ACCOUNTING FOR FIRE FOLLOWING EARTHQUAKES IN THE DEVELOPMENT OF PERFORMANCE BASED BUILDING CODES

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SUMMARY

This paper examines the implications of the post earthquake fire scenario for the development of performance based fire and life safety building codes, with specific reference to North America. Performance based codes will offer designers significant flexibility in their designs and more cost effective techniques for achieving fire and life safety objectives, particularly in the rehabilitation of existing buildings which are not adequately addressed in existing codes. It is likely therefore that more effective use will be made of current and emerging technology in fire detection and suppression systems. It is important that in adopting such solutions, that the exposure of buildings to the hazards of fire following earthquakes is not inadvertently increased to an unacceptable level. Various strategies for assessing the risk factors associated with fire following earthquakes are explored and it is recommended that performance based fire and life safety codes incorporate explicit objectives to control and limit the vulnerability of large urban areas to the uncontrolled spread of fire following an earthquake. It is considered that this approach will minimize the risk of adopting design solutions which pose unacceptable hazards in a post earthquake scenario although meeting established objectives for fire and life safety in the more typical fire scenario of an individual fire event occurring under more normal detection and suppression conditions.

INTRODUCTION

One of the events that can be set in motion by a large earthquake occurring in a heavily built up area is a large scale fire or conflagration. This hazard has particular significance for Japan and the west coast of North America where many of the conditions leading to such fires exist. Fires following major earthquakes can have a devastating effect on heavily built-up urban areas, particularly areas contain significant numbers of buildings constructed of combustible materials or industrial facilities containing hazardous or toxic materials. The effects of a major earthquake can lead to a complex chain of events in which fire growth can increase rapidly and overwhelm the ability of fire fighters to control its spread from building to building. In addition to the direct damage to structures and buildings, the earthquake may disrupt lifeline systems such as fire protection water supply, electricity, sewer and gas; it may sever most forms of road and rail transport, and disrupt phone and radio communication. It also creates conditions which can lead to multiple ignitions due to gas leaks, fuel spills, tank ruptures, electrical faults and general damage to building fabric and contents. In addition, the population may respond to a lack of water, gas and electrical services by using liquid fuelled stoves or defective electrical equipment which may significantly heighten the fire risk. Ignitions may also occur following the earthquake as gas and electrical services are restored or as after shocks cause further damage to buildings and services.

In this scenario the ability of fire fighting organizations to mount an effective response can be dramatically impaired. This can be due to a variety of causes such as loss of effective reporting and communications, damaged fire department facilities and equipment, blocked or otherwise impassable streets, inability to mobilize off duty personnel, use of fire fighters to effect urban search and rescue operations and a lack of fire fighting water due to damaged storage and distribution facilities. An inadequate response to urban fires in their initial

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stages can lead to rapid growth of fire involving entire city blocks depending on the local geography and the prevailing wind and weather conditions.

DEVELOPMENT OF PERFORMANCE BASED CODES IN NORTH AMERICA

The Canadian Codes Commission is moving rapidly ahead with development of an objective based code in its current code development cycle. This objective based code is scheduled to be released by 2003, with the Fire Code to be released in an objective based format by the year 2001. The USA and Japan are similarly making the transition toward performance based codes. The International Codes Commission and the National Fire Protection Association are developing performance based codes and various technical societies such as the Society of Fire Protection Engineers and the Structural Engineers Association of California (SEAOC) are developing performance based analysis and design methods.

The concept proposed by SEAOC[1] in their Vision 2000 guidelines defines acceptable seismic performance levels for buildings depending on their importance and the probability of seismic disturbances of various intensities. This is a useful model when considering fire following earthquake. While building codes aim at certain levels of fire and life safety in more typical fire scenarios, a lower performance level may be appropriate for the lower probability occurrence of post-earthquake fires.

