (site observation as opposed to review of drawings) that may indicate deficiencies such as apparent soft or weak stories, apparent mass or stiffness configurations that could result in severe torsional response, or apparent short (shear critical) columns. It should be remembered, however, that such buildings may or may not have these deficiencies pending engineering analysis and, perhaps more important, that buildings with no visual clues may have serious deficiencies that could lead to collapse.

Attributes Requiring Engineering Review/Evaluation

The attributes listed in Table 1 beginning with "Confirmed configuration deficiencies" require engineering evaluation, most including at least rudimentary calculations. The identification of visual attributes or combinations of visual attributes that will allow subcategorization of concrete buildings into at least into the two risk groups discussed above is a critical need. Without such a rapid screening technique or a simplified engineering technique, it is not possible to priority rank the additional attributes regardless of the level of engineering involvement.

Summary of Recommendations

The recommendations of this study are summarized in Table 2. The basic level attributes, occupancy and height, are shown in the left column. These attributes were discussed in more detail in Chapter 4. The highest priority enhanced attribute, structural system type, is shown in the columns to the right with likely matches of structural system and occupancy highlighted. The highlighting is for demonstration purposes only and likely matches or prevalent structural systems in any community should be determined by local experts or systematically established by drawing or building review.

The first assignment of relative risks can be made by planners considering the importance of buildings in terms of post-earthquake response or occupancy load. Additionally, relative risk of structural failure can be gauged by reviewing the common deficiencies of various occupancies and structural system types noted in Chapters 4 and 5. No numerical system for this assignment of structural risk is included in this study, and such a rating would be dependent on the judgment of local experts.

Table 2 Recommended Attributes for Collection of Concrete Building Inventory Data

Occupancy *Group*[a] *(Basic Iinventory*	Height[b]	Total Number	**Structural System Types**[c] *(Enhanced Inventory)* C1g	C1s	C2b	C2f	C3m	C3c	PC2	PC2b
Warehouse/manufacturing	L									
	M									
Warehouse/manufacturing higher occupancy	L									
	M									
Small commercial	L									
Large commercial	M									
	H									
Low-rise residential/dormitory	L									
Hotel/motel residential	M									
Mid-/high-rise (small plate) residential	M									
	H									
Institutional/monumental/ academic	L									
	M									
Parking garage	L									
	M									
Assembly	L									
Essential services (police, fire, EOC)	L									
	M									
Hospital	L									
	M									
Schools K-12	L									
	M									
Special use ("other")	L									
	M									
	H									

Example of likely structural types for given occupancy. Likely structural types may change from city to city or region to region. See also Tables D-4 through D-7 in FEMA 154 (FEMA, 2002). For Enhanced Inventory, the number of buildings in each cell would be collected. See also discussion of Enhanced Inventory in Chapter 3.

[a] Occupancy group; see Chapter 4.

[b] Building height in stories: L = 1 to 3, M = 4 to 8; H = >8

[c] Structural system types; see Chapter 5. Types shown:

- C1g Moment frame-column/girder
- C1s Moment frame-column/slab
- C2b Shear wall-bearing wall
- C2f Shear wall-gravity frame
- C3m Frame with exterior masonry infill
- C3c Frame with exterior concrete infill or punched shear wall
- PC2 Precast-miscellaneous combination
- PC2b Precast shear wall-bearing wall

Chapter 4
DESCRIPTION OF RECOMMENDED OCCUPANCY GROUPS

General

As previously discussed, data concerning occupancy and height (or number of stories) are usually the most readily available when collecting inventory information. For example, both can be obtained from typical assessor files or from the street.

However, with any occupancy classification scheme, there are grey areas. What types of medical facilities qualify as hospitals? If a building has an institutional or academic owner but is basically an office building, should it be classified as commercial or institutional/monumental/academic? What about multiple occupancies? Fortunately, when collecting initial inventory primarily for the purpose of identifying a next step, these close calls are not critical. The description of typical attributes of the various occupancies categories in this section are intended to assist in assignment of occupancy. Although the actual occupancy and the building description given herein will not always match in the field due to the huge variation in construction types in the United States as well as changes in occupancies during the life of the building, the descriptions provided below are intended to give general direction to the inventory collector.

Similar to the issue of assignment of occupancy itself, structural attributes and collapse risk cannot be strictly assumed based on occupancy. Certain attributes often can be assigned based on the original occupancy, and when the combination of attributes that can lead to collapse is better understood, even a first-level (occupancy group) inventory will lead to an improved assignment of overall risk,

The recommended height ranges are somewhat arbitrary, but they are the same as those used in HAZUS and serve to refine the most common likely attributes of the building. For convenience, buildings of 1 to 3 stories are characterized as low-rise, 4 to 8 stories as mid-rise, and greater than 8 stories as high-rise.

Occupancy Descriptions

Warehouse/Manufacturing

<u>General Description.</u> Concrete buildings in this group usually are supported by a regular pattern of columns with very few permanent walls. The floor structure typically has a high load capacity that generally results in higher seismic mass at each level. The exterior walls of older warehouse-type buildings often are infill, either unreinforced masonry or a relatively thin (6 inch) and lightly reinforced concrete.

The elements of the “frame” are variable and may consist of round or square columns and floor systems of girder-joist-slab, beam-slab, or two-way slabs with or without drop panels. Due to the absence of structural walls, the *de facto* lateral system is the gravity frame dominated by the stiffer infilled exterior lines.

Warehouse buildings usually have moderate spans and are low- or mid-rise. Manufacturing buildings may have longer spans and larger floor plates, and they usually are low-rise.

<u>Potential Seismic Deficiencies.</u> The configuration of the perimeter infill can create short, shear critical columns if installed partial height. Solid infill at property lines on one or more sides can create a torsional irregularity. If infill is not presentincluded at the ground floor to create commercial space or a more open façade, a vertical irregularity can be created.

