CHAPTER 5

EARTHQUAKE VULNERABILITIES

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5. EARTHQUAKE VULNERABILITIES

5.1. General Considerations

Vulnerability is defined as the degree of loss to a given element at risk, or a set of such elements, resulting from the occurrence of a hazard. Vulnerability functions (or Fragility curves) of an element at risk represent the probability that its response to earthquake excitation exceeds its various performance limit states based on physical and socio-economic considerations. The vulnerabilities of lives, structures, systems, and the socioeconomic structure are the main factors influencing the earthquake risk and losses. Vulnerability analysis involves the elements at risk (physical, social and economic) and the type of associated risk (such as damage to structures and systems and human casualties). Vulnerability assessments are usually based on past earthquake damages (observed vulnerability and, to a lesser degree, on analytical investigations (predicted vulnerability). Primary physical vulnerabilities are associated with buildings, infrastructure and lifelines. These vulnerabilities are agent- and site-specific. Furthermore they also depend on design, construction and maintenance particularities. Secondary physical vulnerabilities are associated with consequential damages and losses. Socio-economic vulnerabilities include casualties, social disruption and traumas and economic impacts.

Industrial facilities consist of buildings, their contents, pipelines, storage areas and/or tanks, silos, chimneys, cranes, conveyor systems, etc. When trying to assess the fragility of an industrial facility, one is faced with the complex problem of estimation of vulnerabilities of several components the facility is comprised of. Estimated fragilities of the buildings, of their contents (often referred as machine and equipment), of non-building structures at the site and of stock and storage are then combined with the losses due to business interruption, loss of function and also in many cases with loss of market to describe the losses a facility may experience in case of an earthquake.

Estimation of earthquake losses to the industry is very important for the insurance market, as well as the owners. After the 1999 Kocaeli earthquake, which hit the industrial heartland of Turkey, there was increased concern in the insurance and reinsurance industry about the industrial losses that can be experienced in Istanbul and vicinity in case of a strong event which may take place in the Marmara sea within the next few years.

Yanev (1990) notes that seismic damage to well-engineered facilities is normally limited to only a few items except for sites receiving high ground accelerations with peaks larger than 0.5g. EQE International over the years has compiled a substantial database on earthquake damages to industrial facilities, water- and other lifeline systems, as well as on seismic experience of equipment and nonstructural items. The database covers damage data from more than 80 earthquakes worldwide with Richter magnitudes ranging between 5.7 and 8.1 (Moat et al, 2000). In general it can be said that heavy industrial facilities perform more reliably than mechanical systems found in buildings mainly due to better engineering practice and not to necessarily due to better codes and regulations (Scawthorn et al, 1990).

Primary Physical Vulnerabilities

Earthquake vulnerability is a measure of the damage a building or a non-building structure is likely to experience given that it is subjected to ground shaking of specified intensity. The dynamic response of a structure to ground shaking is a very complex behavior that is dependent on a number of inter-related parameters that are often very difficult, if not impossible, to precisely predict. These include: the exact character of the ground shaking that the building will experience; the extent to which the structure will be excited by and respond to the ground shaking; the strength of the materials in the structure; the quality of construction and condition of individual structural elements; the interaction of the structural and non-structural elements of the building; the weight of furnishings and contents present in the building at the time of the earthquake; and other factors. Most of these factors can be estimated, but never precisely known. As a result, it is typically necessary to define vulnerability functions for buildings within levels of confidence.

Intensity based vulnerability matrices relate descriptive damage classes of buildings to earthquake motion intensities. Coburn and Spence (1992) provide observed vulnerability functions (percent of buildings damaged) for common building types. ATC-13 (1985) provides loss estimates for 78 different building and facility classes for California. To overcome the data limitations, the damage probability matrices and time estimates for restoration of damaged facilities were obtained by aggregating the expert opinions. Intensity-based vulnerability matrices also exist for different parts of the world, and for indigenous building typologies. In these vulnerability functions the distinction between damage and loss is not explicit, since only very limited data exist on the cost of repairs.

In addition to buildings and non-building structures, many other engineered urban structures; infrastructures, lifelines and services are vulnerable to the effects of earthquakes. Direct damage to lifeline facilities exacerbates damage to socio-economic fabric by interrupting business. These secondary losses may exceed the direct loss. The earthquake vulnerability of lifelines is critical in the control of induced losses and socio-economic losses.

Observations acquired from past urban earthquakes (EERI, 1986), supplemented by the worldwide experience can be used as a guide to assess their physical vulnerabilities. A compilation of lifeline vulnerability functions and estimates of time required to restore damaged facilities are provided in ATC-25 (1991). The vulnerability functions are based on the review of existing models and the expert opinion in ATC-13(1985) supplemented by an expert technical advisory group.

Secondary Physical Vulnerabilities

Only limited vulnerability models exist for secondary damages for secondary hazards, such as: post-earthquake fire, hazardous material release, explosions and water inundation.

Recent developments in fire following earthquake models include three stages: ignition, spread and suppression, and provide first-order estimates of total losses as functions of intensity, wind, building density and fire engine number. There does not exist any practical method for modeling hazardous material release and/or explosions. Tsunamis, seiches and dam failures may immediately precede an earthquake and contribute significantly to the losses. High resolution mapping of areas susceptible to inundation necessitates accurate prediction of water run-up heights and water velocities affected by the interaction of onshore structures and topography.

Socio-Economic Vulnerabilities

In addition to the physical vulnerabilities, the socio-economic vulnerabilities of industrial facilities need to be assessed in terms of casualties, social disruption and economic losses.

Casualties in earthquakes arise mostly from structural collapses and from other collateral hazards. Lethality per collapsed building can be estimated by the combination of factors representing the population per building, occupancy at the time of the earthquake, occupants trapped by collapse, mortality at collapse and mortality post-collapse. Lethality for collateral hazards are difficult to generalize and may require facility specific assessments.

It is generally known that loss due to collateral hazards and the indirect economic losses constitute a major portion of the total earthquake loss in industrial systems. Indirect economic losses arise from discontinued service of damaged facilities and include: Production and/or sales lost by firms in damaged buildings; Production and/or sales lost by firms unable to supplies from other damaged facilities; Production and/or sales lost by firms due to damaged lifelines; Losses arising from tax revenues and increased unemployment compensations. Partial quantification of these indirect economic losses can be found in ATC-25 (1991).

5.2. Building Vulnerabilities – Direct Physical Damage

5.2.1. Introduction

There are two main approaches for generating vulnerability relationships. The first approach is based on damage data obtained from field observations after an earthquake or from experiments. The second approach is based on numerical analysis of the structure, either through detailed time-history analysis or through simplified methods.

The first approach used in developing vulnerability estimates is also called the experience data approach. The experience data approach is based on the fact that certain classes of constructed facilities tend to share common characteristics and to experience similar types of damage in earthquakes. A series of standard vulnerability functions can be developed for these classes of buildings. In USA the commonly used reference for such standardized vulnerability matrices is ATC-13 (1985). The empirical vulnerability relationships categorized in ATC-13, are constructed from the field damage observation. They play an indispensable role in the fragility curve development study, because only they can be used to calibrate the vulnerability relationships developed analytically. Loss estimates that are made using this approach are more valid when used to evaluate the risk of large portfolios of facilities, than for individual facilities. This is because when applied to large portfolios of facilities, the uncertainties associated with estimation of the vulnerabilities of the individual components of the portfolio tend to balance out.

The standard tool for the analytical computation of the vulnerability relationship (also called the fragility curve) is the so-called spectral capacity method, a simplified method that estimates the response of a structure from spectrum demand and spectral capacity curves. In this study the earthquake vulnerability of buildings in industrial facilities will be provided in terms of intensities only in line with the scope of the project.