PROPOSED OBJECTIVES RELATING TO POST-EARTHQUAKE FIRE RISK

In evolving objectives for a performance based code, the fundamental aim is typically life safety with property damage as an important but generally less critical objective. In the case of fire following earthquake, these two criteria are irretrievably intertwined. In most earthquakes, the occupants do not need any second bidding to flee the building, and few deaths or injuries are caused by people being trapped in the initial fire outbreaks occurring directly after the earthquake. Instead, most risk to life safety from post-earthquake fires is caused by people returning to damaged buildings with impaired fire safety systems and/or entrapment of the population in rapidly advancing fire fronts.

Accordingly, the following three objectives are advanced:

Life Safety: Impairment of fire safety systems and loss of incoming lifeline services should not create unacceptable life safety hazards for continued occupation of the building.

Property Damage: Loss of incoming life-line services should not result in an unacceptable fire growth situation which could rapidly outstrip the ability of the fire department to contain a fire.

Fire Spread: Loss of incoming life line services should not result in an unacceptable level of risk of spread of fire to adjacent buildings beyond the ability of fire fighters to control adjacent exposures and prevent development of a conflagration.

PERFORMANCE CRITERIA BASED ON A TWO LEVEL ANALYSIS

The risks posed by fire following earthquake could be evaluated by using engineering risk management analytical techniques. This would typically require construction of a probabilistic time dependent fire outbreak and development model together with an accurate time dependent event tree modeling of the response. Even if reliable probabilistic data were available, this type of analysis would require technical skills and resources beyond the means of most practitioners in building design and construction. Currently, such analyses are restricted to major hazards such as oil refineries, nuclear plants, weapons complexes and hazardous materials facilities.

It is proposed instead to use a two level approach to performance based fire safety design in earthquake areas in order to account for the vulnerability of the water supply and the electrical service to interruption in earthquake conditions. This two level approach involving normal loss evaluation and maximum foreseeable loss is an accepted tool of risk management. A similar philosophy is used in structural design where a two level design philosophy is employed for ductile braced frames. The structure is analyzed under "normal" earthquake loading, and then re-evaluated to lower criteria for the case where a critical member is removed from the structural model.

The first level of fire analysis addresses the typical range of fire hazards encountered under normal operating conditions. The performance of a building is evaluated under a variety of typical fire outbreak scenarios and compared to the objectives required under the prevailing code. The second level of fire analysis is to analyze the performance of the building under post-earthquake conditions in which the fire department response capability and the lifeline services are impaired. This analysis then compares the performance of the building to a different set of objectives established for this post-earthquake condition.

This second or post-earthquake performance level should predict performance of a building's fire safety systems and assess how the performance of the building will be affected. This analysis should take into account the vulnerability of the building's fire and life safety systems including sprinklers, standpipes, smoke control systems, fire alarm and compartmentation of exit enclosures etc. It will need to evaluate the reliability of incoming power and water services and whether or to what extent, backup or emergency services are required for the building. Emergency power supplies can be supplied from a diesel generator set, emergency water supplies from on site storage, either tanks or dedicated local area cisterns or reservoirs.

Table 1 sets out recommendations for achieving five different performance levels of the building's fire safety systems and lifeline services based on typical seismic conditions prevailing in Western North America for the 1 in 475 year seismic event. Hospitals and emergency response facilities may have to meet the requirement to remain fully operational; whereas other facilities could meet lower performance requirements.

Table 1 Recommended Fire Safety Systems Design Criteria for the 475 Year design Level Earthquake.

