Revised DRAFT

The International Macroseismic Scale

Part III. Building typology, vulnerability and damage

(Building Guide)

Prepared for the IMS Working Group

by

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Contents

1 Introduction

1.1 Aims

Part III of the International Macroseismic Scale (IMS) is intended to be read in conjunction with Part I, the Core Scale, and Part II Guidelines, and should be read by anyone intending to make intensity assignments at IMS intensity VI and above using IMS, either in the field or from documentary evidence, or to interpret IMS assignments made by others.

Part III aims to do three things:

- To describe in general terms the principal types of buildings which are likely to be encountered anywhere in the world, and to briefly describe major regional variations of these types.
- To identify the likely vulnerability characteristics of each principal building type and its regional variations, so that a vulnerability class (according to the vulnerability classes defined in the Core Scale) can be assigned to any individual building or group of buildings encountered.
- To identify the types and patterns of damage which are likely to be suffered by each principal building type and some variations, so that a damage grade (according to the five damage grades defined in the Core Scale, Damage Grade 1 to 5) can be assigned to an individual building or a group of buildings.

A key principle of IMS is that intensity assignments made using IMS should always be consistent with those made using EMS-98, so that any intensity assignment previously made using EMS-98 would not be altered if IMS had been used. In EMS-98 treatment of building types other than masonry and reinforced concrete was limited, especially regarding how damage grades in other building types differ from damage to masonry and reinforced concrete structures. This was conditioned by the evolution of EMS from the MSK scale in a European context. The application of the scale in a global context requires a more thorough examination of patterns of deformation in all the principal building types that may be encountered. This is the function of the following sections of the IMS.

Part III is organised by the principal structural materials, and has separate sections dealing with masonry structures, reinforced concrete structures, steel frame structures and timber frame structures. Buildings built using these four materials (used alone or in combination), constitute the vast majority of the existing building stock worldwide, and also virtually all buildings being built worldwide at the present time, and it seems unlikely that this will change in the near future, although building processes and design methods are constantly evolving. Each of these four principal types has a number of sub-types and regional variations of which the most important are described. These descriptions are intended to be understandable by people who are not specialists in buildings, but who may need to categorize buildings in the field or from documentary evidence. A number of photographs are given to aid identification of building types.

Annex II provides information about regional variations of each of the main structural typologies with some notes on their performance in past earthquakes and an estimate of the likely range of vulnerability classes.

For each principal structural material, an important section deals with vulnerability, and aims to define how a building class found in the field can be allocated to a vulnerability class. The most probable vulnerability class is defined if this is possible, and a likely range of vulnerability classes is given depending on observable characteristics of the building. The features of a building (e.g. age and condition, existing damage, configuration) leading to modification of the most likely vulnerability class are then identified, and guidance is given about the extent of vulnerability modification associated with each feature.

For each principal structural material the document provides a set of diagnostic descriptions and diagrams by which the grade of damage (Grade 1 to Grade 5) can be identified. The diagrams show examples of damage to a representative building of the particular typology at each damage grade. A number of photographic illustrations of each damage grade are also given.

1.2 Definitions and terms used

Some terms and definitions are commonly used throughout Part III, and such generic definitions are explained in this section.

1.2.1 Country groups

It is considered useful to offer a preliminary classification of countries with significant seismic risk into separate categories, to enable vulnerability classifications applicable to a building type in one country to be extended (with appropriate caution) to another country. "Significant seismic risk", means either countries in which structural design codes for normal buildings require consideration of earthquake loading or countries which have some experience of damaging earthquakes in the last 50 years.

Four country groups are identified, according to the level of seismicity and seismic awareness in the construction of buildings and the level of application of seismic codes. The four country groups are:

Group 1. Countries with high seismicity and awareness: high levels of seismic design and construction expected.
Group 2. Countries with lower seismicity, but generally good levels of design and construction.
Group 3. Countries with high seismicity, but lower awareness and poor quality of much construction.
Group 4. Seismicity mixed but very poor level of seismic awareness and generally unreliable quality of construction.

Group 1 countries are a small group of high income countries or regions of countries , with high earthquake risk and recent experience of destructive earthquakes , which have developed high standards of earthquake awareness and earthquake resistant design standards, which are effectively enforced.

Group 2 countries are other earthquake-prone high-income countries which have effectively enforced earthquake design standards, but with relatively lower levels of earthquake risk.

Group 3 countries all have a high level of seismic risk (at least in some parts of the country), and may have good design standards, but have lower standards of earthquake awareness and a poorer standard of construction and enforcement of earthquake regulations than Group 1 and Group 2 countries. These countries are mainly in the upper middle-income group, but may include some urban areas in lower middle-income countries.

Group 4 countries are earthquake prone countries characterised by very poor levels of seismic awareness, and poor levels of enforcement of earthquake resistant design regulations, leading to an unreliable and often very poor level of construction. These countries are generally in the lower middle-income and low-income group of countries.

1.2.2 Vulnerability modifiers

The effect of the modifier on the expected vulnerability class is summarised using one of the following three levels of modification:

- *Increase/decrease vulnerability by 1 class* - modifier affects vulnerability and may increase or decrease the vulnerability by 1 class or more.
- *Increase/decrease vulnerability by less than 1 class* – modifier affects vulnerability but in conjunction with other modifiers may increase or decrease the vulnerability by less than 1 class.
- *Minor increase/decrease in vulnerability* – although the modifier affects vulnerability it is unlikely on its own to cause a shift in the vulnerability class.

Vulnerability shifts resulting from each vulnerability modifier are independent of one another, and in principle are additive. Thus if a building has poor workmanship as well as significant irregularity, each of which would require a change of one vulnerability class to higher vulnerability, the combined effect would be a change of two vulnerability classes. However, a shift of more than 2 vulnerability classes should not be used in the case of multiple factors. Also, the vulnerability cannot in any case be classed as higher than vulnerability class A. If the factors affecting vulnerability seem likely to result in a greater vulnerability than class A (or two classes higher than the most likely vulnerability class based solely on the level of ERD), then such buildings should not be used for intensity assignment.

1.2.3 Levels of seismicity

The degree of earthquake resistant design for reinforced concrete structures is defined partly in relation to the level of seismicity for which a building is designed.

These levels of seismicity are assumed to be based on the peak ground acceleration (PGA) of the earthquake with a 10% probability of exceedance in 50 years (ground motion with 475-year return period), which is generally the basis of seismic loading defined in national or international earthquake codes

- *High seismicity* areas are those where the expected 475-year ground motion is PGA > 0.24g
- *Moderate seismicity* areas are those where the expected 475-year ground motion is PGA > 0.1g but PGA<0.24g
- *Low seismicity* areas are those where the expected 475-year ground motion is PGA< 0.1g.

1.2.4 Country vulnerability summaries

Tables are given for each construction material giving expected levels of vulnerability according to country groups (Section 1.2.4) and three code levels (pre-code, early code and modern code. The meaning of these code levels is as follows:

The level of the code refers to the code which was applicable at the time of construction of the buildings being investigated (but not necessarily fully enforced):

- *Pre-code* refers to buildings built before any earthquake-resistant design code was in use (i.e. design for gravity and/or wind loads only).
- *Early code* refers to codes which specify a seismic load, but do not incorporate any provisions for the ductile detailing of the structural components and connections (typically referring to codes in practice prior to the 1980s).
- *Modern code* refers to codes which specify seismic loads (usually in the form of a design response spectrum), and also incorporate ductile detailing requirements (typically codes introduced since the 1980s).

1.3 Assigning damage grades

It is important to use the scale as intended: a building's vulnerability class should be assigned without reference to the level of damage the building has suffered. That is, it is not appropriate to say: "There are two adjacent unreinforced load-bearing masonry (LBURM) buildings one is damaged at level 5 and the other at level 4,therefore they are vulnerability A and B respectively." Instead, the appropriate statement is: "There are two adjacent LBURM buildings, with expected vulnerability class A, one is damaged at level 5 and the other at level 4."

The following are brief guidelines for assessing damage to buildings in the field and applying a damage grade based on the written descriptions and diagrams of different damage grades.

- Conduct the survey from outside the building.
- Use the diagrams and text to identify the positions where damage is most likely, e.g. gable-end walls, beam-column connections, and use this to guide inspection points.
- Inspect as many sides of the building as possible so that in-plane and out-of plane failure may be observed.
- Where possible, move away from the building to inspect the roof.
- Observe both structural and non-structural damage (only external if the building has significant structural damage). Where possible, structural rather than non-structural damage should be the basis of the damage grade assignment.
- Note that the absence of damage outside the building does not necessarily imply absence of damage inside, especially, but not only, in the case of non-structural elements.
- Surveyor safety is of paramount importance. Ensure the team has the correct equipment to conduct the survey and does not enter damaged buildings.

1.4 Limitations

The buildings types described in this document are typical of those found in many of the areas of the world in which IMS is intended to be applied. However, worldwide coverage has not yet been achieved. In particular the coverage of building types is strongest for Europe and Turkey, North and South America, India, Pakistan and New Zealand. It is less good for Russia, Iran, Central Asia, Central America, Caribbean, North Africa, Oceania, China and sub Saharan Africa, for which additional building typology descriptions and regional variations are intended to be added in due course.

Vulnerability classes may be assigned using the guidance given in this document for low-rise (1 to 3 storey) and mid-rise (4 to 7 storey) buildings. Less experience is available in assigning intensities using buildings of 8 or more storeys and some caution should be used in identifying vulnerability classes for such structures.

In some parts of the world, rural masonry is significantly weaker (more vulnerable) than that characterised by vulnerability class A as defined here. For such buildings a high proportion (many or most) buildings collapse (suffer damage grade 5) at intensities determined by other classes of buildings as EMS VIII or less. Rather than introducing a new vulnerability class A- for such buildings, it is recommended, in the absence of sufficient detailed field evidence, that such buildings should at present not be used for intensity assignment. Such buildings have been found in rural parts of Eastern Turkey, Southern Iran and Western Pakistan.