5.2.2. Intensity Based Vulnerabilities

The 1998 European Macroseismic Scale (EMS, 1998)**,** an updated version of the MSK-81 scale, differentiates the structural vulnerabilities into six classes (A to F). Reinforced Concrete buildings with low levels of earthquake resistant design are assigned an average vulnerability class of C. Due to deficiencies in design; concrete quality and construction practices, the bulk of the reinforced concrete building stock in industrial facilities in the region may be considered in this vulnerability class. As illustrated in Figure 5.2.2 (after, EMS, 1998), damage to reinforced concrete buildings are classified as:

D1: Negligible to slight damage;
D2: Moderate damage;
D3: Substantial to heavy damage;
D4: Very heavy damage and
D5: Destruction.

Coburn and Spence (1992) associates these damage grades with following definitions:

Table 5.2.1. Description of Damage Grades in MSK-81 Intensity Scale (After Coburn and Spence, 1992).

Damage Grade	Masonry Buildings	R/C Buildings
D1-Slight	Hairline cracks	Infill panels damaged
D2-Moderate	Cracks 0.5-2cm	Structural Cracks <1cm
D3-Heavy	Cracks >2cm. or wall material dislodged	Heavy damage to structural members, loss of concrete
D4-Partial Destruction	Complete collapse of individual wall or roof support	Complete collapse of individual structural member or major deflection of structure
D5-Collapse		Failure of structural members to allow fall of slabs.

The ratio of the cost of repair of the damage to the cost of reconstruction, expressed as the Repair-Cost Ratio, corresponding to the damage grades D1 through D5 can be approximately given as 0.05, 0.20, 0.50, 0.80 and 1.0. Damage levels encompassing damages D3, D4 and D5 (i.e. D>=D3) is an important descriptor of the earthquake damage since D3 represents an approximate borderline between repair and replacement of the building stock exposed to an earthquake.

For the vulnerability class C, EMS (1998) provides the following definitions of intensity.

Intensity VI: A few buildings of vulnerability class C sustain Damage of grade 1.
Intensity VII: A few buildings of vulnerability class C sustain damage of grade 2.
Intensity VIII: Many buildings of vulnerability class C suffer damage of grade 2; a few of grade 3.
Intensity IX: Many buildings of vulnerability class C suffer damage of grade 3; a few of grade 4.
Intensity X: Many buildings of vulnerability class C suffer damage of grade 4; a few of grade 5.

Where “Few” describes less than 20% and “Many” describes between 20% and 60%.
The ratio of the cost of repair of the damage to the cost of reconstruction, expressed as the Repair-Cost Ratio, corresponding to the damage grades D1 through D5 can be approximately given as 0.05, 0.20, 0.50, 0.80 and 1.0. Damage levels encompassing damages D4 and D5 (i.e. D > D3) is an important descriptor of the earthquake damage since D3 –D4 border represents an approximate borderline between repair and replacement of the building stock exposed to an earthquake.

In five urban earthquakes of the last decade (Erzincan, 1992, Dinar 1995, Adana/Ceyhan 1998, Kocaeli 1999, Duzce, 1999) some 20,000 people have been killed, the vast majority of them through the collapse of residential buildings. Altogether in these earthquakes about 70,000 buildings have been damaged, and some 20,000 buildings destroyed (Table 5.2.2). There does not exist any statistics pertaining to buildings in industrial facilities. It is believed that their performance is better than that residential buildings.

Table 5.2.2. Losses in Recent Earthquakes in Turkey.

Event	Number of Casualties	Number of damaged buildings	Number of heavily damaged or collapsed buildings	Displaced households	Economic Loss/ billion $
Erzincan, 1992	500	8,000	1,450		0.75
Dinar, 1995	100	6,543	2,043	24,000	0.25
Adana/Ceyhan,1998	150	21,057	2,000		0.5
Kocaeli, 1999	>17,000	24,000	6,000	600,000	16
Duzce, 1999	759	10,121	(?)		1

Most common type of building in industrial facilities is the cast-in-situ reinforced concrete frame with or without masonry infill walls. Almost all of the administration and social buildings in industrial facilities are of this type. For infill walls 20-30 cm thick horizontally perforated burned clay bricks or, sometimes, concrete blocks are used with no reinforcement.

The empirical vulnerability relationships for mid-rise R/C frame buildings obtained from 1999 Kocaeli earthquake damage distribution are provided in Figure 5.2.3 and Figure 5.2.4 (After A. Coburn, RMS).

Based on available empirical data, compilations from referenced works and engineering interpretations, the vulnerability curves for the general medium-rise (4-8 storey) R/C Frame type buildings in Turkey are provided in Figure 5.2.5. The horizontal axis indicates the range (uncertainty) of MSK intensities and the vertical scale indicates the percentage loss for the five different damage grades, D1 through D5, as described in EMS (1998). Figure 5.2.5 compares satisfactorily with Figure 5.2.4. Considering the damage level relations between low, medium and high rise R/C frame structures, the vulnerability curves for low-rise and high-rise R/C frame type buildings are obtained by half a unit left shifting of the intensity scale in the horizontal axis of the vulnerability curves of the medium rise R/C frame buildings. The resulting vulnerability curves are illustrated in Figure 5.2.6.

5.2.2.1. Empirical Earthquake Vulnerabilities of the Building Stock in Turkey.

It is prudent and rational to assume that the earthquake vulnerabilities of reinforced concrete (R/C) buildings in industrial facilities are given by vulnerability curve in Figure 5.2.6, similar to low-rise R/C buildings. This vulnerability curve differentiates damage with respect to five damage grades. (D1 to D5).

Intensity based mean damage ratios for type of buildings generally used in industrial facilities are proposed CAR-BU (1999) study. These are for low-rise buildings, up to 3 storeys. The loss parameter used is the mean damage ratio (MDR), which is an index that expresses the cost of the damage in relation to the replacement value of the building in percentage terms. The seismic intensity of MSK-I is the a parameter that quantifies the strength of the ground shaking. Vulnerability relationships for low-rise engineered Reinforced Masonry, R/C with shear walls, R/C Moment Resisting Frame (MRF) with Unreinforced Masonry (UM) Infills and Steel MRF and UM Infills are provided in Figure 5.2.1

Unbraced Steel Frame with Unreinforced Masonry Infill

Buildings are the preferred structural system for modern industrial buildings. However, they should not be confused with the steel structures common in the USA or Japan. The steel frame is usually filled with unreinforced hollow clay brick masonry that is very brittle and not well tied to the rest of the structure.

Precast Concrete Frame

This is an important class of construction for industrial buildings and warehouses. They can be single or two storeys. The structure consists of vertical columns with fixed bases (socketed foundations), with projecting brackets on to which the main floor and roof beams span, with wet (insitu concrete) connections. Floor and roof planks then form a secondary level of structure spanning onto these main beams. Insitu concrete panels or masonry infill panels in the sidewalls provide bracing. The performance of this building type in the 1999 Kocaeli and Duzce earthquakes has been very poor, with many collapses or partial collapses in areas of intensity VIII-IX. For finished prefabricated buildings, it will be justifiable to assume that their earthquake vulnerabilities are given by Figure 5.2.6 in terms of intensities.