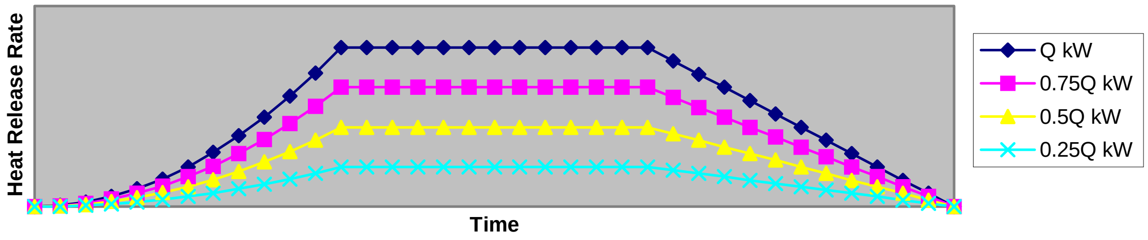
Performance Level	*Service*	*System*	*Comments*
Fully Operational	Water	On Site Storage	Fully hardened system designed to resist Maximum Considered Earthquake (MCE)
Operational	Water	On Site Storage	Fully hardened system designed to resist Design Level Earthquake (DLE).
Life Safe	Water	Municipal Water Supply	Municipal Water Supply. Interior sprinklers and standpipes to be seismically restrained to design level earthquake.
Near Collapse	Water	Municipal Water Supply	Municipal Water Supply.
Collapse	Water	N/A	
Fully Operational	Power	Back-up Power	Minimum two back-up diesel generator sets individually capable of providing minimum operating power requirements. Designed to resist Maximum Considered Earthquake (MCE)
Operational	Power	Back-up Power	Back-up diesel generator set capable of providing minimum operating power requirements. Designed to resist Design Level Earthquake.
Life Safe	Power	Back-up Power	Back-up power for life safety systems only.
Near Collapse	Power		Normal Code Back-up Power
Collapse	Power		N/A
Fully Operational	Passive Measures	Walls, Exit Enclosures, Rated Ceilings	Part of or rigidly attached to building structure. Designed to remain an effective barrier to smoke and flame at maximum expected deformations of building under MCE.
Operational	Passive Measures	Walls, Exit Enclosures,	Part of or rigidly attached to building structure. Designed to remain an effective barrier to smoke and flame at maximum expected deformations of building under DLE.
Life Safe	Passive	Walls,	Designed to remain in place under DLE.
Near Collapse	Passive	Walls,	May fail under DLE but failure conditions which render the exits unusable are prevented.
Collapse	Passive	Walls,	N/A

SEISMIC FIRE FACTORS BASED ON LIFE SAFETY CONSIDERATIONS.

The primary life safety of the building be reviewed to ensure that excessive reliance is not placed on active fire safety systems which could fail following an earthquake. It is proposed therefore to carry out a second level analysis to check that the building can be exited safely and in a reasonable time after an earthquake under conditions in which the sprinkler water supply and incoming power has failed. Typically power for fire alarm and fire safety systems is already on a back-up system, but the reliability of this system under the design level earthquake (DLE) should be evaluated. In the immediate aftermath of an earthquake, occupants will typically not need a fire alarm to indicate that they should evacuate the building.

A Seismic Fire Factor is proposed to modify the design fire for the second level analysis in which it is assumed that incoming power and water supply services are disrupted. This factor is applied to the design fire scenarios selected in the first level performance evaluation of the building in which incoming power and water services may fail. It is thus in inverse relationship to the reliability of the incoming water and power services. A lower limit on the Seismic Fire Factor of 0.25 is suggested on the basis that total reliability of incoming power and water services cannot be assured under seismic conditions, and also to provide an overall limit on the degree of reliance on the operation of active fire suppression systems. Then application of these factors to an idealised design fire condition is shown in Fig 1.

Fig 1 Idealised Design Fire Levels



The Seismic Fire Factor and associated reliability levels for various types of water supplies is contained in Table 2; it is assumed that the sprinkler system itself is adequately restrained against the effects of earthquakes. Thus, use of the Seismic Fire Factor in a performance based code analysis will limit reliance on municipal water and power services which could fail systematically and dramatically across a wide area. It may also be argued that passive systems could fail, but in most cases, failure is incremental and total failure does not occur to all buildings in the subject area simultaneously.

Table 2 Seismic Fire Factors and Reliability levels for Life Safety.