Buildings of high public importance such as hospitals, buildings for the emergency services etc. are likely to have been designed to higher standards of earthquake resistance than normal buildings, and these should be used with caution in intensity assignments.

Use of this document for making assignments of intensity in historic earthquakes outside the European area, based on contemporary damage descriptions, should be done with caution, as there is little experience available in this activity.

1.5 Evidence used

For brevity, individual sources of evidence for each section of this document are not given. Rather this section summarises the sources used throughout the document, and a full list of individual sources is given in Annex II.

For the building typology descriptions use was made first of the descriptions as given in EMS-98. These were amplified by reference to building typology descriptions given in HAZUS (FEMA, 2003), in the GEVES study of Cambridge Architectural Research Ltd (CAR) (Spence et al 2007), in the World Housing Encyclopaedia (*www.**world-housing**.net*) and in the Earthquake Engineering Handbook (Chen and Scawthorn, 2005). Most of the sub-sections on regional variations (Annex II) make use of information given in the Housing Reports of the World Housing Encyclopaedia (WHE), individually referenced in the text. It is worth noting that in estimating vulnerability classes, authors of individual WHE Housing Reports were asked to identify classes according to the EMS-98 definitions, and these have been largely used.

The proposed vulnerability modifiers derive from studies by Michel and Sira (2012), Lagomarsino and Giovinazzi (2004), and Zuccaro (2002), but also from damage studies assembled in the Cambridge Earthquake Impact Database (CEQID), www.ceqid.org.

Damage grade descriptions have made use of the definitions of EMS-98, and where these have been extended, note has been taken of equivalent damage grade descriptions in HAZUS (FEMA, 2003). Photographic examples of building typologies and damage are mostly taken from EEPImap (Earthquake Engineering Photographic Investigation Map; www.eepimap.com) , and the diagrammatic representations of damage make reference also to the photographic examples in EEPImap, and those in ATC-20 (ATC, 1989).

Data on income-based categorisation of countries is from World Bank data.
http://data.worldbank.org/data-catalog/GNI-per-capita-Atlas-and-PPP-table

2 The Vulnerability Table

	Type of structure		Vulnerability Class A	B	C	D	E	F
Masonry	Vernacular unreinforced masonry	Adobe or earthen	○——	——|				
		Rubble stone or fieldstone	○					
	Unreinforced masonry	Cut stone masonry	|- - -	- - -○				
		Concrete block or brick masonry	|- - -	- - ○ - -	- - -|			
		Massive stone		|——	——○- - -	- - -|		
		Unreinforced with RC floors		|——	——○- - -	- - -|		
	Structural masonry	Reinforced			|- - -	- - ○——	——|	
		Confined		|- - -	- - - -	- - ○——	——|	
Reinforced concrete	Frame	Without ERD	|- - -	- - - ——	——○- - -	- - -|		
		With moderate level of ERD		|- - -	- - ——	——○——	——|	
		With high level of ERD			|- - -	- - ——	——○——	——|
	Wall	Without ERD		|- - -	- - ○——	——|		
		With moderate level of ERD			|- - -	- - ○——	——|	
		With high level of ERD				|- - -	- - ○——	——|
Steel	Frame	With no ERD or moderate level of ERD		|- - -	- - ——	——○——	——|	
		With high level of ERD				|- - -	- - ○——	——|
Timber	Frame	With no ERD or moderate level of ERD		|- - -	- - ——	——○——	——|	
		With high level of ERD				|- - -	- - ○——	——|

3 Masonry structures

3.1 Description

Masonry buildings vary worldwide depending on the building's age, purpose of construction and their geographic location. Buildings are traditionally comprised of units of material, for example stone or brick, which can be irregular or regular shapes, laid in courses and often but not always held together by mortar.   The term masonry can also be used to describe rammed (compacted) earth or mud wall constructions. Walls are the lateral load resisting system. Floors and roofs can be timber or reinforced concrete (RC) with the latter improving the seismic vulnerability of the structure. Improvements to seismic vulnerability can also be made by interventions such as reinforced concrete or wooden ring beams, reinforcement bars running through the units of material (reinforced masonry) and the use of masonry panels within a frame made from reinforced concrete to give more lateral resistance (confined masonry). For easy reference, the information on masonry buildings presented in this chapter is organised in three sections. In each section, the relevant masonry subclasses are listed:

- *Vernacular unreinforced masonry*: adobe or earthen; rubblestone or fieldstone.
- *Unreinforced load-bearing masonry*: cut stone masonry (EMS-98: simple stone; unreinforced); concrete block or brick masonry (EMS-98: unreinforced with manufactured stone units); unreinforced masonry with RC floors; massive stone.
- *Structural masonry*: reinforced masonry; confined masonry. (EMS-98: reinforced or confined).

3.1.1 Vernacular unreinforced masonry [VURM]

This construction type is practiced in countries regardless of their seismic risk and often in rural or poorer regions of countries. Regions where this building type is found include: Africa, Europe, Middle East, South Asia, Central and South America. This construction type generally has a high vulnerability to earthquakes. Performance can be somewhat improved by cost-efficient seismic strengthening methods. There are two subcategories of vernacular unreinforced masonry:

Adobe or earthen

Adobe and earthen construction is found in many countries with seismic risk such as Latin America, Africa, the Indian subcontinent and other parts of Asia, the Middle East and Southern Europe. According to the World Housing Encyclopedia, around 30% to 50% of the world's population lives or works in adobe or earthen buildings. Adobe construction is mud made into sun-dried blocks (unfired clay masonry units), earthen construction is mud rammed into the form of walls. Adobe mud blocks are widely used building materials and this type of construction is mainly used in rural areas and houses are typically single-storey. Adobe houses are also found in the urban areas of developing countries. In some countries, like Argentina and Chile, adobe construction is banned by building codes because of its poor seismic performance. The weight of the roof is one of the most important factors in the performance of such houses. Adobe and earthen construction in Iran may use a vaulted masonry, dome, steel-beam jack-arch or more recently a concrete roof. If these heavy roofs collapse, this results in increased fatalities. The type of housing encountered in some parts of Europe, where a wooden frame is filled in with laths covered with clay (known as "wattle and daub") is discussed in Section 5.1.

Rubblestone or fieldstone

Rubblestone masonry is commonly found in rural areas of countries in Europe and Asia. It is a traditional form of construction where rough, unhewn stones are used as the basic building material, usually with poor quality (mud or lime-based) mortar, leading to buildings which have heavy, thick walls with little resistance to lateral loading. Floors are typically of wood, and provide no horizontal stiffening and therefore no resistance to lateral loading. Roofs can be made of almost any material, either lightweight or heavy.

3.1.2 Unreinforced load-bearing masonry [LBURM]

This construction type is practiced in countries regardless of their seismic risk and in both rural and urban areas and is widespread. Regions where this building type is found include: Africa, North, Central and South America, Asia, Europe, the Middle East, Australia and New Zealand. This construction type generally has a high vulnerability to earthquakes but performs better than vernacular unreinforced masonry typologies. Unreinforced load-bearing masonry construction differs from vernacular unreinforced masonry construction as the masonry units are regular shapes; bricks have been moulded, dried and baked and stones have been dressed/hewn before construction, and concrete blocks cast in moulds. Units are sometimes arranged using techniques to improve the strength of the structure, e.g. larger and stronger stones to tie in the walls at the corners. The vulnerability of buildings is greatly influenced by the types of materials and quality of workmanship as well as the use of the building. Massive stone construction and historic buildings often perform better, however, large open volumes can introduce weaknesses. Performance can be improved by seismic strengthening methods. There are four subcategories of unreinforced load-bearing masonry.

Cut stone masonry (EMS-98: simple stone)
This construction type is practiced in countries regardless of their seismic risk, for example Africa, Central and South America, North America, Asia, Europe, the Middle East, Australia and New Zealand. Cut stone masonry is formed from regularly shaped units bonded together with mortar. Effective bonding between mortar and masonry units is essential to provide seismic resistance. The shape, size and material of the units and the type of mortar used can vary considerably.

Cut stone masonry is generally made from blocks of locally available natural stone material, e.g. limestone, sandstone and slate. Cut stone masonry houses generally use mortars which are either mud, lime or cement based.

Floor construction can be historic vaulted brick masonry spanning over the ground floor with timber joists and floor boards at the upper floor levels, or timber joists at all levels above ground, or more modern precast concrete joist systems or solid RC slabs. The latter are discussed in the section on unreinforced masonry with reinforced concrete floors. A variety of roofing systems can be used including tiled roof supported on timber trusses, fibre cement or steel sheets on steel trusses, and RC slab (flat or pitched).

Cut stone construction is relatively simple and cheap and therefore commonly used worldwide in residential buildings. Houses of this construction type are found both in urban and rural areas, with the quality of construction in the former usually superior to that of the latter. Houses in rural areas are generally smaller in size and have smaller openings and are typically single-family dwellings. Buildings in urban areas are often of mixed use, i.e. with a commercial ground floor and multi-family residential area above.

Concrete block or brick masonry (EMS-98: unreinforced with manufactured stone units)
This construction type is practiced in countries regardless of their seismic risk, for example: Pakistan, Australia and USA.

- Concrete block masonry consists of concrete block units cast from sand, gravel, aggregate and cement, bonded together by mortar.
- Brick masonry is clay which is used to form regular-sized masonry units, dried and burnt in a kiln. Unburnt clay units are referred to as adobe or earth bricks. Brick buildings generally use mortars which are either mud or lime or cement based.

Floor and roof materials are similar to those found in cut stone construction but newer methods are also being increasingly used in many parts of the world (e.g. pre-stressed concrete beams or perforated concrete or brick blocks, covered by a layer of concrete).