This building subtype often features large floor plates. Expansion joints were often used to break these buildings into smaller pieces, and the placement of these joints may cause eccentricities between the center of mass of each piece and the effective center of resistance.

The most important attribute influencing collapse potential may be the column design. Round columns often are built with spiral transverse reinforcing, reducing the possibility of shear failure and increasing capacity with improved confinement. Rectangular columns sometimes were built with spirals but not often. The presence of spirals in columns may force failures in the column-floor joint which could lead to collapse of corner columns or cause punching shear or other brittle shear failures in the horizontal floor framing.

Warehouse/manufacturing higher occupancy

The warehouse districts in many U.S. cities have been gentrified due to changing demographics. Buildings in these areas may be converted to studios, residential units, restaurants, or commercial spaces. In some cases, seismic upgrading was not required, either because seismic provisions were not enforced at the time or because upgrading requirements were forgiven to spur development. In such cases, the potential seismic deficiencies of the building subtype are the same as previously described for warehouse/manufacturing but the risk may be much higher due to the larger occupant load.

Small Commercial

<u>General Description.</u> This group includes office and “small” retail occupancies, repair garages, and other semi-industrial occupancies. The group consists of buildings primarily in the 1- to 3-story height range. In older cities, these buildings often were built property line to property line and are immediately adjacent to or against the neighboring building. The street front is usually open, at least at street level. In some areas, precast construction was used for this building type.

Framing systems are highly variable but often have solid concrete walls on the non-street sides. The roof structures may be of steel or wood construction.

Potential Seismic Deficiencies. The open store front may allow excessive drift leading to failure of the column elements. If the building is restrained by adjacent buildings, drift may be prevented, but the stiffness from adjacent buildings of shorter height may cause soft-story failure directly above the adjacent building. Truss elements in the roof construction may be inadequately tied to the supporting walls or columns and become dislodged. Precast concrete buildings designed without adequate seismic considerations may have inadequate connections between floor and column/wall elements or an inadequate load path to stiff vertically oriented components, allowing the structure to break apart and collapse.

Large Commercial

General Description. This group includes mid- and high-rise office buildings, hotels, department stores, and similar buildings. Framing, like that in the warehouse category, is open with few walls; however, the floors will be lighter than those in the warehouses. Concrete structural walls or masonry walls may be found surrounding elevators, stairs, and other shafts. Unreinforced masonry infill façades can be found but are unusual. Concrete exterior walls, either infill within frames or heavier bearing walls with no clearly identified column component, are more common. Exterior facades also may be nonstructural cladding.

Floor framing systems can be found with a full range of combinations of concrete components, but the column layout is typically regular. Concrete wall elements, if present at shafts or at the perimeter, will initially resist lateral loads. If this system is of inadequate strength, it will likely degrade and lateral loads eventually will be resisted by the frame system.

Potential Seismic Deficiencies. Torsional or vertical irregularities can be created by concrete walls if present. Short columns can be created by the façade configuration. Since these buildings are over four stories, drifts may be amplified by P-delta effects, causing column shear failure or side-sway collapse.

Low-Rise Residential/Dormitory

General Description. The dormitory-type residential building group is intended to include rectangular plan, low-rise configurations. Some of these buildings may be as tall as four stories but are characterized here as low-rise. The plan of a dormitory-type building is typically a double-loaded corridor. The structural system typically is a frame rather than a bearing wall system, and it is recommended that any bearing wall buildings of this type be placed in the residential hotel/motel category. The plan configuration of apartment or condominium buildings of this subtype may be more complex than a simple double-loaded corridor, but the distinguishing feature is the frame structural system rather than a bearing wall system.

Stair towers may be masonry or lightly reinforced concrete. Exterior walls may be unreinforced brick or clay tile masonry or lightly reinforced concrete masonry units (CMUs), but these buildings also may have light exterior walls of studs and stucco.

The floor framing systems in these buildings typically will be one of the column and beam systems, but the spans usually are moderate. One-way slabs are often employed between beam lines.

Potential Seismic Deficiencies. The wall system at stairways is seldom adequate to provide lateral resistance so the gravity frame or exterior frame with infill typically forms the effective lateral system. This creates the typical potential deficiencies for frames without seismic detailing, including short columns created by exterior enclosure material, inadequate overall strength or stiffness, and shear critical columns.

Hotel/motel Residential

General Description. This group represents a narrowly defined building subtype that is normally rectangular and mid-rise and characteristically built with bearing walls that also serve as demising walls between rooms and corridor walls. The floors are cast slabs or precast planks with or without topping. The exterior walls are window wall construction. Construction materials are either CMUs or cast-in-place concrete walls; although both perform similarly, only concrete is considered here.

Potential Seismic Deficiencies. The structures with precast planks without topping may be high risk, not only because the planks form a poor diaphragm but also because the connection between plank and wall is exceptionally weak without topping. With or without topping, the support bearing area of the precast planks at each wall often is very small and can suffer a vertical load failure under seismic loading. Another deficiency, often caused by the need for open space at the ground or lobby level, is that upper bearing walls may stop without adequate consideration of seismic loading. Therefore, although the buildings are often quite strong, a weak story could be created at the ground floor, exacerbated by potential shear failures in the walls.

Mid-/High-Rise (small plate) Residential

General Description. This building subtype is intended to represent another narrowly defined configuration and structural system. These buildings are mid- to high-rise buildings with 4 to 10 units per floor, all with perimeter exposure. The exterior is mostly glass. Many pre-milestone buildings were designed for lateral forces – at least wind and, in the West, also seismic. The lateral system typically consists of shear walls either concentrated in a central tower or distributed to also serve as bearing walls between units. Most of these buildings have gravity columns in some locations. In zones of higher seismicity, buildings over 160 feet in height will have a moment frame backup – theoretically with ductile detailing.