Steel Braced Frame

The lateral-force-resisting system of these buildings is braced frames. The Turkish earthquake data for these type of buildings are very limited and does not allow for any statistical treatment. Thus for these type of structures it will be appropriate to borrow the vulnerability relationships developed in HAZUS (1999). For low rise (< 5 stories) steel braced frame structures with moderate-code seismic design level (the level considered appropriate for Industrial facilities in Istanbul) the following equivalent-PGA structural fragility relationships are reported by HAZUS (1999):

Damage State:	Slight	Moderate	Extensive	Complete
Median EquivalentPGA	0.20g	0.26g	0.46g	0.84g

The following descriptions are associated with the damage states:

Slight Structural Damage

Few steel braces have yielded which may be indicated by minor stretching and/or buckling of slender brace members; minor cracks in welded connections; minor deformations in bolted brace connections.

Moderate Structural Damage

Some steel braces have yielded exhibiting observable stretching and/or buckling of braces; few braces, other members or connections have indications of reaching their ultimate capacity exhibited by buckled braces, cracked welds, or failed bolted connections.

Extensive Structural Damage

Most steel brace and other members have exceeded their yield capacity, resulting in significant permanent lateral deformation of the structure. Some structural members or connections have exceeded their ultimate capacity exhibited by buckled or broken braces, flange buckling, broken welds, or failed bolted connections. Anchor bolts at columns may be stretched. Partial collapse of portions of structure is possible due to failure of critical elements or connections.

Complete Structural Damage
Most the structural elements have reached their ultimate capacities or some critical members or connections have failed resulting in dangerous permanent lateral deflection, partial collapse or collapse of the building.

In HAZUS (1999) the cost of damage is expressed as a percentage of the complete damage state. The assumed relationship between damage states and repair/replacement costs, for both structural and non-structural components, is as follows:

Slight damage	: 2% of complete
Moderate damage	: 10% of complete
Extensive damage	: 50% of complete

5.2.2.2. Vulnerability of Building Contents

Buildings can suffer major functional and economic loss by damage to the equipment and furniture they house, even though the structures experience little damage. Especially in research laboratories, administration buildings and offices, unanchored office equipment is highly vulnerable to earthquake damage.

The average range of percent earthquake losses for building contents are provided in the following Table 5.2.3, after ATC- 13 (1985), can be taken as a guide.

Table 5.2.3. Average Range of Percent Losses of Building Contents (ATC-13, 1985)

	EARTHQUAKE INTENSITIES				
	VI	VII	VIII	IX	X
Office Equipment	0-5	1-8	4-15	8-25	15-50

5.2.2.3. Vulnerability of Nonstructural Components

Critical equipment are generators, transformers, pumps etc, computers, HVAC (heating, ventilating, air conditioning) ducting, all fire protection related equipment, water supply tanks, fire pumps, gas, water and other lines, all elevator system related equipment and also nonstructural components such as suspended ceilings, lighting, windows etc. Critical systems are expected to ensure that no damage occurs to human life as a result of an earthquake, and/or in many cases the system continues to function after an earthquake. Among such systems is fire detection; alarm and suppression systems, communication systems, emergency power supply and uninterrupted power supply systems, safe-shut down systems, system control centers, hazardous material suppression systems, such as natural gas, etc.

Generally factors affecting the performance of critical equipment are building dynamics, building pounding and systems interaction. Especially in irregular buildings experienced accelerations and displacements vary greatly. High accelerations are created when two adjacent buildings pound in an earthquake, which can affect particularly nonstructural elements, systems and equipment. System interaction, where two components damage each other in earthquake shaking, is also an important factor.

Experience (Scawthorn et al, 1990) from past earthquakes is that the performance of such systems is highly unpredictable. Very different levels of performances have been observed during past earthquakes. In addition it has been repeatedly noted that the functionality and the operability of critical systems and equipment are not adequately addressed in current codes and practice (Scawthorn et al, 1990).

In recent years system functionality has become an area of interest (Johnson et al, 1998). During the 1994 Northridge earthquake significant damages and service disruption took place in critical facilities due to primarily non-structural or equipment failures (Gates and McGavin, 1998). With the move of the philosophy from preserving life-safety to functionality and/or continued function, the need to improve the code requirements was realized (Gates and McGavin, 1998). Johnson et al(1998) developed model code provisions where the reliability of a system or facility is assessed considering the effects of individual component performance.

For most facilities it seems appropriate that a seismic evaluation procedure for equipment and non-structural elements are carried out in a systematic way. Examples of such methodologies can be found in Murray and Sommer (1998), Roche et al (1998), Johnson et al (1998) and in FEMA 74.

Reitherman (1998) notes that with the move of the profession towards performance based design there is a need to form a statistical basis of the behavior of non-structural components. Non-structural damages should be correlated with acceleration and drift levels at the limit states defined by the performance levels such as collapse, near-collapse, life safe, operational and fully operational (Arnold, 1998).

The development of fragility curves for non-structural elements, components in a facility and industrial equipment requires substantial amount of field data. Fragility curves can be found in the literature for power supply equipment, emergency power equipment, rotating machinery, automatic valves, control and instrumentation equipment (Swan and Kasawara, 1998), Generally it is noted that industrial equipment is reliable even under higher levels of ground accelerations more than 0.5g. Similar type of fragility curves is developed by Porter and Scawthorn (1998) for fire occurrences, automated sprinkler system behavior, property loss and fire fatality in high-rise buildings. Although all these curves are region specific it is possible to apply them in other parts of the world under the assumption that design and construction of industrial systems and equipment are less dependent on local factors than they are for regular buildings and systems.

As far as the non-structural components are concerned, vulnerabilities of and typical damages to equipment are well defined. Fragility curves have been derived for many components of critical systems in terms of peak ground acceleration and can be reached in analytical format (Johnson et al, 1999).

In HAZUS (1999) nonstructural components are classified as architectural components (such as partition walls, exterior cladding, penthouses etc), mechanical and electrical components (such as manufacturing and process machinery, piping systems, elevators, HVAC equipment etc) and contents (such as file cabinets, office equipment, computers, storage etc). Four damage classes are used for nonstructural components, which are slight, moderate, extensive and complete. For non-structural components peak building response is given as either as peak spectral response or as peak spectral displacement depending on whether the non-structural component in question is acceleration or drift sensitive. Generally walls and cladding are displacement sensitive components, whereas all mechanical and electrical components and other non-permanent items called as contents are basically acceleration sensitive. Damage to acceleration sensitive components is a function of floor acceleration they are anchored to or on and damage to drift sensitive components is dependent on the interstory drift. Fragility curves for nonstructural components in HAZUS are given for drift-sensitive and acceleration-sensitive components. So there are two basic types of nonstructural fragility curves.

For drift sensitive elements fragility curves can be drawn using median spectral displacement and log-standard deviation values provided for each structural type, damage state and seismic design level. Median spectral displacement values are basically the same for each seismic design level; lognormal standard deviation values however differ slightly.

For acceleration sensitive components, the nonstructural damage acceleration values are assumed to be the same for each building type. They vary however by the seismic design level. There also slight differences in standard deviation values from building type to building type. Fragility curves for acceleration sensitive nonstructural elements are found using the median spectral acceleration and log-standard deviation values provided for each building type, seismic design level.