Concrete block and brick masonry construction are relatively simple and cheap and therefore commonly used worldwide in residential buildings. Houses of this construction type are found both in urban and rural areas. Houses in rural areas are generally smaller in size and have smaller openings and are typically single-family dwellings. Buildings in urban areas are often of mixed use, i.e. with a commercial ground floor and multi-family residential area above. Concrete block masonry construction is the most common type in urban areas, where clay may not be readily available, and ranges from one-storey houses to multi-storey buildings. This construction type is often highly vulnerable. Concrete block construction has started to replace stone and brick masonry in a number of regions because of its lower cost, particularly in Central and South America.

Concrete blocks and bricks are also commonly used as infill material within RC frame construction (see Section 4.1.1). However, this construction typology refers to situations where the blocks are used as load-bearing members without reinforcement. Concrete blocks are also used to make non-structural partition walls in a number of different types of buildings.

Unreinforced masonry with RC floors

Unreinforced masonry with RC floors is common in countries where cut stone, concrete block and brick masonry buildings are found. RC floors are more likely in countries with a higher awareness of seismic risk and codes for masonry building design and are used for floor structures in multi-storey masonry buildings. The horizontal elements of unreinforced masonry buildings strongly influence the resistance of a structure to lateral loading. Unreinforced masonry walls with RC floors (the horizontal elements), will behave significantly better than unreinforced masonry (cut stone, concrete block and brick) with timber floors when the masonry walls are of good workmanship (strong masonry units and good quality mortar). Where the walls are connected and tied together with a rigid floor slab with ring beams, the risk of out-of-plane collapse of the walls is reduced. This improved performance will only be realised if the RC floor is properly connected to the walls.

Massive stone

Buildings such as monuments, castles, large civic buildings, etc. use stone masonry consisting of large blocks. These buildings often have much lower vulnerability than other unreinforced masonry buildings. Special buildings of this type such as cathedrals or castles would not normally be used for intensity assessment for reasons given in Section 1.4. However, some cities contain areas of 19th century public buildings of this type, and therefore this construction type is important when making intensity assignments from historic documents.

3.1.3 Structural Masonry [SM] (EMS-98: reinforced and confined masonry)

This construction type is practiced in countries with a higher seismicity and often in countries which have a better awareness of earthquake resistant design, for example Slovenia, Argentina, Mexico, USA and Chile. This construction type generally has a lower vulnerability to earthquake than either of the unreinforced masonry typologies. There are two subcategories of structural masonry.

Confined masonry (EMS-98: reinforced and confined masonry)

Confined masonry construction consists of masonry sections confined by RC frame elements (both beams and columns) which are bonded or connected to the masonry, thus reducing the masonry walls into smaller panels that are more capable of withstanding earthquake shaking. This type of construction is used both in urban and rural areas, either for single-family residential construction or for multi-storey construction up to four or five stories in height.

It is important to note that in confined masonry it is not intended that the RC elements should act as a moment resistant frame (see Section 4.1.1) where the masonry panels would only act as non-structural infill. Additionally, a number of countries worldwide use mixed masonry and RC construction, which does not constitute a formal confined masonry construction and is likely to have a higher vulnerability than properly confined masonry. Examples of mixed construction (not confined masonry) are buildings where: concrete elements and masonry are not bonded; the concrete frame is poured prior to construction of the masonry panels; or the spacing between the concrete elements is too wide for the masonry panels to be considered confined.

Reinforced Masonry (EMS-98: reinforced and confined masonry)
In reinforced masonry, bars or steel mesh are embedded (in mortar or grout) in holes in the units, providing vertical reinforcement and between layers of masonry units in the mortar, providing horizontal reinforcement. This creates a composite material acting as a highly resistant and ductile wall system. The masonry units are either perforated brick or hollow concrete block. The floors and roofs are either wood, steel or concrete. For buildings with concrete floors, the roof and floors above ground-level may be composed of precast concrete elements, supported on interior beams and columns of steel or concrete; or in the case of larger commercial buildings, made of cast in-situ concrete slabs supported by the walls.

This construction type does not include strengthened unreinforced load-bearing masonry buildings, which are discussed in Section 3.2.6.

3.2 Vulnerability and vulnerability modifiers

The vulnerability range of masonry buildings is A to E. This range can be refined by subtype and then by subcategory as shown in Table 3.1.

Table 3.1 Expected vulnerability of masonry buildings

Masonry sub-type	*Masonry subcategory*	*Vulnerability*		
		Lower bound	*Upper bound*	*Most likely*
Vernacular unreinforced	Adobe or earthen	A	B	A
	Rubblestone or fieldstone	A	A	A
Unreinforced load-bearing	Cut stone masonry*	A	B	B
	Brick or concrete block masonry**	A	C	B
	Unreinforced masonry with RC floors	B	D	C
	Massive stone	B	D	C
Structural	Reinforced	C	E	D
	Confined	B	E	D

*EMS-98: simple stone; **EMS-98: unreinforced with manufactured stone units

Once an expected vulnerability class has been selected, the vulnerability can be modified further because of secondary vulnerability features. The remainder of this section explores the features of masonry buildings of all sub-types and sub-categories that can modify the expected vulnerability of the building. Similar vulnerability modifiers are also used for RC, steel and timber structures. A modifier may act to increase vulnerability of a structure, e.g. from class B to A, or decrease vulnerability, e.g. from B to C. Some modifiers can cause either an increase or decrease, for example, quality and workmanship: a well constructed masonry building would decrease the vulnerability, but a poorly constructed building would increase the vulnerability.

3.2.1 Quality and workmanship

Modification: Increase/decrease vulnerability by less than 1 class.

The use of good quality materials, i.e. strong masonry units and mortar and good construction techniques will result in a building with a lower vulnerability. Weak units and poor quality mortar increase a building's vulnerability. The quality of the mortar and the bond produced between masonry units is particularly important. If the mortar is of high quality, even vernacular masonry units can produce a reasonably strong building. Masonry buildings without mortars will have a much higher vulnerability.

Areas with poor quality of construction are also often areas where there is poor code implementation. In areas where there is good code implementation, work will be supervised and inspected, and quality of construction is likely to also be good. Conversely where code implementation is poor, quality of construction is also likely to be poor. It is important to note that even if there is good code implementation, if construction standards are poor, the building will have a higher vulnerability.

3.2.2 Floor and roof

Modification: Increase/decrease vulnerability by 1 class.

Both the material of the floor and the roof and the connections between horizontal and vertical elements influence a building's vulnerability.

- The floor material: Wooden or other flexible flooring increases vulnerability. RC floors decrease seismic vulnerability considerably (as described in Section 3.1.2).
- The roof material: Lightweight roofs suffer relatively less damage while buildings with heavier roofs suffer more damage. RC roofs with well-built and properly connected load-bearing walls can improve vulnerability, but buildings with RC roofs and low strength load-bearing walls are more vulnerable.
- A good connection between walls at the corners and junctions ensures 3-D behavior or a "box-like" structure and the redistribution of lateral forces among walls. The connection between the walls and the horizontal elements (floors and roof) highly influences the seismic performance of the building.

3.2.3 State of preservation

Modification: Minor increase in vulnerability

The condition of masonry buildings may also affect their vulnerability. Poorly built buildings may deteriorate over time by at least one vulnerability class. One should note that a building may appear to be in good condition because attention has been paid to maintaining the aesthetic appearance of the building only, e.g. new rendering and this does not necessarily mean that the structural system of the building is also in good repair.

Vulnerability of structures can also be increased if the structure has been weakened by damage from previous earthquakes. Such damage may have been poorly repaired or even covered; in such cases the building may have been left in a dangerous condition with a high vulnerability. For the same reason, damage from aftershocks may be much greater than would be expected if the building had not previously been damaged. Poorly repaired previous damage is difficult to identify in a field investigation, and it is important to know the recent earthquake history of a location before defining the vulnerability class of a group of vulnerable buildings.

3.2.4 Regularity

Modification: Increase vulnerability by less than 1 class.

Buildings which are irregular either horizontally (in plan), or vertically (in elevation), are commonly found to be more severely damaged in earthquakes than regular buildings. Two main features of irregularity in masonry buildings are:

- The number, size and position of openings: Large openings or a number of openings increases vulnerability.
- Wall intersections and the density and distribution of structural walls: Long walls without perpendicular stiffening increase vulnerability. Cavity walls with internal and external skins which are not properly connected increase vulnerability.

3.2.5 Position

Modification: Minor increase in vulnerability

The position of a building with respect to other buildings in the vicinity can affect its behaviour in an earthquake. In the case of a row of houses in an urban block, it is often those houses at the end of a row or in a corner position that are worst affected (vulnerability increase). One side of the house is anchored to a neighbour while the other is not, causing an irregularity in the overall stiffness of the structure which will lead to increased damage.

3.2.6 Strengthening

Modification: Decrease vulnerability by 1 class.

Over the past 30 years, there has been extensive research on the development of strengthening techniques. Typical strengthening techniques widely implemented include the following:

- Installation of an RC ring beam (or band) at the roof level.
- Stitching and grouting. Wall cracks are stitched with reinforcement and grouted with mortar to restore the wall integrity.
- Installation of metal ties. These ties can anchor a wall to the floor and roof diaphragms or to an opposite wall.
- Crack injection with cement paste or epoxy.
- Repointing.
- Shotcreting: strengthening of walls with shotcrete jackets.
- Reinforced cement coating or reinforced concrete overlay. These methods help the lateral load resistance of walls similar to shotcreting.
- Installation of vertical columns. These columns are anchored to the wall by metallic anchors to prevent the out-of-plane failure/overturning of the wall.

It should be noted that some of these techniques have been shown to have no or a negative effect on a building's vulnerability. For example, techniques where weak masonry walls are strengthened by shotcreting or jacketing, or timber floor diaphragms have been stiffened by a reinforced concrete overlay. As a result, unless detailed information about the building and local construction methods is obtained, it may be difficult to assess whether a vulnerability modification (increase or decrease) should be applied.