Potential Seismic Deficiencies. The base shear requirement for pre-milestone buildings was small and the lateral system may simply be exceptionally weak and may degrade under even relatively small ground motions, leading to dangerously large drifts. The tendency to have a more open ground floor or parking under the building also may create discontinuities in the shear wall system. Because of a likely high height-to-depth ratio, potentially large drifts and the potential for inadequately detailed gravity systems, this building subtype may be a high risk.

Institutional/Monumental/Academic

General Description. This group includes a wide variety of configurations and structural systems. Some of these building, if publicly owned, will not be listed in assessor files. However, many of the buildings intended for this subtype are low- to mid-rise and feature heavily fenestrated reinforced concrete facades. There are also examples of this building subtype that have masonry exterior walls with terra cotta fenestration. The gravity systems can be any of the systems previously described. The functional occupancy could vary from office to courtroom to museum.

Potential Seismic Deficiencies. In the case of heavy exterior concrete or masonry walls, unbalanced façade designs create structures subject to torsion. The exterior walls may degrade rapidly and stability will depend on the gravity framing system.

Parking Garage

General Description. Pre-milestone parking garages usually are low- to mid-rise structures and many have large floor plates. The framing is as open as possible and features one or more spans in the 60-foot range for drive aisles. Girders, often precast, span the drive aisle with slabs in between. All or parts of the flooring system may be prestressed or post tensioned. Concrete or masonry walls typically surround stairways and are sometimes structurally separated to allow shortening from the prestressed concrete floor elements. Pre-milestone garage structures that include seismic design may have a shear wall system but only few walls were used. The drive ramps connecting levels can significantly affect the structural response of these structures as described below.

Potential Seismic Deficiencies. Garages employing precast elements may have inadequate connections between elements, inadequate bearing details for girders, and inadequate load paths from the floors to lateral-force-resisting elements. Columns seldom have adequate shear/confinement ties and could be configured as “short” columns at perimeters or at ramps. Also, framing patterns often result in certain columns carrying an exceptionally high gravity load. The ramps complicate the lateral force system by acting as struts between floors or creating large holes in the diaphragms. The typical employment of very few lateral-force-resisting elements often creates large diaphragm spans and large chord and collector forces.

Assembly

General Description. This group includes a wide variety of configurations and structural systems. It is categorized separately here to capture the potential increased risk of high occupancy (e.g., theaters, churches, and auditoriums). These buildings are typically low-rise and often only one story. The street frontage typically is relatively open for entrance to a lobby. A portion of the building will be framed with spans of 40 feet or more to form the meeting space. The roof may be framed with steel or wood trusses. Churches constructed of concrete often employ precast components or systems.

Potential Seismic Deficiencies. The open front may allow excessive drift leading to failure of the column elements. Truss elements in roof construction may be inadequately tied to the supporting walls or columns and become dislodged. Precast concrete buildings, designed without adequate seismic considerations, may have inadequate connections between floor and column/wall elements or an inadequate load path to stiff, vertically oriented components, allowing the structure to break apart and potentially collapse.

Essential Services (police and fire stations, emergency operations centers)

General Description. This group includes a wide variety of configurations and structural systems. It is categorized separately here to capture the occupancy and its importance to emergency planning. Inventory data for these buildings often are available from the local jurisdiction and, because they are public buildings, will not be found in assessor files. These buildings are typically low- or mid-rise.

Potential Seismic Deficiencies. The variety of buildings in this subtype is too great to permit meaningful suggestions about structural attributes or characteristic seismic deficiencies.

Hospital

General Description. This group includes a wide variety of configurations and structural systems. It is categorized separately here to capture the occupancy and its importance in post-earthquake response. Inventory data for this occupancy often will be available from local, state, or regional agencies or associations. This occupancy group shares many of the characteristics of the monumental/institutional/academic group. Due to requirements for flexible planning, hospitals are seldom supported with a bearing wall system but shear walls may be employed in isolated locations. A typical hospital configuration includes a patient tower on a larger base. Since the functions and interior planning change abruptly at the transition between tower and base, discontinuities of both the gravity and lateral force systems may occur at this location. Many hospitals are built in stages, potentially creating incompatible structures immediately adjacent or even abutting one another. Expansion joints are sometimes, but not always, used between the “additions.” Utilities often do not have flexile connections at these joints.

Potential Seismic Deficiencies. In those buildings with heavy concrete or masonry exterior walls, unbalanced façade designs will create structures subject to torsion. The exterior walls may degrade rapidly and stability will depend on the gravity framing system. Tower walls that are discontinuous at the base may cause failure of supporting systems under seismic loading.

Schools K-12

General Description. This group includes a wide variety of configurations and structural systems. It is categorized separately here to capture the occupancy, which is often of special concern to the community. Public schools will not be listed in assessor files but private schools typically are. The group can include classrooms, administration buildings, gymnasiums or auditoriums or shops, all of which may have different characteristics. These buildings are most commonly low-rise but urban schools, particularly high schools, may be in the mid-rise height range. College or university buildings could be put in this occupancy group, could be put into the group containing academic buildings, or could be placed into a separate group of their own if locally appropriate.

Potential Seismic Deficiencies. The variety of buildings in this subtype is too great to permit meaningful suggestions about structural attributes or characteristic seismic deficiencies.

Special Use ("Other")

General Description. The group is simply a placeholder for gathering other inventory data. Unique occupancies that do not fit in any of the recommended categories can be placed here and included in the total count. It is recommended that the characteristics that make the building unusual be noted.