5.2.3. Building Damage Due to Ground Failure

Building damage that is characterized by four damage situations as Slight, Moderate, Extensive and Complete are simplified for ground failure to contain only one combined Extensive/Complete damage situation. Buildings are assumed to be either undamaged or severely damaged due to ground failure. In fact, Slight and Moderate damage can occur due to ground failure, but likelihood of this damage is considered to be small relative to ground shaking damage. Given the earthquake demand in terms of permanent ground deformation (PGD), the probability of being in the Extensive/Complete damage state is estimated using fragility curves of a form similar to those used to estimate shaking damage. Separate fragility curves distinguish between ground failure due to lateral spreading and ground failure due to ground settlement, and between shallow and deep foundations.
In the 1999 Kocaeli earthquake, some damages relevant to ground failures occurred. Many buildings and facilities located near the surface fault were destroyed by the fault rupture and collapsed along the southwestern shore of the Gulf of Izmit. The subsidence of Ford factory represents an important case study. In Adapazari, many buildings placed over liquefiable silts and sands such as soft young riverbed and lake sediments sank about 1.5m. Some of them tilted due to shear failure of the foundation soil and liquefaction.

A comprehensive study of terrain stability, landslide and liquefaction possibility should be an important consideration of any earthquake performance assessment of any industrial facility.

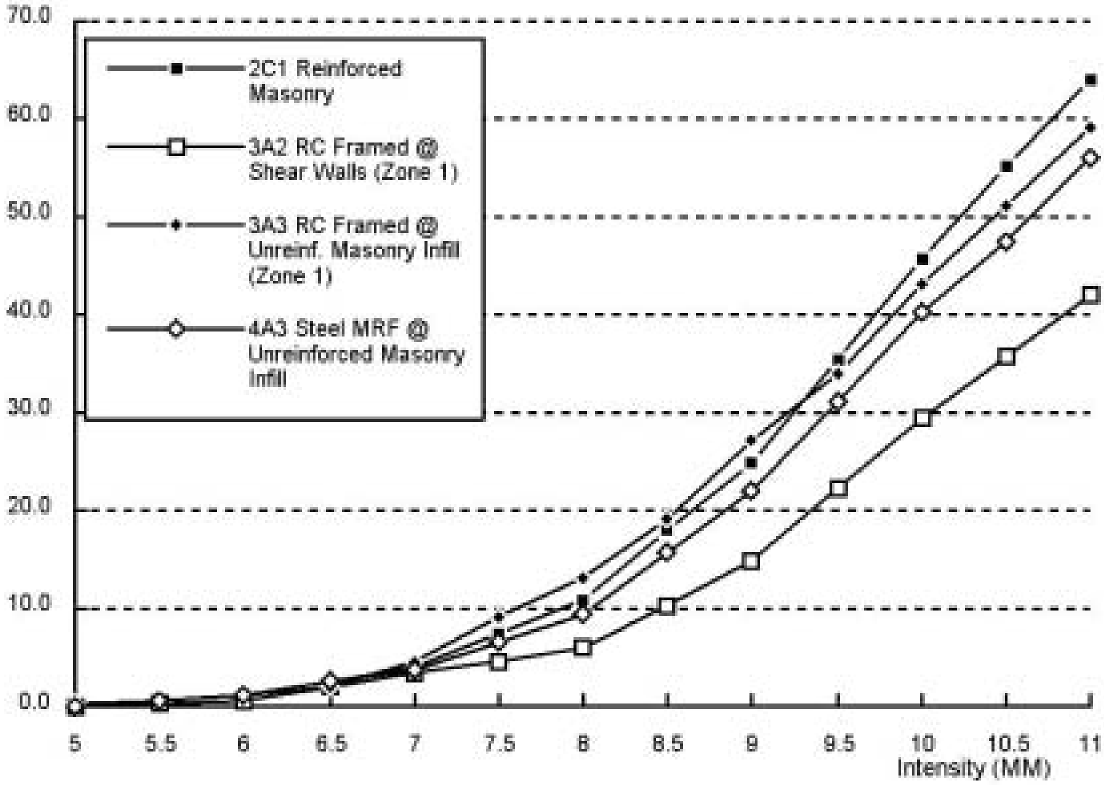


Figure 5.2.1. Vulnerability curves for low-rise engineered building types in Turkey.
(After CAR, BU, 1999)

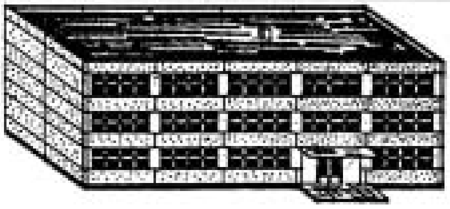
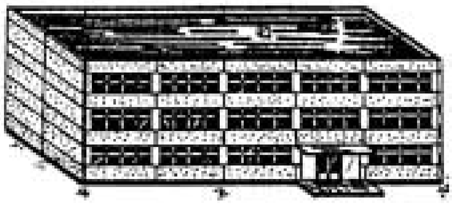
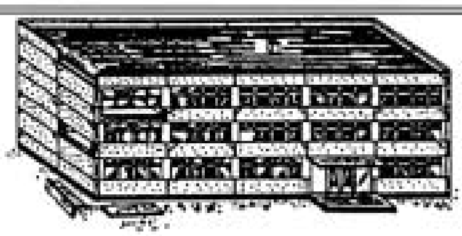
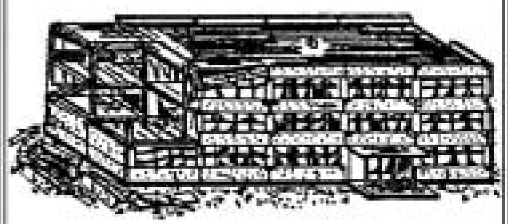
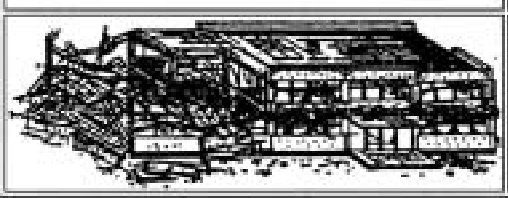
Classification of damage to buildings of reinforced concrete	
	**Grade 1: Negligible to slight damage** **(no structural damage,** **slight non-structural damage)** Fine cracks in plaster over frame members or in walls at the base. Fine cracks in partitions and infills.
	**Grade 2: Moderate damage** **(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. Falling mortar from the joints of wall panels.
	**Grade 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 of conrete cover, buckling of reinforced rods. Large cracks in partition and infill walls, failure of individual infill panels.
	**Grade 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 rebars; bond failure of beam reinforced bars; tilting of columns. Collapse of a few columns or of a single upper floor.
	**Grade 5: Destruction** **(very heavy structural damage)** Collapse of ground floor or parts (e. g. wings) of buildings.

Figure 5.2.2. Classification of damage to reinforced concrete buildings (EMS, 1998).