3.2.7 Country vulnerability summary

In a number of countries, masonry buildings are designed and built to comply with construction codes of practice. This can include both retrofitting or strengthening existing LBURM structures to make them code compliant (as described in the previous section) or the building of new, code compliant, structural masonry structures. Examples of these codes include: International Building Code; Eurocode (EC6); American Society of Civil Engineers (ASCE Seismic Rehabilitation of Existing Buildings), Caribbean Uniform Building Code (CUBiC), National Building Code of Canada (NBCC); New Zealand Masonry Standards; Chilean INN Building Codes (NCh1928, NCh2123, NCh433).

Table 3.2 lists the likely effect of country group and code level on the vulnerability of LBURM and SM buildings. The table is divided by country group (first column) and code level (pre-code, early code or modern code) (second column).

Table 3.2 Expected vulnerability classes for masonry classes LBURM and SM by country group, seismicity and level of code application

Country group	*Code level*	*Vulnerability class loadbearing unreinforced masonry (LBURM)*			*Vulnerability class structural (reinforced and confined) masonry (SM)*		
		Lower bound	*Upper bound*	*Most likely*	*Lower bound*	*Upper bound*	*Most likely*
Group 1 and 2 countries	Pre-code or early code	A	C	B	B	D	C
	Modern code	A	D	C	C	E	D
Group 3 countries	Pre-code or early code	A	C	A	B	D	C
	Modern code	A	D	B	C	E	D
Group 4 countries	All	A	B	A	B	C	B

3.3 Damage grade descriptions

Table 3.3 gives the written description of damage grade levels specific to masonry buildings. Figure 1.1 shows diagrammatic representations of the different damage levels for a generic masonry building. Figures ….. show photographs of buildings of the different masonry sub-types and sub-categories which have suffered different levels of damage.

Table 3.3. Damage grade diagnostics for masonry buildings

Grad e	IMS Definition	IMS Description	Further details for URM and RM (unreinforced and reinforced masonry
1	Negligible to slight damage (no structural damage, slight non-structural damage	Hairline cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.	

2	Moderate damage (slight structural damage, moderate non-structural damage	Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.	URM: Larger cracks around door and window openings in walls with large proportion of openings; movements of lintels; cracks at the base of parapets. RM: minor separation of walls from the floor and roof diaphragms.
3	Substantial to heavy damage (moderate structural damage, heavy non-structural damage)	Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roofline; failure of individual non-structural elements (partitions, gable walls).	All: Diagonal and X-shaped cracks near or between openings; vertical corner cracks; horizontal upper wall cracks. URM: Masonry walls may have visible separation from diaphragms. Out-of-plane failure of large pieces of the external wythe of masonry walls. Out-of-plane failure of gable wall especially in taller masonry buildings RM: Some walls may have visibly pulled away from the roof.
4	Very heavy damage (heavy structural damage, very heavy non-structural damage)	Serious failure of walls; partial structural failure of roofs and floors.	URM: Beams or trusses may have moved relative to their supports. Out-of-plane failure of load-bearing walls; wedge-shaped separation of walls at the corner(s). RM: Large, through-the-wall diagonal cracks and visibly buckled wall reinforcement. • *Wooden diaphragms* may exhibit cracking and separation along plywood joints. • *RC diaphragms* may exhibit cracking. Partial collapse of the roof may result from failure of the wall-to-diaphragm anchorages or the connections of beams to walls.
5	Destruction (very heavy structural damage)	Total or near total collapse.	Collapse due to in-plane or out-of-plane failure of the walls. 15% or above of the total area of URM buildings and 5 – 15% of high-rise, mid-rise and low rise RM buildings respectively expected to be collapsed.

4 Reinforced concrete structures

4.1 Description

Reinforced concrete is today probably the most common structural material used in the construction of urban housing worldwide, and constitutes a growing proportion of the total building stock. Its use has been widespread since the 1950s for urban housing, as well as for commercial buildings (hotels, offices), and in many cities for mixed-use buildings with commercial use or car parking located on the ground floor and housing above. Its popularity derives from its cheapness, from the ability of reinforced concrete to be used for multi-storey construction, enabling greater density of population in congested urban areas with high land prices, and also because of the flexibility of space planning within a building, allowing for larger openings and greater flexibility in placing partition walls than are possible in masonry buildings.

In most European countries the proportion of the urban housing stock which is built using some form of reinforced concrete ranges from 25% to over 75%. It is also used very widely in the urban areas of the developing world, comprising for example approximately 75% of the building stock in Turkey and about 60% in Colombia. However in a few highly earthquake-prone countries and regions (Japan, Western USA, New Zealand) most housing is built in the form of low-rise timber frame buildings.

The basic components of reinforced concrete frame construction are vertical columns and horizontal beams forming the frame, with reinforced concrete slabs spanning between the beams to form the floors and roofs. All these elements are reinforced with steel reinforcing rods which are arranged to provide continuity of reinforcement between columns, beams and slabs, creating a monolithic construction. If properly designed, such a structural arrangement is capable of carrying both gravitational loads and the lateral loads arising from wind or earthquake loading.

However, early reinforced concrete frame buildings were often found vulnerable to earthquakes because of poor materials, poor arrangement of the structural members, or poor detailing of the reinforcement. It has been found that using reinforced concrete walls, oriented in both longitudinal and transverse directions, rather than comparatively slender columns, as the vertical elements of the structure, enables buildings to be more robust in their earthquake response, and reduces their vulnerability to earthquake ground shaking. This guide, and the IMS Vulnerability Table (Core Scale), make a primary sub-division of reinforced concrete structures between reinforced *concrete frame* and *reinforced concrete wall* structures.

Another distinction, which can have important implications for earthquake vulnerability, is between *cast-in-place* concrete construction, in which the concrete is cast on site, allowing direct continuity of reinforcement between one cast section and the adjacent one, and *precast* concrete construction, in which the individual elements are cast off-site and joined together on site by welding or stitching of projecting reinforcing bars.

4.1.1 Reinforced concrete frame structures (RCF)

The structural system of a reinforced concrete frame structure consists of interconnected beams and columns in transverse directions, with floor and roof slabs spanning onto the beams. Joints between beams and columns are moment resisting - i.e. designed to carry bending moments and shear force.

Reinforced concrete frames are most commonly cast in place so that joints are monolithic, with reinforcement continuity between beams and columns and between beams and slabs. But frames made from precast components are also used, in which case a variety of proprietary arrangements are used to transfer the loads from beams to columns and slabs to beams. Sometimes the beams and columns are cast in place, but the slab is made from precast concrete ribs with masonry infill blocks, or slabs are of prestressed concrete. If the beams are integral with the slab, and of the same depth, the form of construction is called *flat-slab* construction.

Walls are generally formed by non-structural infill materials, such as lightweight concrete blocks or hollow terracotta blocks or other perforated bricks, which are not designed to provide lateral stiffening of the frame. These are sometimes built between the columns, which are often designed to have the same thickness as the walls, in which case they will have a stiffening effect on the frame (even though this is not allowed for in the design). In other cases the walls are either built partly or fully outside the concrete frame, depending on the floor plan, or infilling only part of a storey height, which can create weakness. In some cases the infill walls may be designed to carry lateral loads and use strong masonry units which are fully bonded with the RC frame.

Reinforced concrete frame structures can be of any height from single storey to high-rise structures. In many countries, the most common height is 3 to 7 storeys. Structures more than 5 or 6 storeys will generally have a mechanical lift in addition to stair access to higher floors; these stair and lift shafts may be built of cast-in-place concrete, but such *core* structures should still be classified as frame rather than wall structures.

Reinforced concrete frame structures often have the ground floor left partly or totally free of walls, in order to facilitate commercial or car parking use. The ground floor storey height may also be higher than that of upper floors. Such structures are often referred to as *soft-storey* structures.

The lateral resistance of reinforced concrete frame buildings is sometimes enhanced by reinforced concrete walls. Such *dual frame-wall systems* are expected to have improved earthquake vulnerability compared with frames without such lateral elements, but cannot be described as concrete wall buildings as defined in Section 4.1.2, unless the walls are of sufficient length and suitably placed to justify the term.

In undamaged buildings, reinforced concrete frame buildings can usually be distinguished from masonry buildings with some confidence, either through visible columns in the face of the building, or from the size and height of the building, or from the size of the openings, especially on the ground floor. In damaged buildings finishes or infill walls often fail exposing the frame; and local deformation at beam to column joints can often be seen. It is sometimes more difficult to distinguish RC frame buildings from steel frame buildings in the undamaged state, and knowledge of local practice may be needed to make this distinction.

4.1.2 Reinforced concrete wall structures (RCW)

The structural system of a reinforced concrete wall building is similar to that of a reinforced concrete frame building except that the vertical elements are walls (substantially longer than their width) rather than columns. The walls carry both vertical and lateral loads and are continuous throughout the building's height. They are continuously reinforced, normally in both faces of the wall, and special attention is given to the reinforcement of the wall end zones, and adjacent to door or window openings. The slabs span directly onto the walls with no beams.

A combination of walls and vertical columns may be used (so called dual-system), in which case the columns are linked by beams as in frame construction. But for the benefits of wall construction to be realised, the proportion of walls should be similar in each of the two directions (longitudinal and transverse) and total not less than about 5% of the plan area of each floor.

In some cases, cast-in-place walls are provided only at the centre of a building, for stair or lift towers, with the remainder of the building using a frame. Such core systems cannot be classed as reinforced concrete wall structures.

Reinforced concrete wall buildings may be either cast-in-place or constructed using precast concrete elements, using stitching or welding to create reinforcement continuity. In a number of countries, especially Russia and former USSR Republics, hundreds of thousands of housing units have been constructed using such precast concrete wall systems.