Chapter 5
DESCRIPTION OF TYPICAL STRUCTURAL SYSTEM FAMILIES

General

Model building type categorization systems generally have been based on material and lateral load system. For example, the FEMA system previously discussed includes concrete moment frames (C1), concrete shear walls (C2), steel moment frames (S1), steel braced frames (S2), etc. Although a convenient system for many purposes, it often is inadequate when trying to describe individual structures, particularly older buildings without a well defined (or designed) lateral system. Considering U.S. concrete construction, dozens (or possibly even hundreds) of individual structural types have been built given all the various gravity systems and all the possible real or effective lateral force resisting systems used. FEMA 547 (FEMA, 2007) notes that the C2 (shear wall) category was inadequate even to make the important distinction between shear wall-bearing wall buildings and shear wall-gravity frame buildings. When trying to identify seismic collapse potential, currently the first priority when considering older concrete buildings, documenting the details of the gravity system probably is as important as knowing what type of lateral-force-resisting system is used.

The FEMA lateral force system categories and letter designations (C1, C2, etc.) are maintained here but are expanded to *families* to include all the different gravity systems likely to be found within the broad category.

Much of this chapter presents only slightly edited text from FEMA 547 (FEMA, 2007).

Structural Frame Families

Concrete Moment Frame Family (C1)

Description of the Structural System. These buildings consist of concrete framing, either a complete system of beams and columns or columns supporting slabs without gravity beams. Lateral forces are resisted by cast-in-place moment frames that develop stiffness through intended or unintended rigid connections of the column and beams or slabs. The lateral-force-resisting frames can consist of the entire column and beam system in both directions or the frames can be placed in selected bays in one or both directions. An important characteristic is that no significant concrete or masonry walls are present or that they are adequately separated from the main structure to prevent interaction. Some buildings of this type have frames specifically designed for lateral loads as well as interacting walls apparently not accounted for in the design. These buildings can be assigned, as they are here, to the Moment Frame Family in light of the potentially interacting walls or to the Shear Wall with Gravity Frame Family (C2g). Older concrete buildings may include frame configurations that were not designed for lateral load, but if no walls or braces are present, the frames become the effective lateral force system and should be included in this building category. Buildings of this type that include an integral concrete frame with infill concrete or masonry walls on the perimeter should be placed in the Concrete Frames with Infill Masonry Shear Walls Family (C3). Floors may be a variety of cast-in-place or precast concrete.

Variations Within the Building Type. The primary variation within this building type is the type of frame and the number of frames included. Frames can range from column-girder systems of one bay on each face of the building to systems that employ every column coupled with two-way slabs. Frames classified as ductile or semiductile by code beginning in the late 1960s and early 1970s – but still pre-milestone – are far more constrained in configuration due to prescriptive rules governing girder configuration, strong column-weak beam, and limitations on joint shear.

It is unreasonable to develop alpha-numeric designations for each combination of girder frame, flat-slab frame, perimeter frame, and one-bay frame coupled with several variations in gravity system. It is recommended that such designations be developed at the local level if needed. It is also recommended to maintain at least the basic FEMA designation (C1) in any such system.

Floor and Roof Diaphragms. The floor and roof diaphragms in this structural type are essentially the same as those in the bearing wall system and are almost always cast-in-place concrete. The diaphragms are stiff and strong in shear because the horizontal slab portion of the gravity system is either thick or frequently braced with joists. However, one-way joist systems could be inadequate in shear in the direction parallel to the joists. Collectors are seldom in place and transfer of load from diaphragm to shear wall must be carefully considered.

Seismic Response Characteristics. This building type must be separated into older frame systems, often not even designed for lateral loads and including few, if any, features that would assure ductile behavior, and frames specifically designed to exhibit ductility under seismic loading. Rules for design of ductile concrete frames were developed during the 1960s.

Older, nonductile frame buildings, assuming an insignificant amount of concrete or masonry walls are present, will be far more flexible than other concrete buildings and will probably be relatively weak. Most important, the columns often will not be stronger than the beam or slab system, forcing initial yielding in these key elements. In addition, unless spiral ties were used, the column typically will fail in shear before a flexural hinge can form. Buildings with these characteristics are among the most hazardous in the U.S. inventory and are in danger of collapse in ground motion strong enough to initiate shear failures in the columns. Buildings of this type that are configured such that initial hinging occurs in the floor system rather than the columns will exhibit stiffness and strength degradation and large drifts but, unless exceptionally weak, are far less likely to collapse. The ratio of the inherent strength of the frame – designed for lateral loads or not – compared with the seismic demand has a large influence on the performance, and frames in low and moderate seismic zones may be at less risk for this reason.

Semiductile frames, with some but not all of current design features for concrete frames, likely will perform better, particularly if the columns are relatively strong and are designed to be flexurally controlled. However, many of these early concrete frames may be excessively weak and suffer from high ductility demands that could have serious consequences if a soft or weak story is also present due to architectural configuration or column layout.

Concrete Shear Wall (Bearing Wall Systems) Family (C2b)

<u>Description of the Structural Family.</u> Reinforced concrete walls in a building will act as shear walls whether designed for that purpose or not; therefore, cast-in-place concrete buildings that contain any significant amount of concrete wall will fall into this category. However, there are two distinctly different types of concrete wall buildings, those that contain an essentially complete beam/slab and column gravity system and those that use bearing walls to support gravity load and have only incidental beam and column framing. In these recommendations, these structural types have been separated and are designated as either in the Gravity Frame System Family (C2f) or the Bearing Wall Family (C2b). This discussion covers the bearing wall type. In this type of building, all walls usually act as both bearing and shear walls. The structural type is often used in mid- and low-rise hotels and motels. This system also is used in residential apartment/condominium type buildings.