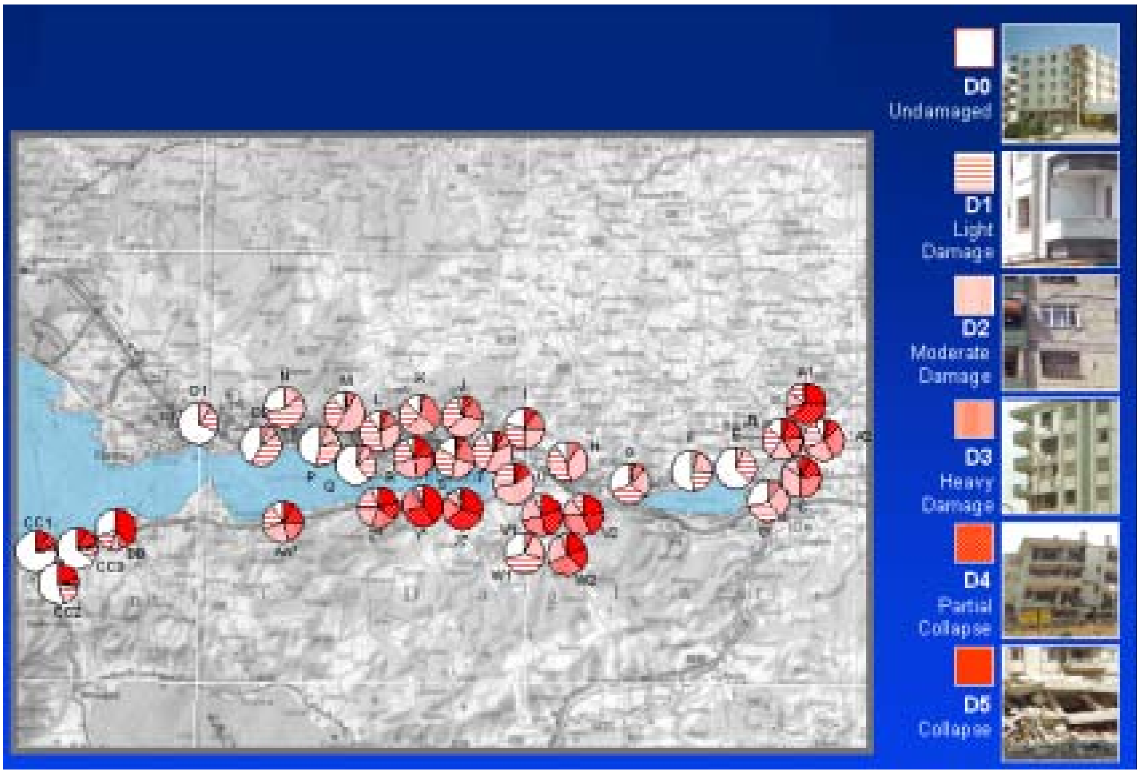


Figure 5.2.3. The damage distribution for mid-rise R/C frame buildings from 1999 Kocaeli earthquake (After A. Coburn, RMS).

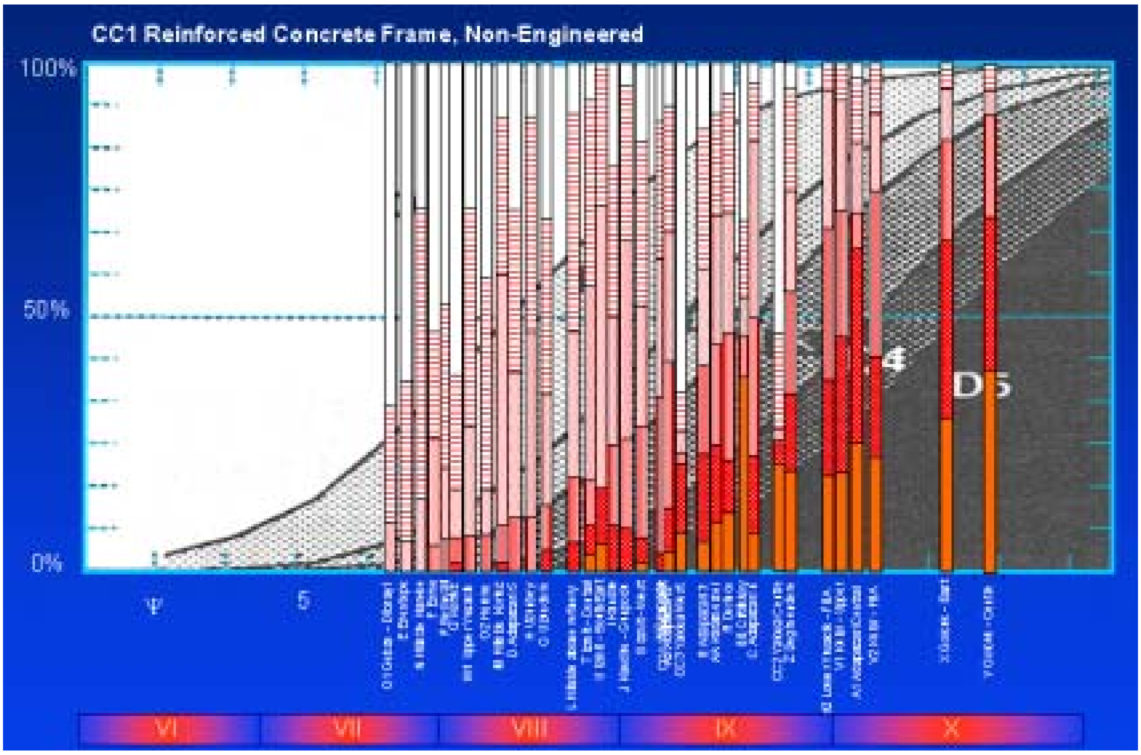


Figure 5.2.4. The empirical vulnerability relationships for mid-rise R/C frame buildings obtained from 1999 Kocaeli earthquake damage distribution (After A. Coburn, RMS).

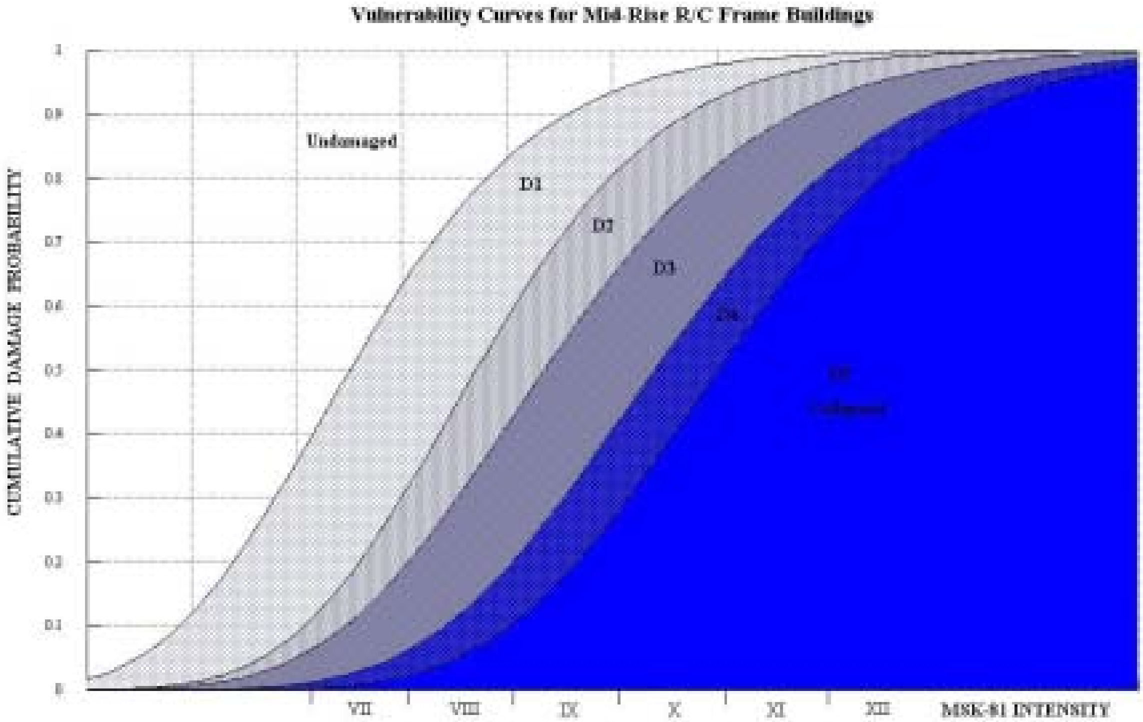


Figure 5.2.5. Vulnerability curves for mid-rise R/C frame type buildings in Turkey.