A form of concrete wall construction used widely in the USA and Australia for low-cost low-rise commercial buildings is *tilt-up construction*. Tilt-up buildings consist of perimeter reinforced concrete wall panels, cast horizontally on site, and subsequently tilted up into their final position. They are connected longitudinally to each other, and by connectors to timber floor and roof panels which provide rigidity and continuity. Performance of tilt-up construction in recent US earthquakes has been poor.

Recognising reinforced concrete wall buildings in the field, is not always straightforward as in many respects they are similar to reinforced concrete frame buildings. The presence of large walls without openings on one side of the building may be an indicator, and openings are generally smaller than for frame buildings. In damaged buildings loss of finishes and wall cladding can reveal the walls, which can also perhaps be seen where it is possible to enter the building. Otherwise knowledge of local practice may be needed to identify RC wall buildings with confidence.

4.2 Vulnerability and vulnerability modifiers for RC structures

The vulnerability range of RC structures is A to F. This range can be refined by subtype and then by subcategory as shown in Table 4.1.

Table 4.1 Expected vulnerability classes by expected levels of earthquake resistant design in reinforced concrete frame and wall buildings. .

Reinforced concrete sub-type	*RC subcategory*	*Vulnerability*		
		Lower bound	*Upper bound*	*Most likely*
Frame	without ERD	A	D	C
	with moderate level of ERD	B	E	D
	with high level of ERD	C	F	E
Wall	without ERD	B	D	C
	with moderate level of ERD	C	E	D
	with high level of ERD	D	F	E

4.2.1 Earthquake resistant design: general principles

The principal sub-categorisation of reinforced concrete structures in the IMS Vulnerability Table (Core Scale) is by the level of earthquake-resistant design. The Vulnerability Table distinguishes six subclasses as follows

- Frame without earthquake-resistant design(ERD)
- Frame with a moderate level of ERD
- Frame with a high level of ERD
- Walls without ERD
- Walls with moderate level of ERD
- Walls with high level of ERD

These subcategories are associated with likely vulnerability class C for frame and wall without ERD, D for frame and wall with moderate ERD and E for frame and wall with a high level of ERD, but a range of possible actual vulnerability classes is possible in each case resulting from both variations in the resistance level actually found in code-compliant buildings, from the extent of compliance with codes and from other vulnerability factors leading to modification of vulnerability, of which the most important are quality of construction, state of preservation and structural regularity. In general the probable range is greater for frame structures than for wall structures.

Selecting the most likely vulnerability class for a building or group of buildings for which the design criteria are not known is not straightforward. In all countries where reinforced concrete buildings are common, design requirements vary across the country according to the expected degree of seismicity, and have changed over time to respond to improving engineering knowledge; and it is not easy to judge, from the external appearance of any building or group of buildings, either when they were built, or whether the earthquake codes current at the time were properly implemented. Indeed this last vital point can probably only be known after an earthquake has occurred, though general country standards can in some cases be judged from performance in earlier earthquakes. Thus selection of the appropriate vulnerability class will remain highly uncertain, especially in those countries where building standards are poorly controlled. A conservative approach to the allocation of vulnerability class should therefore be adopted, allocating a building to the moderate ERD and high ERD category only where there is good evidence (from past earthquakes) of code compliance.

The following sections will first give a general definition of what is intended to be meant by each of the six primary sub-categories; secondly, the factors other than ERD which may affect the vulnerability are discussed and possible extent of resulting vulnerability modification is indicated; thirdly, a Table is included (Table 4.2), which gives the likely vulnerability classes for RC frame and wall buildings by country group taking into account code level and code level. For several countries the regional variations in Annex II may also be consulted to assess, for particular regions, the general building standards to be expected.

4.2.2 ERD level definitions for RC frame buildings

Definitions of the 3 levels of earthquake-resistant design to be used in deciding on appropriate vulnerability classes for RC frame buildings follow. See Table 4.2 for country-group variations.

Frame without earthquake resistant design
These are frames designed without taking account of earthquake loads and without ductile detailing either because:

1. The area is, or was at the time of construction, considered an area of low seismicity or
2. Although an earthquake code was in place defining appropriate earthquake loads it was not implemented, or was only poorly implemented

Such frames are designed for gravity and wind loads only which will provide some limited lateral resistance and ability to survive small seismic ground motion.
Vulnerability classes A to D are probable, with C most likely.

Frame with a moderate level of ERD
These are either:

1. frames designed taking account of earthquake loads at a level appropriate for areas of moderate seismicity (see Section 1.2.3) where detailing rules to ensure ductile behaviour in earthquakes are implemented, or
2. frames designed for areas of high seismicity (see Section 1.2.3) in which less than full implementation of code requirements in respect of detailing and/or construction quality is expected.

Vulnerability classes B to E are probable, with D most likely.

Frames with a high level of ERD
These are frames designed taking account of earthquake loads at a level appropriate for areas of high seismicity (see Section 1.2.3); modern (generally post-1980) codes are applied and ductile detailing is expected to have been implemented.
Vulnerability classes C to F are probable with E most likely.

For each class the most probable range may not be reached by some structures because of secondary vulnerability features discussed below. They may also be exceeded in structures of particular social importance which are subject to enhanced design requirements (see Section 1.4).

4.2.3 ERD level definitions for RC wall buildings

Definitions of the 3 levels of earthquake-resistant design to be used in deciding on appropriate vulnerability classes for RC wall buildings follow. See Table 4.2 for country-group variations.

Wall without earthquake resistant design
These are buildings with concrete walls as described in Section 4.1.2, but designed without taking account of earthquake loads and without ductile detailing because:

1. The area is, or was at the time of construction, considered an area of low seismicity or
2. Although an earthquake code was in place defining appropriate earthquake loads was not implemented, or was only poorly implemented.

Such buildings are designed for gravity and wind loads only which will provide some lateral resistance and ability to survive small to moderate seismic ground motion, but they will have low ductility and be vulnerable to more substantial seismic ground motion.
Vulnerability classes B to D are probable, with C most likely.

Walls with a moderate level of ERD
These are either:

1. Concrete wall buildings designed taking account of earthquake loads at a level appropriate for areas of moderate seismicity (See Section 1.2.3) where detailing rules to ensure ductile behaviour in earthquakes are implemented, or
2. Concrete wall buildings designed for areas of high seismicity (see Section 1.2.3) in which less than full implementation of code requirements in respect of detailing and/or construction quality is expected.

Vulnerability classes C to E are probable, with D most likely.

Walls with a high level of ERD

These are concrete wall buildings designed taking account of earthquake loads at a level appropriate for areas of high seismicity (see Section 1.2.3); modern (generally post-1980) codes are applied and ductile detailing is expected to have been implemented.
Vulnerability classes D to F are probable with E most likely.

For each class the most likely class may not be reached by some structures because of secondary vulnerability features discussed below.

4.2.4 Quality and workmanship

Modification: increase by 1 class

Quality of construction and workmanship are important modifiers of vulnerability for reinforced concrete structures, which are built worldwide often by builders who have limited understanding of the complexity of the structural action needed to resist earthquakes. Poor quality concrete due to inadequate mix, poor quality of bond between concrete and reinforcing steel, inadequate placing and detailing of reinforcement in columns and walls, beams and beam-column joints are often found vulnerable in post-earthquake damage surveys, even when the design has been done by engineers according to the relevant code. Such defects can be sufficient to change the vulnerability class by at least one class (e.g. from C to B).

Areas where poor quality of construction is found often overlap with those where there is poor implementation of the code of practice, and the two factors can interact with each other. Thus where the code implementation is good, work will be supervised and inspected, and quality of construction is likely also to be good. Conversely where code implementation is poor, quality of construction is also likely to be poor. But quality of construction and code implementation are not the same, and a level of vulnerability worse than that associated with the lowest level of design code is possible where construction standards are poor.

4.2.5 State of preservation

Modification: increase vulnerability by less than 1 class

The condition of RC buildings may also affect their vulnerability. Poorly built buildings may deteriorate over time, especially where the reinforcement has not been provided with adequate concrete cover, allowing it to corrode. A number of local weaknesses from such deterioration can be sufficient to increase a building's vulnerability by up to one vulnerability class.

A second cause of vulnerability increase which occurs in some cases is the weakening of the structure by damage from previous earthquakes. Such damage may have been poorly repaired or even covered; in such cases the building may have been left in a dangerous condition with a high vulnerability. For the same reason, damage from aftershocks may be much greater than would be expected if the building had not previously been damaged. Poorly repaired previous damage is difficult to identify in a field investigation, and it is important to know the recent earthquake history of a location before defining the vulnerability class of a group of vulnerable buildings.

A relatively small vulnerability shift less than 50% of one vulnerability class can normally account for the effect of poor state of preservation, unless major previous earthquake damage is visible in which case it is very difficult to identify the current vulnerability class.

4.2.6 Structural Regularity

Modification: increase by 1 vulnerability class for either horizontal or vertical irregularity

Buildings which are irregular in their structural organisation, whether in their floor plan, or in vertical arrangement, or the organisation of the structural members, are commonly found to be more severely damaged in earthquakes than regular buildings subject to the same ground motion.

In buildings built according to modern codes of practice, the regularity of the structural system will have been taken into account in the loading and design detailing, and performance of irregular structures should, as a result, be not markedly worse than that of regular buildings. Conversely, where early codes are used, or code implementation is poor, lack of regularity can significantly increase the vulnerability.

Gross irregularity is easy to identify: for example buildings with L-shaped floor plans are subject to torsional effects which may increase the damage. However, even where the floor plan is regular, damage may be increased if there is asymmetry in the arrangement or relative stiffness of the structural members, particularly columns and walls, stair wells and lift shafts.

An important class of irregularity, frequently encountered, is where one storey (usually the ground floor), is left free of internal walls, or has fewer columns or walls, or may be of greater height than other floors, introducing a serious lateral weakness. These are known as *soft storey* structures, and the weakness has often led to serious damage or collapse of the whole building. Continuous strips of window or other openings in otherwise infilled external walls can cause so-called captive-column local failures.