Seismic Fire Factor	Parameters	Reliability Index %
0.25	Sprinkler system fed from dedicated emergency water tanks gravity fed or from below grade storage via fire pump powered by twin back-up generator sets designed to resist MCE with	80 - 100
0.5	Sprinkler system fed from on site storage facilities powered by back-up generator set designed to operate under the DLE.	60 - 80
0.70	Sprinkler system fed from municipal supply water supply likely to sustain significant pressure loss and localized failures at DLE.	35 - 60
1.00	Sprinkler system fed from municipal water supply considered likely to fail rapidly at DLE.	0 - 35

SEISMIC FIRE FACTORS FOR PROPERTY PROTECTION

When evaluating the building against "External" objectives such as property damage and spread of fire, wider parameters need to be reviewed. Currently fire spread objectives can be met under the code by using the principle of "each unto his own." However this approach is based on fire department response within relatively short time frames, often together with operation of an automatic sprinkler system to control the growth of the fire and compartment temperatures. In order to evaluate the post-earthquake response it is necessary to evaluate the vulnerability or fragility of the lifeline services together with the response capability of the fire department and/or emergency services.

Vulnerability and Response Parameters for Property Protection

Vulnerability and Response factors for use in a generic performance based code have been developed. using a scale of 0 to 10. These factors are employed to derive fire criteria modification factors for use in any second level design procedures.

Accordingly the following factors are defined:-

Response Factor - Re Re = 10 Assumes Unimpaired Response Capability following a major earthquake

Re = 0 Assumes no effective response after a major earthquake.

Vulnerability Factor - Ve Ve = 10 Assumes high risk of spread of fire following a major earthquake.

Ve = 0 Assumes low vulnerability to fire spread after a major earthquake.

Response Factor - Re

The Response Factor is used to evaluate the likely effectiveness of the fire department response under the design level earthquake. This factor is considered dependant on four major variables, i.e. Preparedness, Resources, Transportation, and Water Supplies. These parameters are described below together with a proposal for their quantitative evaluation.

R1 - Preparedness The level of preparedness of the fire and emergency services to cope with a major disaster.

R2 - Resources An assessment of the resources available to the fire department to combat fires following an earthquake. This includes an allowance for mutual aid from neighbouring fire departments.

R3 - Transportation An assessment of the likely condition of transportation routes after the design level earthquake.

R4 - Water Supply An assessment of the probability of having adequate water supplies to fight the fires and/or to boost a building's sprinkler and standpipe system.

It is proposed that these factors could be calculated as reliability factors for the area using engineering risk analysis, or selected on the basis of experience and judgement. Suggested values and reliability indexes are shown in Table 3. The reliability index is an assessment of the percentage of functionality of the relevant factor or item remaining after the earthquake.

Once these parameters are evaluated as described above, the Response Factor Re can be calculated using the empirical relationship:-

$Re = (R1 + R2 + R3)*R4$

This relationship, together with the limits for R1 through R4 has been selected to give values of Re in the range of 0 to 10.

Vulnerability Factor Ve

A similar treatment can be applied to evaluation of the Vulnerability Factor Ve. The Vulnerability Factor is used to evaluate the likely vulnerability of the Region, City or Locality to earthquake induced fires under the design level earthquake. This factor is considered dependant on four major variables, i.e. Structural, Combustibility, Density and Sprinkler Dependency. These parameters are described below together with a

Table 3 Response Factors and Parameters.