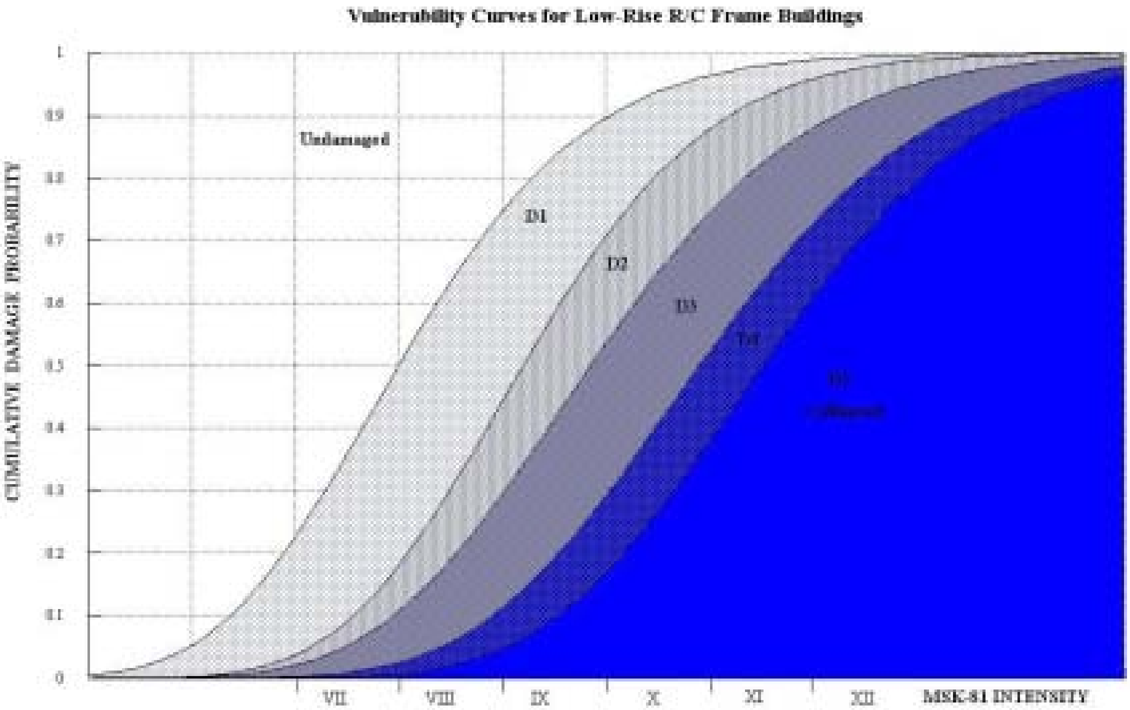


Figure 5.2.6. Vulnerability curves for low-rise R/C frame type buildings in Turkey.

5.3. LIFELINE VULNERABILITIES – DIRECT PHYSICAL DAMAGE

5.3.1. Introduction

An extensive compilation of lifeline vulnerability functions and estimates of time required to restore damaged facilities are provided in ATC-25. Physical damages of lifeline systems covering electric, water supply, natural gas, telecommunication and wastewater systems will be evaluated by ATC-25 and ATC-13 approaches.

5.3.2. Telecommunication

Disruption of the communication systems is mainly due to collapse of buildings or poles. In Turkey past earthquakes have shown that main damages on the telecommunication systems arise mostly from the weakness of the structural system rather than the behavior of the system equipment.

5.3.3. Electrical Transmission

The performance of most power system components and overall system performance have been good in response to a moderate or big earthquake. However a large earthquake may cause long duration power outages over a large area. The damage on the electrical system directly affects all power dependent systems such as communications, water supply and wastewater treatment systems.

Substations are the most vulnerable elements in the electrical power delivery system. Major substations contain switches, porcelain insulators, circuit breakers, transformers, and control equipment. Damage generally occurs in improperly anchored electrical equipment. For non-upgraded electrical transmission substations, ATC-25 assigns 16, 26, 42 and 70 per cent damage values, respectively for earthquake intensities of VII, VIII, IX and X. The respective damage percentages are 8, 13, 25, and 52 for the distribution substations.

5.3.4. Natural Gas Transmission

In general, transmission lines in the natural-gas system consist of 2-25 inch distribution pipes and are located underground except where they emerge for connection to compressor or pumping stations. Being the main transmission lines, they function under high pressure and therefore are manufactured to have high strength against external factors. They are virtually always welded steel and operate at high pressures. The vulnerability function obtained for this component will give us the amount of breakings per km of pipelines as a function of intensity.

Compressor stations include a variety of electrical and mechanical equipment, as well as structures and buildings. The control equipment is usually located in a control building. Compressors are typically used to boost pressures in long distance transmission lines. The distribution mains in the natural gas system are located underground. Shut-off valves, which automatically function when line pressure drops below a certain threshold pressure are frequently used.

Pipelines may be buried underground, on grade or supported above soil. The behavior of the pipes is related with the damage of the soil they are buried or supported. Damage very rarely occurs due to inertia forces. Damages usually concentrate on soft soils and on lines where soil type changes. Pipes may buckle, bend or rupture. During earthquakes the greatest damage to pipelines occur in zones of faulting, poor ground, liquefaction and landslide. Ruptured gas lines lead to leaks and fire hazard. According to ATC 25, about 0.5-1 pipe breaks per one kilometer pipe in intensity VIII earthquakes depending on the soil and pipe conditions.

5.3.5. Water and Wastewater Transmission

In general, various types of transmission aqueducts can be used for transporting water depending on topography, head availability and environmental and economic considerations.

Pipelines are most susceptible to damage from surface faulting and soil failures such as differential settlement, liquefaction or landslide. Unreinforced linings are more susceptible to damage than reinforced linings. Small fractures in the lining can result in a transmission aqueduct being taken out of service. Also pumping stations suffer damage closely related to the performance of the soils on which they are constructed. Recent experience has shown that water systems are susceptible to severe damage due to ground shaking, landslides, liquefaction and surface faulting. For water supply lines, ATC-25 assigns 0.5, 1, 4 and 12 breaks/km, for earthquake intensities of VII, VIII, IX and X. Damage rates should be doubled for sanitary sewer mains. The underground and surface waters are transported from their source by a series of pipeline and flumes and stored in tanks and reservoirs. The line breaks, failure of piping connections and buckling are the expected damages for storage tanks. Because all the ground water wells and pumping stations are dependent upon electrical power, they can be inoperative due to lack of electricity after the earthquake. Hence, portable emergency generators should be provided at all water production facilities. Most of the damage to waste water system caused by an earthquake is broken underground pipes in surface faulting and liquefaction areas.

5.4. FIRE FOLLOWING EARTHQUAKE AND HAZARDOUS MATERIAL RELEASE

Fire following earthquakes is a common occurrence, and can cause significant additional damage. Losses become significant if the fires spread in an uncontrolled manner. Many factors affect the severity of such spreads. Among them are the number of fires started initially, which in their turn depends on the type of equipment in use and fuel storage and distribution methods, the density of combustible material available, and the rate of spread, which will also depend on the weather and climatic conditions, and the ability of the fire fighting services in suppressing fires. The effectiveness of the fire fighting activities depend on the capability of the services, the availability of water, accessibility of the fires, and the extent of involvement of the fire fighting services in activities such as search and rescue (Coburn and Spence 1992). With increased use of natural gas in urban centers, post-earthquake fire hazards may cause substantial damages in future earthquakes. Regarding the fire occurrence aspect of the August 17, 1999 Kocaeli earthquake, owing to the date and time of the event (summer night time), the occurrence and spreading of urban fires were rather low. The event, on the other hand, caused one of the most important and dangerous fire events of Turkey, namely the TUPRAS refinery (a large state owned refinery with a production of twelve million tons per year) fire. The refinery, the associated tank farm with crude oil and the product jetties have undergone considerable structural damage and the fire starting at one of the naphtha tanks caused extensive additional damage and endangered the whole region for several days (Erdik, 2000).