In some cases buildings which previously had a good level of regularity may be adversely affected by subsequent modifications. For example conversion of a ground floor to commercial space could create a soft storey. Equally, either horizontal or vertical extensions to existing buildings can introduce irregularity and lead to enhanced damage.

All of these factors are likely to affect the performance of both reinforced concrete frame buildings and reinforced concrete wall buildings, although vulnerable soft storeys are much more prevalent in frame buildings. The vulnerability of reinforced concrete wall buildings is badly affected by large openings and discontinuity of walls over the height of a building, or by irregular placing of walls in plan. Core systems (with walls placed only at the centre of the plan, for lift and stair towers) have been found to behave in a less ductile way than frame, wall or dual frame-wall systems.

For buildings not built to a code, major irregularity either horizontally or vertically could give rise to up to one vulnerability class modification (e.g. from D to C or C to B).

4.2.7 Position

Modification: minor increase/decrease in vulnerability

The relationship of a building to the adjacent building can affect the level of damage experienced. For multi-storey reinforced concrete frame buildings of several storeys severe damage may result from the lateral sway of adjacent buildings causing them to smash into each other, causing an effect known as *pounding*. Pounding damage is not a primary measure of the strength of the earthquake shaking and such damage should, as far as possible, be discounted when assigning intensity. Position is unlikely to result in a significant shift of vulnerability class for RC buildings.

4.2.8 Strengthening

Modification: depends on level of code applied

Measures taken to retrofit a building to strengthen it against earthquakes can alter the earthquake performance. In the case of reinforced concrete structures such retrofitting may be done in order to convert a weak frame building into a stronger wall building. Such retrofitting is likely to have been done to bring the performance of the building in line with the current code of practice, in which case the appropriate vulnerability class from Table 4.2 should be used.

4.2.9 Country vulnerability summary

Table 4.2 summarises the likely effect of country group and code level on the vulnerability of RC frame and RC wall buildings.

Table 4.2 Expected vulnerability classes for RC classes by country group and level of code application

Country group	*Code level*	*Vulnerability class RC frame buildings*			*Vulnerability class RC wall buildings*		
		Lower bound	*Upper bound*	*Most likely*	*Lower bound*	*Upper bound*	*Most likely*
Group 1 and 2 countries	Pre-code	A	D	C	B	D	C
	Early code	B	E	D	C	E	D
	Modern code	D	F	E	D	F	E
Group 3 countries	Pre-code	A	D	B	B	D	B
	Early code	B	E	C	C	E	C
	Modern code	C	F	D	D	F	D
Group 4 countries	Pre-code	A	C	B	B	C	B
	Early code	B	D	C	C	D	C
	Modern code	C	E	D	D	E	D

4.3 Damage grade descriptions

Damage grade diagnostics specific to reinforced concrete frame and reinforced concrete wall buildings are as shown in Table 4.3. Figure 1.2 shows diagrammatic representations of the different damage levels for a typical reinforced concrete frame building. Figures …….. show photographs of buildings of the different reinforced concrete sub-types and sub-categories which have suffered different levels of damage.

Table 4.3 Damage grade diagnostics for reinforced concrete frame and wall buildings.

Grade	*IMS Definition*	*IMS Elaboration (with edits)*	*IMS additional diagnostics: damage to particular building types and structural elements*	*IMS additional diagnostics: indicative damage to non-structural elements*
1	Negligible to slight damage (no structural damage, slight non-structural damage)	Fine cracks in plaster over frame members or in the walls at the base. Fine cracks in partition and infill walls.		Few cracks at intersections of partition walls and ceilings; a few ceiling tiles have moved; untied HVAC equipment moves.

2	Moderate damage (slight structural damage, moderate non-structural damage)	Cracks in columns and beams of frames and in structural walls. Cracks in partition and infill walls; fall of brittle cladding and plaster. Spalling (i.e detachment) of mortar from the joints of wall panels.	Cracks at frame-infill interfaces in frame structures; several fine cracks in columns and/or beams of frame structures; some fine diagonal cracks in structural walls of wall structures; minor concrete spalling at connections of precast members.	More extensive cracking of partitions; loss of ceiling tiles and damage to supporting rails; some light fittings damaged; a few connections of pipework leak; lift-rails out of alignment.
3	Substantial to heavy damage (moderate structural damage, heavy non-structural damage	Cracks in columns and beam-column joints of frames at the base and at joints of coupled walls. Spalling (i.e. failure) of concrete cover to reinforcement, buckling of reinforcing bars. Large cracks in partition and infill walls, failure of individual infill panels.	Extensive cracking in infills in frame structures, and some crushing of infills around beam-column joints; moderate shear failure of single to few columns in frame structures (particularly in soft storeys or short columns) but building standing and not leaning; larger diagonal cracks in walls in concrete wall structures and concrete spalling at wall ends; observable movement at joints in precast concrete structures.	Most partitions severely cracked or failed; partial collapse of ceiling and falling of light fittings at some locations; leaks develop in pipework at many locations.
4	Very heavy damage (heavy structural damage, very heavy non-structural damage)	Large cracks in structural elements with compression failure of concrete and fracture of reinforcing bars; bond failure of beam reinforcing bars; tilting of columns. Collapse of a few columns or of a single floor.	In frame structures: infill walls extensively damaged with some falling out-of-plane; extensive shear failures in numerous columns; structure may have permanent lateral displacement (leaning) and is in need of immediate shoring; In wall structures: large through-the-wall diagonal cracks, extensive spalling, and buckling of wall reinforcement; In precast structures: critical frame connections have failed resulting in partial collapse.	Complete failure of partitions, ceilings and suspended light fittings; exterior wall panels severely damaged and some fallen; pipes and ducts broken with extensive leaking; lift rails buckled.
5	Destruction (very heavy structural damage)	Collapse of ground floor or parts (e.g. wings) of buildings.	Failure of main structural elements leads to partial (more than 10% of floor area) or total collapse.	

5 Steel frame structures

5.1 Description

This construction type is practiced in countries regardless of their seismic risk and most often in urban areas. These buildings are typically residential, commercial or light-industrial. Regions where this building type is found include: Colombia and Chile, Europe, Iran, Japan, USA, New Zealand, China, the Caribbean. This construction type with a high level of ERD is often but not exclusively practiced in urban areas of more developed countries with higher seismic risk.

Steel buildings have a frame as the lateral load resisting system. Steel buildings generally have a low vulnerability, however the following factors should be taken into account when assessing the expected vulnerability of a steel building: the bracing; connections between beams and columns; the presence of infill; the presence of shear walls; the dimensions of the steel members.

Steel structures usually have exterior non-structural walls (curtain walls) which can be made of any material, including: brick; concrete; lightweight cladding such as metal panels; glass. The floors and roof can be concrete slabs or a metal deck with concrete fill. The main vulnerability modifier for all categories of steel building is the level of earthquake resistant design.

The effect of ERD on the behaviour of steel frame buildings is discussed in Section 5.2. The following common variants of steel frame building can be found and are described in this section:

- Moment-resisting Frame
- Braced Frame
- Frame with unreinforced masonry walls
- Frame with reinforced concrete walls
- Light steel frame

Moment Resisting Frame
Moment resisting frame structures consist of a frame of steel columns and beams. The beam-column connection must be rigid in order for the building to act as a moment-resisting frame to resist lateral forces. The floor and roof act as either flexible or rigid diaphragms and are usually made of cast-in-place concrete slabs, precast slabs or metal deck with concrete fill supported on steel beams, open web joists or steel trusses. The structure is usually concealed by exterior nonstructural walls, which can be of almost any material (curtain walls, brick masonry, precast concrete panels or glass). Properly detailed MRFs are capable of dissipating large amounts of energy and therefore perform well in earthquakes, however MRF buildings are typically more flexible than either reinforced concrete frame or braced frame buildings, which can result in large inter-story drifts that may lead to more non-structural damage. The vulnerability of these structures is generally low.

Braced Frame
Braced frame structures are frame structures with diagonal steel members providing bracing in the vertical plane. Lateral forces are resisted by tension and compression forces in the braces. Diagonal brace connections can either be concentric to beam- column joints (concentric braced frame (CBF), all member stresses are primarily axial) or eccentric to the joints (eccentric braced frame (EBF) both bending and axial stresses in members). Similarly to MRF structures, floors and roofs act as diaphragms and are concrete or metal deck with concrete fill. The structure is usually concealed by exterior non-structural walls. There is some debate about the performance of braced frames in earthquakes. Poor performance of BF structures in earthquakes in Mexico (1985), Northridge (1994) and Kobe (1995) led to changes in seismic design requirements for braced frames. Therefore the approximate age of these buildings is important in determining the expected vulnerability.

Incomplete braced frames, i.e. structures with either braces in only one direction or bays with missing braces, can significantly increase a structure's vulnerability. This is due to large inter-storey drifts in unbraced bays leading to possible instability and collapse. The vulnerability of these structures is generally low and often lower than MRF structures.

Frame with Unreinforced Masonry Infill Walls

A frame with unreinforced masonry infill walls is generally found in older buildings. These structures consist of a frame of steel columns and beams. The infill walls are either panels or walls that encase the steel frame. The seismic performance of this type of construction depends on the interaction between the frame and infill panels and the combined behaviour may be more like a shear wall structure than a frame structure. The floor and roof are rigid diaphragms and are made of concrete. The vulnerability of these structures is generally higher than an MRF or BF structure with different infill.

Frame with RC Walls

These buildings consist of a frame of steel columns and beams with cast-in-place reinforced concrete walls. In older structures of this type, the steel frame is designed for vertical loads only and the concrete walls resist the lateral forces. In modern structures of this type, the steel frames are designed to work together with the concrete walls and depending on the frame stiffness and the beam-column connection capacity, the steel frame may provide a secondary lateral force resisting system. The floor and roof act as rigid diaphragms and are made of cast-in-place concrete slabs. The structure is usually concealed by exterior non-structural walls, which can be of almost any material (curtain walls, brick masonry, precast concrete panels or glass).