<u>Variations Within the Building Type.</u> In order for this framing system to be efficient, a regular and repeating pattern of concrete walls is required to provide support points for the floor framing. In addition, since it is difficult and expensive to make significant changes in the plan during the life of the building, planning flexibility is not normally an important characteristic of the building occupancy. The occupancy type that most often fit these characteristics is residential including dormitories, apartments, motels, and hotels. These buildings often will be configured with reinforced concrete bearing walls between rooms – also acting as shear walls in the transverse direction – and reinforced concrete walls on the interior corridor acting primarily as shear walls in the longitudinal direction. Sometimes the longitudinal lateral system includes the exterior wall system although this wall is normally made as open as possible. In any case, the wide variation in structural layouts and occupancies that is included in frame buildings (C2g) is not seen in bearing wall buildings.

It is seldom possible to plan a building layout that provides complete gravity support with walls only and often local areas are supported with isolated columns and sometimes with beams and girders (story heights in these buildings are usually small and added depth in the floor framing system for girders is difficult to obtain). The extent of such beam and column framing may suggest a structural system of frames with walls, but structures should have an essentially complete gravity frame system to be considered a frame with walls. If significant plan area is supported solely by walls, the structures normally are classified as bearing wall.

There are important variations in floor framing systems employed in this building type and their adequacy to act as a diaphragm is an important characteristic of this building type as discussed below.

Floor and Roof Diaphragms. The parallel layouts of supporting walls and the need to minimize story heights normally leads to the use of one-way uniform-depth concrete floor systems. Cast-in-place and precast systems, both conventionally reinforced and prestressed, have been employed. The precast systems often are built up of narrow planks, which may not provide an adequate diaphragm unless a cast-in-place topping is provided. In addition, the precast systems may be placed with only a very narrow bearing area on the supporting walls, which may be inadequate to provide vertical support during seismic movements. The adequacy of the shear connection between slab and walls also is often an issue for both cast-in-place and precast systems. Either of these deficiencies could lead to collapse of a bay.

Seismic Response Characteristics. Due to the extent of wall, bearing wall buildings will be quite stiff. Elastic and early post-elastic response will therefore be characterized with lower-than-average drifts and higher-than-average floor accelerations. Damage in this range of response should be minimal.

Overall post-elastic response often may include rocking at the foundation level. If rocking does not occur, the height to length ratio of shear walls in these buildings may force shear yielding near the base, which may lead to strength and stiffness degradation.

Global stability also may be compromised by poor connections between floor slab construction and bearing walls as discussed above.

Shear Wall Behavior. When subjected to increasing lateral load, individual shear walls or piers will often force yielding in spandrels, slabs, or other horizontal components restricting their drift and eventually either rock on their foundations, suffer shear cracking and yielding, or form a flexural hinge near the base. Shear and flexural behavior is quite different, and estimates of the controlling action are affected by the distribution of lateral loads over the height of the structure, which is partially dependent on the exact nature of the time history of ground motion.

Yielding of spandrels, slabs, or other coupling beams can cause a significant loss of stiffness in the structure. Flexural yielding will tend to maintain the strength of the system, but shear yielding, unless well detailed, will degrade the strength of the coupling component and the individual shear wall or pier will begin to act as a cantilever from its base. In this building type, the coupling elements are often slabs and their lack of bending stiffness may reduce or eliminate significant coupling action.

Rocking is often beneficial, limiting the response of the superstructure. However, the amplified drift in the superstructure from rocking must be considered. In addition, if varying wall lengths or different foundation conditions lead to isolated or sequenced rocking, the transfer of load from rocking walls must be investigated. In buildings with basements, the couple created from horizontal restraint at the ground floor diaphragm and the basement floor/foundation (often termed the "backstay" effect) may be stiffer and stronger than the rocking restraint at the foundation and should be considered when present.

Shear cracking and yielding of the wall itself is generally considered undesirable because the strength and stiffness will degrade quickly, increasing drifts in general as well as potentially creating a soft story or torsional response. However, in accordance with FEMA 356, shear yielding walls or systems can be shown to be adequate for small target displacements. Type C2b buildings often will fall into this category.

Flexural hinging is considered ductile in FEMA 356 and will degrade the strength of the wall only for larger drifts. Similar to rocking, the global effect of the loss of stiffness of a hinging wall must be investigated.

Concrete Shear Wall (Gravity Frame Systems) Family (C2f)

<u>Description of the Structural Family.</u> Reinforced concrete walls in a building will act as shear walls whether designed for that purpose or not; therefore, concrete buildings that contain any significant amount of concrete wall will fall into this category. However, there are two distinctly different types of concrete wall buildings, those that contain an essentially complete beam/slab and column gravity system, and those that use bearing walls to support gravity load and have only incidental beam and column framing. In these recommendations, these structural types have been separated and are designated as either in the Gravity Frame System Family (C2f) or the Bearing Wall Family (C2b). This discussion covers the gravity frame type. Although it is typically assumed that the gravity framing is not part of the lateral-force-resisting system, the framing could add stiffness to the building, particularly near the top of taller buildings. This building type is very common and has been used in a wide variety of occupancies and in all sizes.

<u>Variations in Framing Systems.</u> There are wide overall variations within this building type due to the possible configuration and extent of the concrete walls, the many types of vertical framing systems used, and the lateral stiffness interaction between the two. In buildings with incidental concrete walls and a substantial beam-column gravity frame system, this building type merges with the Moment Frame Family (C1).

Gravity frame systems in this building type include cast-in-place concrete beam and slab, one-way joists, two-way waffles, and two-way or flat slabs.

In pre-milestone buildings, the walls were often intended for fire protection of vertical shafts, as exterior closure walls, or as bearing walls. However, buildings built in regions of high seismicity in the 1950s, 1960s, or early 1970s often were designed with a shear wall lateral-force-resisting system, but they are now often found to be deficient due to low global strength, a highly torsional plan layout, or detailing that leads to premature shear failure.