Intensity vulnerability studies should also pay a particular attention to the hazardous materials, i.e. to chemicals, reagents or substances that, if released from their containers in an uncontrolled manner, would cause health or physical hazards. The experience shows that human casualties occur only if the release leads to an explosion. The release of hazardous materials other than explosives may cause physical damages, environmental contamination or temporary health problems in humans, it can also lead to fires. The risk regarding hazardous material release is particularly important in industrialized regions, as it was the case in the August 17, 1999 Kocaeli earthquake (Erdik, 2000). Damage occurring in Toprak pharmaceutical facility caused toxic releases from mixing chemicals. Some tanks in AKSA chemical installation in Yalova experienced damage, which was associated with leakage of chemicals.

5.4.1. Vulnerabilities Of Typical Facilities and Components

ATC13 presents a very good example in the compilation of losses to a very wide variety of structures and systems and in presenting associated loss functions in terms intensity. In ATC 13, the buildings are classified in two ways, 1) engineering classification based on the building's size, structural system and type, 2) social function, a classification based on the economic function of the building. The engineering classification has 78 classes that exist in California and includes buildings, pipelines, chimneys, storage tanks, cranes, conveyor systems, on- and off-shore towers, waterfront structures and equipment. The social function classification has 35 classes and includes 8 industrial classes. The damage probability matrices are produced for each of the 78 engineering classes based on expert opinion. The matrices are valid for facilities with standart construction. Nonstandart construction is classified as construction more susceptible to earthquake damage. Such buildings can be treated by shifting the P_{DSI} one or two intensities down. ATC-13 suggests the shift of the P_{DSI} by two intensities down for nonstandard construction where a lack of earthquake resistant design has been observed or is to be expected.

The industrial classes are among the social function classification used in ATC-13. They are heavy fabrication and assembly, light fabrication and assembly, food and drugs processing, metal and minerals processing, high technology, construction and petroleum. Loss of function/restoration time relationships is provided for each of industrial classes. Equipment classes are residential, office, electrical, mechanical, high technology and laboratory, and vehicles.

Damages to lifelines due to earthquakes can have fatal effects on an urban system. With the advent of technology most of the countries all over the world have become more and more dependent on lifelines, the interruption of which inevitably cause direct losses due to for example fire following earthquake and economic losses due to direct damage as well as business interruption and loss of function.

Vulnerability functions for direct damage and economic losses for a series of lifelines can be found in ATC-25 in terms of intensity. ATC-25 covers highways, railroads, airports, ports and harbors, electric power transmission systems; gas and liquid fuel transmission pipelines, emergency broadcast facilities, hospitals and water supply systems, as well as components comprising these systems. For each of these lifelines vulnerability functions are developed (1) to define direct losses in terms of repair costs expressed as a fraction of total replacement cost of the facility as a function of ground motion given in intensities and (2) restoration curves to estimate the time required to restore damaged facilities to their pre-earthquake state. The curves provided in ATC-25 are based on regression analysis of real damage data from ATC-13 enhanced largely by expert opinion. To describe the approach taken in ATC-25 to produce system vulnerabilities, several cases are summarized from ATC-25 below:

<u>Ports/Cargo Handling Equipment</u>

Building and Equipment Characterization: Warehouse buildings, office buildings, waterfront structures, aprons, scales, tanks, cranes, silos, pipelines, railroad terminals.

Type of Damage: Pore water pressure build-up and excessive pressures lead to deformation of walls and backfill material, liquefaction and associated damages, submarine sliding and associated deformations on the ports. Damages due to shaking are due to loss of bearing and lateral spreading. Quay wall and sheet-pile bulkheads may tilt, slide and deform, block-type quay walls may experience earthquake induced sliding between the blocks, accompanied by extensive settlement and cracking of paved aprons. In case of massive submarine slides piers slide pile supports buckle and yield. Cranes can be derailed and overturn, causing damage to adjacent facilities. Tanks containing fuel may rupture and spill their contents into he water presenting fire and environmental hazards. Pipelines from storage tanks to docks may be ruptured. Failure of access roads and railway tracks can limit port operations.

Direct damage: Vulnerability curves are derived from damage data for cranes (40%) and waterfront structures (60%). Minimal regional variation in construction quality is assumed.

All modes of failure described above have been experienced by the ports around the Izmit Bay in 1999 Kocaeli earthquake.

<u>Fossil Fuel Power Plants:</u>

Building And Equipment Characterization: Power plants fueled either by coal or oil, medium-rise steel braced frame structures.

Type of Damage: Overstressed connections and buckled braces in steel structures, turbine pedestals pound against the surrounding floor of the generation building and damage the turbine generators, boilers may sway causing damage to the support structure, expansion guides and internal tubes of the boiler, water and fuel tanks may have buckled walls, ruptured attached piping, stretched anchor bolts or collapse, piping may be damaged due to due to differential movement or pounding with unanchored equipment, coal conveyors may get misaligned and severely damaged, unstrained batteries and other equipment may fall off their supports, damage in many cases other equipment nearby, transformers may slide and topple.

Direct Damage: Vulnerability curves are derived from damage data for medium-rise steel braced buildings (20%), electrical equipment (30%) and mechanical equipment (50%). Minimal regional variation in construction quality is assumed.

<u>Hydroelectric Power Plants:</u>

Building And Equipment Characterization: Dam (earthfill, rockfill or concrete) and associated equipment such as water-driven turbines, control house and equipment, substation with transformers, switching equipment

Type of Damage: Generally good performance has been observed in past earthquakes, fill dams can experience failures, unless unanchored the equipment performs well, unanchored instruments, batteries, equipment, may slide and topple leading to substantial damage, consequent damages may occur to piping, substation equipment, especially ceramics may be very vulnerable.

Direct Damage: Vulnerability curves are derived from damage data for concrete dams (35%), earth- or rockfill dams (35%) and mechanical equipment (30%). Minimal regional variation in construction quality is assumed.

<u>Terminal Reservoirs/Tanks:</u>

Building and equipment characterization: Underground, on-ground or elevated storage tanks or impounding reservoirs, underground reservoirs are typically reinforced or prestressed concrete with concrete or wood roofs; on-ground storage tanks are anchored or unanchored tanks supported at ground level, they are steel, reinforced or prestressed concrete or wood; elevated tanks are supported by single or multiple columns, have a cylindrical or elliptical shape are mostly braced.

Type of damage: underground tanks receive damage at the columns supporting the roof structure, cracking of walls, sloshing damage to roofs; in case of liquefaction empty tanks may float upward; steel on-ground tanks may be damaged due to the failure of weld between the base and the walls, buckling of tank wall, rupture of attached piping due to sliding or rocking of the tank, implosion of the tank due to rapid loss of contents, differential settlement, bolt and rivet failures, failure of connections between shell and roof, total collapse; concrete tanks may be damaged due to failure of columns supporting the roof, cracking, sliding at construction joints; elevated tanks fail due to inadequate bracing, columns buckling, anchorage failure.

Direct damage: Vulnerability curves are derived from damage data for on-ground storage tanks. Elevated tank are more vulnerable than on-ground tanks, and underground tanks are less vulnerable than them.