Light steel frame

Light steel frames are usually single-storey structures with relatively long roof spans. The building consists of moment-resisting frames in one direction, which are joined by bracing rods or bars or lightweight cladding in the direction perpendicular to the frame. The frames are built in segments and assembled in the field with bolted joints. The roof and walls are usually lightweight panels such as corrugated metal, especially in the non-residential sector. The frames are often designed for maximum efficiency with tapered beam and column sections. The vulnerability of these structures is generally higher than other steel frame buildings.

5.2 Vulnerability and vulnerability modifiers

The IMS vulnerability table distinguishes two categories of steel frame building according to building typology and conformity to building standards which incorporate earthquake-resistant design principles. The two categories are:

- Steel frame built according to recent standards for an area of moderate or high seismicity
- Steel frame structures not built to recent earthquake design standards

As shown in Table 5.1, for buildings built according to recent standards for areas of moderate or high seismicity, the most likely vulnerability class is E with a probable range from D to F. For buildings not built to such standards, the most likely class is D (as in EMS-98), with a possible range from B to E. In determining which vulnerability class is most appropriate for a given set of the buildings, consideration should be given both to any design standards adopted (date and earthquake level assumed), and to the various features discussed in the following sections on vulnerability modifiers.

Table 5.1. Expected vulnerability classes for steel frame buildings

	Steel frame subcategory	*Vulnerability*		
		Lower bound	*Upper bound*	*Most likely*
Steel frame	without ERD or with moderate level of ERD	B	E	D
	with high level of ERD	D	F	E

5.2.1 Design standards for steel buildings

In the majority of countries, new steel buildings are designed and built to comply with construction codes of practice. This can include retrofitting or strengthening pre-code steel structures to make them code compliant. Seismic codes controlling steel construction, dictate the allowed structural systems, bracing, connection detailing and the number and position of openings. These design standards are regularly updated. Buildings which are known (or can reasonably be expected) to have been designed and built to code or an equivalent set of regulations for another country with moderate or high seismicity, can be considered as being in the category of "steel frame structures built according to standards for an area of moderate or high seismicity", for which the most likely vulnerability class is E. In other cases, the most likely vulnerability class should be taken as D, but bearing in mind additional factors affecting vulnerability discussed in Section 5.2.2 to 5.2.5. In some cases an exceptionally well-designed and built structure may be vulnerability class F.

5.2.2 Quality and workmanship

Modification: Increase vulnerability by less than 1 class.

Well-designed buildings and the use of good construction techniques will result in a building with a lower vulnerability. Conversely poor construction will result in buildings with a higher vulnerability Of particular importance are the design and construction of bracing and connections between beams and columns, as well as the construction of infills and floor and roof slabs and their connection to the frame.

As previously discussed for concrete buildings (see section 4.2.4), in areas where there is good code implementation, quality of construction is likely to also be good. Conversely where code implementation is poor, quality of construction is also likely to be poor.

5.2.3 Floor, roof, connections and bracing

Modification: Increase/decrease vulnerability by 1 class.

Both the material of the floor and the roof and the connections between horizontal and vertical elements influence a building's vulnerability.

- For both the floor and roof, a rigid diaphragm will decrease seismic vulnerability.
- A good connection between vertical and horizontal elements in both directions in the structure is needed to enable the structure to resist lateral loads.
- A bracing system which is regular in the vertical plane in both directions (i.e. façade and perpendicular to the façade) is essential for the structure to be considered to behave as a braced frame.

5.2.4 State of preservation

Modification: Minor increase in vulnerability

The condition of steel buildings may also affect their vulnerability. Poorly built and maintained buildings may deteriorate over time by at least one vulnerability class. One should note that a building may appear to be in good condition because attention has been paid to maintaining the aesthetic appearance of the building only, e.g. new non-structural elements and this does not necessarily mean that the structural system of the building is also in good repair.

As for reinforced concrete structures the vulnerability of steel frame structures can also be increased if the structure has been weakened by damage from previous earthquakes. (See section 4.2.5)

5.2.5 Regularity

Modification: Increase vulnerability by less than 1 class.

Buildings which are irregular either horizontally (in plan), or vertically (in elevation), are commonly found to be more severely damaged in earthquakes than regular buildings. Two main features of irregularity in steel buildings are:

- In braced frame buildings, the number, size and position of openings: Large openings or a number of openings increases vulnerability. An incomplete bracing system (for example due to a large entrance) will lead to irregularities in stiffness and large inter-story drifts in unbraced bays.
- Long spans without stiffening increase vulnerability. This refers to both a long span between columns (with or without bracing) and in light steel structures, a lack of stiffening perpendicular to the frame.

5.2.6 Country vulnerability summary

Modification: depends on level of code applied

Table 5.2 lists the likely effect of country group and code level on the vulnerability of pre-code and modern code steel buildings. The table is divided by country group (first column);) and code level (pre-code, early or modern code) (second column).

Table 5.2 Expected vulnerability classes for steel frame buildings by country group and level of code application

Country group	*Code level*	*Vulnerability class steel frame buildings*		
		Lower bound	*Upper bound*	*Most likely*
Group 1 and 2 countries	Pre-code or early code	C	E	D
	Modern code	D	F	E
Group 3 and 4 countries	All	B	D	C

5.3 Damage grade descriptions

Table 4.3 gives the written description of damage grade levels specific to steel buildings. Figure 1.3 shows diagrammatic representations of the different damage levels for a generic steel frame building. Figure 1.4 shows diagrammatic representations of the different damage levels for a generic light steel frame building. Figures 4.1 to 4.10 show photographs of buildings of the different steel sub-types and sub-categories which have suffered different levels of damage.

Table 5.3. Damage grade diagnostics for steel buildings

Grade	IMS Definition	IMS Description	Additional diagnostics for specific building types
1	Negligible to slight damage (no structural damage, slight non-structural damage)	Fine cracks in plaster over steel frame members or at the base. Fine cracks in partitions and infill walls.	
2	Moderate damage (slight structural damage, moderate non-structural damage)	Few cases of visible deformation or distress of frame members, bracing members or structural connections; Cracks in partition and infill walls; failure of brittle cladding and plaster.	In light steel frame structures a few rod braces may have yielded.
3	Substantial to heavy damage (moderate structural damage, heavy non-structural damage)	Limited but visible leaning of building or individual storey; some broken or buckled members in roof trusses; some distortion of columns or damage at connections; failure of some bracing members; large cracks in partition and infill walls, failure of individual infill panels.	In light steel frame structures many braces have yielded. Masonry infilled frames may exhibit crushing of masonry around beam-column connections.
4	Very heavy damage (heavy structural damage, very heavy non-structural damage)	Building or individual storey leaning heavily; many failed members and/or connections; roof members shifting on column support; major distortion of columns.	Most infill walls exhibit large cracks. Masonry infill may bulge out-of-plane and some masonry may be dislodged and fall (in Masonry infilled steel frames).
5	Destruction (very heavy structural damage)	Collapse or partial collapse of entire structure; large permanent lateral displacement.	

6 Timber frame structures

6.1 Description

Timber construction is common for single-family houses in many countries of the world. In western USA, Canada, Japan and New Zealand, timber stud-wall construction is today used for the vast majority of single-family houses, and in many other countries it forms a significant proportion of new building stock. In the Western USA, it accounts for about 98% of existing and new houses constructed; and in some cities timber-frame buildings are also used in multi-family housing; in Japan wood-frame housing constitutes the majority of the housing stock throughout the country. In Europe timber frame housing is used, but constitutes a small proportion (less than 5%) of the housing stock, except in Romania, where post and beam construction amounts to 14% of the existing single-family housing stock. Where it is very widely used, the primary reasons for the popularity of timber-frame housing are the easy availability of suitable timber and its affordability, but contributing to its popularity is the evidence that the experience of past earthquakes has demonstrated the superior performance of timber relative to other (particularly unreinforced masonry) forms of construction.

Timber construction has also been used traditionally in many countries, using a variety of methods, including post and beam construction (Half-timbered or Wattle and Daub construction in Northern Europe (*Colombage* in France, *Fachwerk* in Germany), *Shinkabe*/*Okabe* construction in Japan, *Himiş* and *Bağdadi* construction in Turkey, *Dhajji Dewari* construction in Kashmir, India, lightweight timber frame structures in tropical regions such as Indonesia or South India etc.) and pole structures covered with thatch or mud-plastered walls of bamboo or reeds (*Bajareque* in Central and South America, aka *Taquezal* in Nicaragua; *Quincha* in Panama, Bolivia and Peru; *Tejamanil* in the Dominican Republic) and traditional construction in many parts of Africa. In parts of Southern Europe another variant is construction in the form of the *casa baraccata* (in southern Italy) and *pontelarisma* (in the Ionian Islands of Greece), where a dual system of stone masonry and timber frame is used.

In most of these countries, such buildings form a significant part of the existing building stock and are still built. These forms of construction too, have demonstrated a superior performance in earthquakes compared with local forms of unreinforced masonry or reinforced concrete.

Timber is also, more rarely, used in other ways, such as log construction,(still found in Scandinavia and Northern Europe, Switzerland, the Balkan countries and the Russian Federation) and wood panel construction (a small proportion of recent residential construction in Russia, Scandinavia and Switzerland). And wherever timber is available it is also used for non-residential buildings such as barns and warehouses using a variety of building techniques. However, very rarely is timber used for buildings greater than 3 or 4 stories in height, partly because of structural limitations and also because of fire risk.