Factor	Value	Description	Reliability
R1 - Preparedness	3	Detailed response plan, tested and successfully used in an actual emergency.	70 - 100
	2	Detailed planning, tested in simulation exercise. Limited or not used for actual emergency	45 - 70
	1	Paper planning only. Not tried or tested.	0 - 45
R2 - Resources	4	Fire department staffing and apparatus at required strength for normal operations. Mutual Aid available within 24 hr. from adjoining municipalities or additional resources on hand..	80 - 100
	3	Fire department staffing and apparatus at required strength for normal operations. Limited mutual aid available within 24hr. No additional resources on hand.	60 - 80
	2	Fire department staffing and apparatus significantly below required strength for normal operations or highly dependant on operation of automatic sprinklers. Mutual aid available within 24 hr.	35 - 60
	1	Fire department staffing and apparatus significantly below required strength for normal operations or highly dependant on operation of automatic sprinklers. Mutual aid not available	0 - 35
R3 Transportation	3	"Hardened transportation and road system. Major Bridges and overpasses considered upgraded to remain usable at design level earthquake. High level of redundancy in route selection.	70 - 100
	2	Vulnerable bridges and overpasses but high level of redundancy in system. Hardened transportation and road system with major transportation routes confined to narrow corridors.	45 - 70
	1	Vulnerable bridges and overpasses with major transportation routes confined to narrow corridors	0 - 45
R4	1.0	Dedicated Fire Protection Water Supplies designed to remain operable at MCE.	80 - 100
	0.75	Hardened Municipal supply anticipated to remain operable albeit at reduced pressures at DLE. or Dedicated Emergency Supplies well distributed in City and not dependant on exiting distribution piping.	60 - 80
	0.5	Regular Municipal Supply in firm subsoil regions or good availability of back-up sources such as swimming pools, ponds, ocean etc.	35 - 60
	0.25	Regular Municipal Supply in poor subsoil regions without availability of back-up sources such as swimming pools, ponds, ocean etc.	0 - 35

proposal for their quantitative evaluation.

V1 Structural The vulnerability of the buildings in the area to collapse or major damage under the design level earthquake.

V2 Combustibility The degree of combustibility of building structures and cladding systems in the area.

V3 Density The density of building construction in the area and the level of code conformance to spatial separation requirements designed to control the spread of fire to adjacent buildings.

V4 Sprinkler Dependency An assessment of the reliability of the sprinkler water supplies for sprinklered buildings.

These factors could be calculated as reliability factors for the area using engineering risk analysis, or selected on the basis of experience and judgement. Suggested values and Vulnerability Indexes are shown in Table 4. The

Vulnerability Index is an assessment of the percentage of buildings in the area which exhibit vulnerability to the relevant factor or item.

Once these parameters are evaluated as described above, the Vulnerability Factor Ve can be calculated using the empirical relationship:-

Ve = (V1 + V2 + V3)*V4

Similarly to the algorithm for Re, this relationship, together with the limits for V1 through V4 has been selected to give values of Ve in the range of 0 to 10.

Table 4 Vulnerability Factors and Parameters.

Factor	Value	Description	Vulnerability
V1 - Structural Vulnerability	1	;ood Code Enforcement. Older buildings subject to mandatory Upgrades or area predominantly new (post 1970) seismically resistant buildings..	0 - 25
	2	Good code enforcement. No program for requiring mandatory seismic ıpgrades of vulnerable buildings. Area contains significant percentage of seismically weak buildings.	25 - 45
	3	Lack of consistency in code enforcement. No program for requiring mandatory seismic upgrades of vulnerable buildings. Area contains significant percentage of seismically weak buildings	45 - 75
	4	Lack of consistency in code enforcement. No program for requiring mandatory seismic upgrades of vulnerable buildings. Area contains predominantly older non-conforming buildings.	75 - 100
V2 - Combustibility	1	Area contains predominantly non-combustible buildings.	0 - 25
	2	Area contains significant number (> 20%) wood frame buildings. Few buildings with combustible cladding	25 - 50
	3	Area contains predominantly (> 50%) wood frame buildings. Many buildings with combustible cladding.	50 - 100
V3 - Density	1	Buildings typically spaced with wide streets and open spaces. Typically exceeds current spatial separation requirements.	0 - 25
	2	Buildings spaced fairly close together, would meet current spatial separation requirements in most areas.	25 - 50
	3	Buildings spaced close together. Would not meet current spatial separation requirements.	50 - 100
V4 - Sprinkler Dependency	0.25	Buildings in area not typically dependent on sprinklers or dedicated emergency water supplies provided on site to sprinklered buildings.	0 - 25
	0.50	;ignificant number of large buildings in area dependent on sprinklers. No dedicated emergency water supplies provided on site to sprinklered ›uildings. Sprinkler water supply likely to sustain significant pressure loss and localized failures at DLE.	25 - 45
	0.75	Significant number of buildings in area dependent on sprinklers, particularly related to spatial separation and compartment size. Sprinkler water supply likely to sustain significant pressure loss and localized failures at DLE.	45 - 75
	1.0	Significant number of buildings in area dependent on sprinklers, particularly related to spatial separation and compartment size. Sprinkler water supply likely to fail throughout area at DLE.	75 - 100