<u>Treatment plants:</u>

Building and equipment characterization: complex facilities including a number of reinforced concrete buildings, underground or on-ground reinforced concrete tank structures and basins. Components include trickling filters, clarifiers, chlorine tanks, re-circulation and wastewater pumping stations, chlorine storage and handling, tanks and pipelines, wastewater is conveyed in concrete channels; mechanical, electrical and control equipment and piping in buildings.

Type of damage: soil failure observed frequently, since they are usually on flat and low-lying ground, differential settlement, pipe failures, generic building damage, damage to unanchored equipment, basin walls may crack or collapse.

Direct damage: Vulnerability curves are derived from damage data for medium rise reinforced masonry shear wall buildings (20%), underground liquid storage tanks (30%) and mechanical equipment (50%). Minimal regional variation in construction quality is assumed.

<u>Refineries:</u>

Building and equipment characterization: complex facility with many different types of buildings, equipment, and structures; tank storage consists of unanchored vertical storage tanks supported on ground, horizontal pressurized storage tanks supported on steel or concrete plinths, spherical tanks supported on legs; steel stacks anchored to concrete foundations, extensive runs of ground and elevated piping, pumps, heat exchangers, furnaces, motors, generators, transformers, sitchgear, motor control centers, control equipment, cooling towers, refueling stations, administrative buildings, wharf loading facilities.

Type of damage: fire is the primary concern for refineries (TUPRAS refinery case after the Kocaeli earthquake), loss of contents of any tanks lead to fire, toxic release, air emissions are dangerous, large cylindrical steel tanks can suffer wall buckling, bottom rupture, wall-to-bottom weld failure, roof damage, differential settlement, pipe failure. Piping systems can be damaged, mechanical equipment with inadequate anchorage may slide or topple, buildings can experience generic structural damage, and stacks or columns may be damaged at the anchor bolts.

Direct damage: Vulnerability curves are derived from damage data for on-ground liquid storage tanks (40%), steel chimneys (30%) and mechanical equipment (30%) . Minimal regional variation in construction quality is assumed.

Air Transportation System:

Air transportation systems consist of terminals, and runways and taxiways. Air transportation terminals include terminal buildings, control towers and hangars. Generally control towers are reinforced concrete shear-wall buildings, whereas hangars are typically steel structures. The main terminal building can be either RC or steel. Equipment at air terminals are control, gate and x-ray equipment and standart electrical and mechanical equipment to be found in any commercial facility. Fuel tanks and underground pipelines are used for airplane refueling.

Expected damage includes generic building damage and equipment damage, ranging from broken windows, cracks in walls and frames to partial and total collapse. Unanchored and improperly anchored equipment may slide and topple causing damage to attached piping as well. Gate equipment may become misaligned and inoperable. Fuel tanks and pipes can rupture or be damaged. Tank damage may range from wall buckling, settlement, ruptured piping to loss of contents and even collapse leading to fires and explosions. Airports in low-lying areas, alluvial plains in most cases, may suffer damage due to flooding or tsunamis as well. Runway damage depends on the strength of the underlying soil. They can be damaged by liquefaction, compaction, faulting, flooding and tsunamis. Damage includes misalignment, uplift, cracking or buckling of pavement.

Two national airports exist in Istanbul to serve international and domestic lines: Atatürk International Airport on the European side and Sabiha Gokcen International Airport on the Asian Side. In addition there are military airports and smaller size civil airports which serve smaller private or commercial aircrafts, and also serve for educational purposes such as Hazerfan airport to the immediate north of the Büyükcekmece Lake and Samandira airport on the Asian side.

Transmission Lines:

Transmission lines can be underground or aboveground. Towers are usually steel supported by concrete footings, which may or may not be on piles. Most transmission lines are ac. For dc long-distance lines there are converter stations at each end of the line.

Transmission towers are more susceptible to secondary damage due to landslides, rock falls, and liquefaction and other ground failures, which also hold for underground lines. Conductors supported by towers can slap against each other and burn down.

Transmission Substations:

Transmission substations in the electrical system receive power at high voltages and step it down to lower voltages for distribution. They consist of one or more control buildings, steel towers, conductors, ground wires, underground cables and extensive electrical equipment including banks of circuit breakers, switches, wave traps, buses, capacitors, voltage regulators and massive transformers.

Control buildings may experience generic building damage ranging from dropped suspended ceilings and cracks in walls to partial and total collapse. Un- or improperly damaged anchored control equipment may slide or topple, experiencing damage and damaging nearby piping, equipment etc. Steel towers are usually damaged only due to soil failures. Porcelain bushings, insulators, and lightning arresters are brittle and vulnerable to shaking and are damaged frequently. Transformers are large, heavy pieces of equipment that are frequently un- or inadequately anchored. They can shift, tear the attached conduit, break bushings, damage radiators and spill oil.

Transmission substations are to be found in many large-scale industrial facilities.

Tanks:
In general most tanks are unanchored cylindrical tanks resting directly on ground. They can be of welded, bolted or riveted steel. Foundations may consist of sand or gravel or a concrete ring wall supporting the shell.

Damage mechanisms include failure of weld between base plate and wall, buckling of tank wall (elephant foot), rupture of attached rigid piping due to sliding or rocking of the tank, implosion of the tank resulting from rapid loss of contents and associated negative internal pressure, differential settlement, anchorage failure or tearing of tank wall, failure of roof-to-shell connection or damage to roof seals for floating roofs (and loss of oil), failure of shell at bolts or rivets because of tensile hoop stresses and total collapse. Torsional rotations of floating roofs may damage attachments such as guides, ladders etc.

Theoretically it is always possible to use the damage data provided in ATC-13 and the approach used in ATC-25 to derive vulnerability relationships for the industry classes used in our analysis, assuming that the design and construction quality of industrial systems do not change significantly from country to country.

5.5. VULNERABILITIES FOR HUMAN LOSSES

5.5.1. Casualty Vulnerabilities Due to Building Damage

The earthquake casualties for total deaths can be expressed by the following general equation (Spence and Coburn, 1997):

$K = K_s + K' + K_2$

Where K_s is the fatalities due to structural damage, K' is fatalities due to non-structural damage and K_2 arises from follow-on hazards, such as fire, landslide etc.

The above equation can also be used to express all levels of injury severity, such that:

$K_i = K_{si} + K'_i + K_{2i}$

Where K_i is the i^{th} level of severity as defined in Table 5.5.1.

Table 5.5.1. Injury severity description as given by HAZUS99

Injury severity	**Injury description**
Severity 1	Injuries requiring basic medical aid without requiring hospitalization
Severity 2	Injuries requiring a greater degree of medical care and hospitalization, but not expected to progress into a life threatening status
Severity 3	Injuries that pose an immediate life threatening condition if not treated adequately and expeditiously. The majority of these injuries result because of structural collapse and subsequent collapse or impairment of the occupants.
Severity 4	Instantaneously killed or mortally injured

Casualty rates for R/C structures in Turkey are given in Table 5.5.2.

Table 5.5.2. Casualty rates for Reinforced Concrete Structures

Injury Severity	Casualty Rates for R/C structures (%)			
	Low Damage	Medium Damage	Heavy Damage	Very Heavy Damage
Severity 1	0.05	0.2	1	10-50
Severity 2	0.005	0.02	0.5	8-15
Severity 3	0	0	0.01	4-10
Severity 4	0	0	0.01	4-10

The percentages given in the tables above should be multiplied by the number of people in the building at the time of earthquake.

It should be noted that the casualties in industrial facilities will be controlled not necessarily by collapsed buildings, but rather by collateral hazards such as fire, explosion and chemical substance releases. As such, the assessment of the casualties will be highly facility-specific and no general assessment of casualty ratios can or should be assessed.

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