This section of Part III will focus on stud-wall construction, as this is the most widespread and current form of timber construction. It is predominantly used for single or two-storey housing, but has been in some cases also used for multi-family housing in two-storey or three-storey terrace blocks (e.g. tenement housing in Japan, etc.). Some other vatiants of timber construction are described in Annex II

Timber stud wall building
A typical timber stud-wall building today typically Canada consists of a reinforced concrete strip foundation, on which the timber ground floor is constructed and anchored to the foundation; the ground floor consists of a platform of softwood timber joists covered with a deck of plywood or other timber-based board; on this platform exterior and interior ground floor walls are built,

consisting of a timber sill plate and regularly spaced (30 to 60 cm centres) vertical timber studs of a suitable width, and with board or panel sheathing nailed to the studs on the outside of the building. The studs are capped with a double header plate and the first floor is built on this, in turn acting as a platform for the first floor walls, on which a roof of timber rafters or prefabricated trusses is built, and covered with tiles or roof sheets. An external cladding or veneer of brickwork or of horizontal timber boarding is also generally used.

Local variants of the above description are that in some cases a basement is built in reinforced concrete, to which the ground floor assembly is bolted; and in some cases the ground floor is elevated above the foundation using short stub or "cripple" walls. In Japan posts of square cross section about 105x105 mm are used at wider spacing (typically at 1.8 to 2m); and in some cases lateral resistance is provided by separate timber shear walls with internal diagonal bracing members.

In the USA, Canada and Japan, most timber frame construction of this type is covered by locally applicable Standards which define minimum requirements for the material properties, sizing and spacing of studs, the thickness of plywood or other stiffening panels, the means of connecting the members, including anchorage to the foundations, and the size of openings. These Standards provide for sufficient resistance to expected earthquake forces in the region and ensure that the building has adequate redundancy to sustain very limited damage in expected earthquakes.

Seismic deficiencies, found in older houses of this type, include inadequate connection of the building to its foundation: in earthquakes, these buildings can move off their foundation causing severe damage to water, electricity and gas connections. A further deficiency found particularly in the USA is the use of unbraced cripple walls, which can overturn or collapse in an earthquake causing severe damage to the main structure.

Older buildings may also lack adequate shear resistance through sheathing boards which are either inadequate in size, not continuous, or insufficiently connected to the vertical studs. In Japan particularly, heavy roofs (needed for typhoon resistance), coupled with inadequate bracing, has often been the cause of collapse of significant numbers of older timber frame houses as occurred in the 1995 Kobe earthquake.

In older buildings the timber may be of poor quality, and may suffer from rot, fungal attack or insect attack, especially if the timber is not treated; and metallic connections may suffer from corrosion. All of these factors will significantly increase the vulnerability of the building.

6.2 Vulnerability and vulnerability modifiers for timber frame buildings

The IMS vulnerability table distinguishes two categories of timber frame building according to building typology and conformity to building standards which incorporate earthquake-resistant design principles. The two categories are:

- Timber frame built according to recent standards for an area of moderate or high seismicity
- Timber frame structures not built to recent earthquake design standards

As shown in Table 6.1, for buildings built according to recent standards for areas of moderate or high seismicity, the most likely vulnerability class is E with a probable range from D to F. For buildings not built to such standards, the most likely class is D (as in EMS-98), with a possible range from B to E. In determining which vulnerability class is most appropriate for a given set of the buildings, consideration should be given both to any design standards adopted (date and earthquake level assumed), and to the various features discussed in the following sections on vulnerability modifiers.

Table 6.1 Expected vulnerability classes for timber frame buildings by country level of code application, seismic zone and code level.

	Timber frame subcategory	Vulnerability		
		Lower bound	Upper bound	Most likely
Timber frame	without ERD or with moderate level of ERD	B	E	D
	with high level of ERD	D	F	E

6.2.1 Design standards for timber frame buildings

Most timber frame housing is built without a formal structural design to resist a given load (or structural demand), but according to a set of locally or nationally applicable design standards. Standards such as the International Building Code (USA), the National Building Code of Canada, the Caribbean Uniform Building Code, the New Zealand Building Regulations and the Japanese Building Standard provide standards for wall stud and floor joist member sizes, sheathing materials and sizes, jointing and foundation connections, cladding connections and other details, which provide for adequate resistance to expected earthquakes with built-in structural redundancy. These design standards are regularly updated. Buildings which are known (or can reasonably be expected) to have been designed and built according to the codes referred to above, and in place from 1980 onwards, or an equivalent set of regulations for another country with moderate or high seismicity, can be considered as being in the category of "timber frame structures built according to standards for an area of moderate or high seismicity", for which the most likely vulnerability class is E. In many countries proprietary timber frame or panel systems are now available which can be provided with earthquake-resistant design of an equivalent standard to that for timber-frame housing, and these can also be considered to be of vulnerability class E or F. In other cases, the most likely vulnerability class should be taken as D, but bearing in mind additional factors affecting vulnerability discussed in Section 6.2.2 to 6.2.5.

6.2.2 Quality of construction and workmanship

Modification: increase or decrease of 1 or more vulnerability class

Because in many parts of the world timber frame buildings are often built by inexperienced builders, or those building their own homes, deficiencies in design and construction very frequently occur. Foundations may be weak or non-existent; floors may be poorly (if at all) connected to the foundations; floors may be raised above the ground without adequate bracing; walls may lack adequate sheathing to transfer lateral forces; floors and roofs may lack bracing sufficient to transfer lateral forces to the walls and frame; connections between roof, floors and walls may be inadequate; the connection between the timber frame structure and masonry claddings may be inadequate. The use of horizontal board sheathing (as opposed to plywood or fibreboard) can create a weakness in resisting lateral forces.
Such defects (often found in combination) can be sufficient to raise the vulnerability class by between 1 and 2 classes (i.e. from D to B).

6.2.3 State of preservation

Modification: increase by 1 or more vulnerability class

Many existing timber frame houses were built more than 50 years ago, and are likely to exhibit deterioration either of the timber frame itself, or of its connection to the roof, foundation and cladding. A particular concern is the susceptibility of timber (especially when untreated) to rot, fungal or insect attack. Termite attack is a very serious problem for timber in tropical locations. Metal connections are also likely to suffer from corrosion, especially in coastal or wet climate areas. Cladding materials may have weathered or disintegrated.
Older timber frame buildings may also have suffered damage from previous earthquakes which will increase their vulnerability in future events. Poor state of preservation of timber frame buildings can be responsible for a further increase of up to 1 vulnerability class

6.2.4 Regularity

Modification: minor increase in vulnerability

Because of the redundancy of most timber frame buildings irregularity in plan is unlikely to have a major impact on the vulnerability. Major vertical irregularity is unusual, though upper floors in buildings of older post and beam construction were often "jettied" beyond the line of the lower floors. If a major vertical irregularity occurs (such as a large overhang or cantilevered projection of an upper floor) this may increase vulnerability by up to 1 vulnerability class.

6.2.5 Strengthening

Modification: decrease up to 1 vulnerability class

Strengthening of existing buildings to bring them to current standards has been practised in some limited cases in the USA, Canada and Japan. This can include: installing missing anchor bolts to foundation, bracing sub-floor cripple walls, adding sheathing to unbraced walls, installing blocking in floors and walls to increase their stiffness, adding metal connector plates to connect walls to floors and transverse walls, and replacing heavy roofs (in Japan) with lighter-weight alternatives. Buildings damaged in previous earthquakes have also been strengthened (notably in Romania) by adding metal connector plates within the timber frame. There is little experience of damage to such strengthened structures by subsequent earthquakes, but reduction of vulnerability by up to one vulnerability class is likely.

6.2.6 Country vulnerability summary

Table 6.2 lists the likely effect of country group and code level on the vulnerability of pre-code and modern code timber buildings. The table is divided by country group (first column); and code level (pre-code, early code or modern code) (second column)

Table 6.2 Expected vulnerability classes for timber frame buildings by country group, and level of code application

Country group	*Code level*	*Vulnerability class timber frame buildings*		
		Lower bound	*Upper bound*	*Most likely*
Group 1 and 2 countries	Pre-code or early code	C	E	D
	Modern code	D	F	E
Group 3 and 4 countries	All	B	D	C

6.3 **Damage grade descriptions for timber structures**

Table 6.3 gives the description of damage grade levels specific to timber frame buildings. Figure 1.5 shows diagrammatic representations of the different damage levels for a typical timber frame building. Figures …… show photographs of buildings of different timber frame construction typologies which have suffered increasing levels of damage.

Table 6.3 Damage grade descriptions for timber frame structures

Grade	*EMS-98 Definition*	*Proposed IMS elaboration (for lightweight timber frame structures)*	*Additional diagnostics: particular building classes*
1	Negligible to slight damage (no structural damage, slight non-structural damage	No damage to structural frame. Few hairline cracks in internal walls or brick or brick chimneys. Fall of small pieces of plaster.	
2	Moderate damage (slight structural damage, moderate non-structural damage	Little or no damage to structural frame. Small cracks in plaster or plasterboard edges; cracks in brick veneers; cracks in masonry chimneys.	.
3	Substantial to heavy damage (moderate structural damage, heavy non-structural damage	Some frame distortion visible. Veneers fail and expose frame. Large cracks in plaster or plasterboard edges. Roof tiles detach. Chimneys fracture at roof line. Failure of individual non-structural elements such as partitions, masonry cladding. Some shifting off unsecured foundations.	Heavy timber frame: Small cracks or wood splitting at bolted connections.
4	Very heavy damage (heavy structural damage, very heavy non-structural damage)	Serious frame distortion. Extensive failure of brick veneers. Toppling of most masonry chimneys. Houses not secured to foundations, shifted off. Failure of cripple walls.	Slack or broken braces in braced timber frame structures. Infilled wood frame structures: Large cracks in infill masonry; overturning of some infill masonry panels
5	Destruction (very heavy structural damage)	Total or near total collapse of entire structure.	Heavy wood and infilled frame: Structure may have permanent lateral displacement, may collapse or be in imminent danger of collapse; structure may slip and fall off foundations; large foundation cracks.