In buildings designed with shear walls, the walls are either strategically placed around the plan or at the perimeter. Shear walls systems placed around the entire perimeter almost always contain windows and other perimeter openings and are often called punched shear walls. On the other hand, older buildings will have concrete walls somewhat arbitrarily placed in plan.

It is unreasonable to develop alpha-numeric designations for each combination of shear wall configuration (core, perimeter, distributed, etc.) or extent (incidental, part of designed lateral system, etc.), each of these further subdivided with several variations in gravity framing. The designations of C2g and C2b were introduced in FEMA 547 and are maintained here. It is recommended that such designations be developed at the local level if needed. It is also recommended to maintain at least the basic FEMA designations (C2) in any such system.

<u>Floor and Roof Diaphragms.</u> The floor and roof diaphragms in this building type are similar to the moment frame system and are almost always cast-in-place concrete. The diaphragms are stiff and strong in shear because the horizontal slab portion of the gravity system is either thick or frequently braced with joists. However, one-way joist systems could be inadequate in shear in the direction parallel to the joists. Collectors are seldom in place and transfer of load from diaphragm to shear wall must be carefully considered.

<u>Seismic Response Characteristics.</u> Shear wall buildings, unless configured with only incidental or minimal walls, will typically be quite stiff. Elastic and early post-elastic response will therefore be characterized with lower-than-average drifts and higher-than-average floor accelerations. Damage in this range of response should be minimal.

Overall post-elastic response is highly dependent on the specific characteristics of the shear walls and the gravity frame components.

<u>Shear Wall Behavior.</u> When subjected to increasing lateral load, individual shear walls or piers will first often force yielding in spandrels or other horizontal components restricting their drift and eventually either rock on their foundations, suffer shear cracking and yielding, or form a flexural hinge near the base. Shear and flexural behavior is quite different, and estimates of the controlling action are affected by the distribution of lateral loads over the height of the structure.

Yielding of spandrels or other coupling beams can cause a significant loss of stiffness in the structure. Flexural yielding will tend to maintain the strength of the system, but shear yielding, unless well detailed, will degrade the strength of the coupling component and the individual shear wall or pier will begin to act as a cantilever from its base.

Rocking is often beneficial, limiting the response of the superstructure. However, the amplified drift in the superstructure from rocking must be considered. In addition, if varying wall lengths or different foundation conditions lead to isolated or sequencing rocking, the transfer of load from rocking walls must be investigated. In buildings with basements, the couple created from horizontal restraint at the ground floor diaphragm and the basement floor/foundation (often termed the “backstay” effect) may be stiffer and stronger than the rocking restraint at the foundation and should be considered in those configurations.

Shear cracking and yielding of the wall itself is generally considered undesirable because the strength and stiffness will quickly degrade, increasing drifts in general as well as potentially creating a soft-story or torsional response. However, in accordance with FEMA 356, shear yielding walls or systems can be shown to be adequate for small target displacements.

Flexural hinging is considered ductile in FEMA 356 and will degrade the strength of the wall only for larger drifts. Similar to rocking, the global effect of the loss of stiffness of a hinging wall must be investigated.

<u>Gravity Frame Behavior.</u> The lateral strength and stiffness of gravity frames will vary considerably among buildings in this type. In some configurations of this building type, the gravity frame will not significantly participate in the response. However, it is not uncommon in these buildings for a stiff and brittle gravity system to dominate both response and the extent of damage. For example, if concrete spandrels or sills on the perimeter of the building restrain the gravity columns (the "short column"), the column must take the full story drift over a short height, potentially causing shear failure and loss of gravity load capacity. Other gravity systems, such as flat slab or heavy beam and column systems, also can be sensitive to drifts, particularly to the increased drifts near the top of buildings with walls of a height-to-width ratio over 3. The frame action of the gravity system of these buildings may be beneficial or could form a deficiency but, in any case, the interaction with the shear walls should be considered.

Concrete Frames with Infill Masonry Shear Walls Family (C3)

<u>Description of the Structural System.</u> Buildings in the infill family are normally older buildings that consist of an essentially complete gravity frame assembly of concrete columns and floor framing systems. The floors can consist of a variety of concrete systems including flat plates, two-way slabs, and beam and slab. Exterior walls, and possibly some interior walls, may be constructed of unreinforced masonry, tightly infilling the space between columns horizontally and between floor structural elements vertically, such that the infill interacts with the frame to form a lateral-force-resisting element. Exterior walls also may be constructed of lightly reinforced concrete, often 6 to 8 inches thick and poorly reinforced. Windows and doors may be present in the infill walls. The buildings intended to fall into this category could have exposed clay brick masonry, terra cotta, or exposed concrete on the exterior.

<u>Variations Within the Building Type.</u> The building type was identified primarily to capture the issues of interaction between unreinforced masonry or other substantial infill material and concrete gravity framing. The archetypical building has solid clay brick at the exterior with one wythe of brick running continuously past the plane of the column and beam and two or more wythes infilled within the plane of the column and beam. The exterior wythe of clay brick forms the finish of the building although patterns of terra cotta, stone, or precast concrete may be embedded into the brick. There are, however, many variations to this pattern depending on the number and arrangement of finished planes on the exterior of the building. For example, the full width of the infill wall may

be located with the plane of the column and beam with a pilaster built out and around the column and a horizontal band of brick or other material covering the beam; the beam also may be slightly offset from the centerline of the column to accommodate the pattern of exterior finishes.

Hollow clay tile masonry also may be used as an exterior infill material. Although this material often has a very high compression strength, the net section of material available to form the compression strut within the frame normally will contribute a lateral strength of only a small percentage of the building weight. The material being brittle and the wall being highly voided, these walls also may lose complete compressive strength quite suddenly. Therefore, walls of hollow clay tile infill probably will not contribute a significant portion of required lateral resistance except in areas of low seismicity and/or when walls are arranged as infill on both the exterior and interior of the building.