APPLICATION TO BUILDING DESIGN AND EVALUATION

In order to use the vulnerability and response parameters in a generic performance based code, it is necessary to derive a Seismic Fire Factor similar in application to that derived for life safety considerations. This factor would be used to modify the design fire intensity or growth rate used to evaluate performance of the building to the required acceptance criteria. It is selected to account for the predicted impairment of lifeline services and fire department response capability on the ability of the building to resist the effects of large scale conflagrations. This property protection Seismic Fire Factor is assigned values in the range of 0 to 1, where a low value indicates low vulnerability to the effects of earthquakes and a high value indicates high vulnerability such that reliance on incoming lifeline systems would not be justified. For practical considerations, a lower bound for the Seismic Fire

Factor of 0.25 is suggested to preclude excessive reliance on incoming water and power services and the fire department response capability in conventional fire safety design. Table 5 presents suggested values for this property damage Seismic Fire Factor which is intended to apply to compartment size and building separation requirements to limit fire spread.

Table 5 Seismic Fire Factors for Property Protection

Response Factor				
8 - 10	**1.0**	**1.0**	**0.7**	**0.5**
5 - 8	**1.0**	**0.7**	**0.5**	**0.35**
3 - 5	**0.7**	**0.5**	**0.35**	**0.25**
0 - 3	**0.5**	**0.35**	**0.25**	**0.25**

CONCLUSIONS AND RECOMMENDATIONS

From the review of the literature, it is concluded that there is a significant risk of a conflagration following a major earthquake in many seismic areas of the world. It is recommended that performance based codes contain a framework to prevent undue reliance on sprinkler systems and other life safety systems which are dependent on seismically vulnerable water and electrical services supplied from municipal or commercial sources. A two level design procedure is proposed to be applied to the fire safety design of buildings located in areas of high seismicity.

The first level design is based on the design fire scenarios occurring under normal conditions with detection and suppression systems considered fully operable and a fire department response within normal operational parameters.

The second level design is based on impaired lifeline services and fire department response following a major earthquake. Seismic Fire Factors are proposed to be applied to reduce the design fire depending on the vulnerability of the building and its surrounding area to post-earthquake fire. Two Seismic Fire Factors are proposed. The Life Safety Seismic Fire Factor is applied to assess the internal life safety conditions in the building and its ability to meet the desired performance criteria under the design earthquake. This Life Safety Seismic Fire Factor is employed primarily to assess the adequacy of exiting and egress facilities of the building. The Seismic Fire Factor for Property Protection is employed to assess the external threat posed by fire in the building to neighboring buildings. This external Seismic Fire Factor is applied primarily to assess the construction requirements and spatial separation requirements of the building.

These post-earthquake Seismic Fire Factors are assigned in the range of 0.25 to 1.00 depending on the vulnerability of the buildings to post-earthquake fires and the response capabilities of the fire fighting and emergency response organizations. A framework for assessing suitable values of these Seismic Fire Factors is proposed based on a Vulnerability Factor Ve and Response Factor Re.

It is anticipated that these procedures will lead to more rational decisions in assessing the level of reliance which may be placed on sprinkler systems in seismic areas and will provide guidance on the acceptability of sprinkler based equivalencies in seismic areas. They will also indicate where dedicated on site storage of water supplies for fire fighting and sprinkler systems together with reliable back-up power supplies are warranted.

REFERENCES

1 Vision 2000 - Performance Based Seismic Engineering of Buildings, SEAOC Vision 2000 Committee, 1995.