More recent buildings may have unreinforced concrete block masonry configured as an exterior infill wall with a variety of finish materials attached to the outside face of the concrete block. Similar to hollow clay tile walls, these walls may exhibit moderate to low compressive strength and brittle behavior that marginalizes their usefulness as lateral elements. In addition, hollow concrete block exterior walls often will not be installed tight to the surrounding framing, eliminating infill compression strut behavior.

This family also includes structures infilled with lightly reinforced concrete walls. Although often integral with the frame members, these frame-wall systems will respond similarly to those using masonry infill. As the concrete infill becomes thicker or the reinforcing becomes more substantial, the concrete infill structure will act more like a shear wall or punched shear wall system. There are no rules of thumb to differentiate this behavior.

It is unreasonable to develop alpha-numeric designations for each combination of various masonry infill materials, concrete infill thickness and reinforcing, each coupled with several variations in gravity framing. However, due to the basic difference in expected response to ground motion, it is recommend to differentiate, when possible, between buildings infilled with masonry and those infilled with concrete. In these recommendations, the designation of C3m is used for masonry and C3c is used for concrete. Additional designations can be developed at the local level if subtypes can be identified. It is also recommended to maintain at least the basic FEMA designations (C3) for any additional subtypes.

<u>Floor and Roof Diaphragms.</u> Floors are often flat plates or two-way slabs. Beam and slab or beam and joist systems also will be found in this building type. Typically these slabs provide adequate diaphragms.

<u>Seismic Response Characteristics.</u> Both in terms of stiffness and strength, the exterior infill walls will form the effective lateral system for this building type. The effectiveness of the system depends on the size and extent of openings and articulation of the plane of the wall. With solid or nearly solid infill panels, strut action will be stiff and strong. As openings in panels increase in size, struts or combinations of struts cannot effectively

form around the opening and the concrete columns and beams may begin to work as a moment frame with "fixity" at the beam-column joint provided by the masonry. For low and moderate intensity shaking, the exterior walls may provide adequate strength to satisfy the specified performance objective. As the shaking demand increases, the masonry will tend to crack and spall, losing stiffness and potentially creating a falling hazard. The complete concrete gravity system characteristic of this building type will provide additional stability but will probably quickly degrade due to inadequate column reinforcing. However, in configurations with large height to width ratios, end or corner columns could fail in compression or in regions of reinforcing splices, leading to partial collapse.

This building type often is characterized by a commercial store-front first floor with little or no infill at that level on one or more faces of the building. This can cause a soft-story condition or a severe torsional response if open on one or two sides only. Such conditions can lead to concentration of seismic deformation at the open level, potentially leading to local P-delta failure.

Precast Concrete Family (PC)

Following the FEMA Model Building Type format, there are two designations for precast buildings, one for tilt-up buildings (PC1) and one for precast frames with shear walls (PC2). The tilt-up category is meant to cover large floor plate, flexible diaphragm buildings with perimeter precast walls. Although seismically vulnerable, tilt-up buildings typically fail at the diaphragm-wall connection, not within concrete components and, as discussed in Chapter 1, are not considered in the general class of older concrete buildings. PC2 must therefore cover all other precast buildings and the FEMA title of "precast frames with shear walls" is limiting, particularly when considering the variety of precast structures found nationwide. Structures have been built with a wide-ranging combination of precast and cast-in-place concrete elements. Precast members may be limited to a floor system of hollow core or T-beam construction, may be used for the complete gravity support system (column or walls), or may include all elements of the gravity and lateral load resisting system.

<u>Description of the Structural Type.</u> For this chapter, Building Type PC2 includes buildings in which any of the horizontal or vertical elements of the lateral load system – including shear walls – are of precast concrete except for PC1 type buildings. Structures that employ precast members primarily to support gravity load but resist lateral loads with cast-in-place concrete components may have characteristics of types C1, C2, and PC2. For example, structures that employ only precast floor "planks" supported on CMUs or cast-in-place concrete walls overlap the definition of the C2b type previously described. However, if such floors also are supported on precast concrete walls, a PC2 family designation may be most appropriate. More definitive descriptions of boundaries between building type families can be developed locally if useful.

Extensive use of hollow core floor systems in buildings with concrete and masonry walls in southern regions of the United States makes this the single largest group of buildings utilizing precast components although, as previously discussed, this type could be placed in the C2b family. Parking garages (used exclusively for parking rather than mixed use) represent the next largest group of PC2 buildings. The PC2 building type also has been used in this country and internationally for a variety of other occupancy types including mid-rise office, hotel and residential buildings and low-rise residential, commercial, and prison buildings.

Precast double-tee roof, floor, and wall systems are prevalent throughout Utah, Arizona, and other portions of the central states. These buildings are typically constructed with precast double-tee bearing and nonbearing walls and precast girders and columns for support of interior loads. Buildings in this category generally are retail or storage facilities where large open spaces are necessary.

Gravity-Carrying Load Systems. Special attention is required for PC2 buildings in which concrete frames (beams, girders, and columns or moment frames) resist gravity load or a combination of gravity and seismic load. Very important to the performance of all concrete buildings with frames, including PC2 buildings, is the lack of ductile detailing in concrete columns not designated as part of the seismic-force-resisting system. As in C1 or C2 buildings, these columns in many instances do not have confining steel adequate to accommodate the drift imposed by the seismic-force-resisting system and, as a result, fail through longitudinal bar buckling and concrete crushing. Requirements for estimation of building drift have changed over time, and understanding of potential building deflection has improved with each observation of earthquake performance. As a result, it is important to revisit the ability of nonductile columns to accommodate estimated drifts even if they were checked when initially designed. In some precast buildings, the division of initial design responsibility between one engineering firm for the gravity load system and a second firm for the seismic-force-resisting system may have contributed to inability to accommodate estimated building deflections. In earthquake performance to date, diaphragm deflections have been a large contributor to deflection of nonductile gravity systems. Vertical elements, and most particularly moment frames, could also contribute significantly to gravity system deflection.

PC2 buildings with gravity and lateral loads supported exclusively by non-precast structural walls do not have the same issues of deflection of nonductile columns. Connections tend to be the primary issue of importance to these systems for both gravity and seismic load systems.

Shear Walls and Frames. Building Type PC2 may have a lateral-force-resisting system of concrete shear walls or moment frames, cast-in-place or precast. In PC2 buildings, critical behavior of shear walls is generally governed by connections including diaphragm to shear wall, shear wall above to shear wall or foundation below, and interconnection of shear walls within a story. In PC2 buildings with precast frames, field connections within the frame are critical to performance as is ductile detailing. Connection practice has varied widely over time and by geographic region.

PC2 buildings with precast bearing and shear wall elements, however, may exhibit more deflection and movement due to the segmental attachment of wall elements. These buildings may respond more like those in the PC1 Building Type except with rigid diaphragms and a higher inertial mass and the consequent torsional considerations.

Floor and Roof Diaphragms. In California, precast floor T-beams or hollow core planks are covered by a cast-in-place topping slab, reinforced to provide diaphragm action. These toppings need to be clearly differentiated from topping slabs place primarily as a leveling medium, which do not serve the same function of structurally interconnecting adjacent members. Welded connections between embedded inserts or plates may also be used to aid in alignment of members during erection, but should not be relied on for diaphragm action.

In other areas of the United States, common methods of joining floor sections include use of grouted hollow core joints (grout placed in the joint between two adjacent panels, relying on adhesion and/or friction for shear transfer) or welded insert plates. Cast-in-place topping slabs are not commonly used. In some areas outside the United States, hollow core planks are installed with no connection or grouting between adjacent planks and have demonstrated the extreme vulnerability of this construction method. Precast tee roof and floor systems before 1970 often were made with a 1-1/2-inch flange thickness. Roof systems were constructed without topping slabs and relied upon welded connections between panels.

As per the discussion of gravity load systems, deflection of the diaphragm system has been seen as a significant contributor to building deflection is past earthquakes.

Seismic Response Characteristics. PC2 buildings occur with a wide range of vertical element types. In most cases, the vertical element type will dictate the building seismic response: shear wall buildings will have short period response while frame buildings will have a longer period. In PC2 buildings, stiff diaphragm behavior will generally be assumed. Parking structure PC2 buildings with long diaphragm spans, however, have been observed to have inelastic behavior concentrated in the diaphragms rather than vertical shear wall or frame elements. To date, this has been brittle behavior resulting in premature diaphragm failure and excessive deflection.

Common Seismic Deficiencies. Construction of PC2 buildings in areas of high seismic hazard in the United States has been of limited quantity and relatively recent compared to most other concrete building types, resulting in limited opportunities to observe earthquake performance. Some of the notable deficiencies observed in PC2 buildings built in the 1970s include brittle welds as a result of improper (non-weldable) rebar spacer bars and the lack of pre-heat of the materials. Similar issues may be present through the 1990s in areas that have had no significant seismic event testing and may have poor code enforcement. Additionally, connection plates with small zones of embedment for dowels and steel connection, especially in parking garages, may be vulnerable to vertical load failure.

Insufficient in-plane shear wall strength and stiffness are possible seismic deficiencies in PC2 buildings and particularly in parking garages where shear wall length is generally limited. Insufficient in-plane moment frame strength is a possible seismic deficiency in

PC2 buildings and particularly of concern where the frame might not have been initially designed for seismic loads. Where strength is a concern, it is likely that stiffness, connections, and ductile detailing will also be inadequate and that major addition or enhancement of vertical elements is required.

PC2 buildings with precast tee and precast roof and floor diaphragms may be subject to performance degradation problems when connections undergo cyclical loading. Roof panels attached with embedded inserts can stress welds beyond capacity when mid-diaphragm deflections are considered on non-topped roofing systems.

Chapter 6
TARGETED PERFORMANCE-BASED DESIGN RESEARCH SUGGESTED BY THIS STUDY

The major recent efforts to collect inventories of older concrete buildings (Anagnos, 2008; Comartin, 2008) have confirmed that a significant deterrent to reducing the overall seismic risk from these buildings is the inability to efficiently rank individual buildings with regard to potential collapse or other performance measures. Unlike unreinforced masonry buildings, all older concrete buildings are not high collapse risks and current evaluation techniques are expensive and conservative. This study has attempted to develop a system within a normal inventory collection process that would assign older concrete buildings such a relative risk. However, although certain building subtypes may *tend* to include certain deficiencies, no reliable method of assigning risks has been identified short of engineering review and evaluation at some level. Current evaluation methods are judged to be too expensive and/or conservative for this purpose.

In order to further current efforts to identify high-risk older concrete buildings, efficient methods of evaluation must be developed that can lead to minimal and effective retrofit. Although performance-based design methods seek to predict all losses, the primary risk of concern from older concrete buildings is collapse. Those buildings for which economic or downtime losses are important also may justify more traditional (and extensive) PBD analysis. Therefore, it is critical to develop the following capabilities:

- Identification of structural attributes and combination of attributes that lead to collapse of older concrete buildings.

- Development of methods to identify such buildings without a traditional ASCE 31 or 41 evaluation. Perhaps these methods could be phased from detailed inventory collection to building-specific engineering review.

- Develop procedures to efficiently identify such buildings, as well as perform other PBD analyses, when construction drawings are not available.

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