BUILDING DESIGN FOR FIRE AFTER EARTHQUAKE

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SUMMARY

This paper describes a systematic review of fires after major recorded earthquakes throughout the world, reporting ignition sources, fire spread, fire fighting activities, damage to fire protection systems and water supplies. The historical survey is used as a basis for proposed improvements to building design, in order to reduce the impacts of fires in the urban environment after major earthquakes, giving priorities for building owners, territorial authorities and fire services.

OVERVIEW

Major earthquakes can cause extreme damage to buildings and infrastructure. Earthquakes are largely unpredictable, and large fires following earthquakes are even less predictable. Historical records show that small fires are often initiated by earthquakes, and these sometimes grow into large destructive fires causing loss of life and severe damage to property. The concern is initially with fire damage in individual buildings, where the potential loss of life is much greater in tall buildings than in low-rise buildings. A subsequent concern is with the possibility of devastation resulting from a large urban conflagration. The factors which affect the likelihood of small fires growing into large ones include the amount of earthquake damage, the type and density of building construction, wind conditions, loss of water supplies, and fire fighting capabilities.

Control of fires in buildings after earthquakes is only possible if the buildings are designed with good earthquake resistance, good fire protection and good overlap between the two. Even if both are provided separately, the necessary coordination is often missing. Co-ordination between seismic design and fire design includes earthquake resistance of both active and passive fire protection systems, fire protection of items such as seismic gaps, and secure city water supplies.

IGNITION SOURCES

A comprehensive report by Botting (1998) summarises an exhaustive study of over forty major earthquakes. From those earthquakes, fifteen were singled out for special study where significant fires had been reported. Reported post-earthquake fires for the selected events are shown in Table 1. Most reports give the number of outbreaks within the first hour of the earthquake. Such reporting is difficult because there may have been many more fires not large enough to create severe problems comparable with the earthquake damage. It can be seen that the number of conflagrations is quite small, but the effects of such disasters is enormous. As with any survey of fires, ignition sources are extremely variable and unpredictable because there is such a wide range of possible sources in any residential or industrial community. Many fires resulted from spills of flammable liquids, toppling of equipment or electrical sources. This identifies seismic restraint of potential ignition items and liquid fuels as an essential part of design against fire following earthquake. A large number of fires were reportedly started after the Kobe earthquake when electricity supplies were resumed prematurely to severely damaged buildings. A small but significant number of arson fires have been reported after recent major earthquakes.

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TABLE 1: Reported initial fire outbreaks after earthquakes

San Francisco, 1906	50 (all grew quickly to conflagration)
Tokyo, 1923	134 (all grew quickly to conflagration)
Napier, 1931	3 (started in Chemists' shops; later caused conflagration)
Long Beach, 1933	15 (confined to buildings of fire origin)
Niigata, 1964	9 (one caused conflagration in a residential area)
San Fernando, 1971	116 (3 in broken gas lines in streets)
Managua, 1972	4 – 5 (developed to a conflagration)
Morgan Hill, 1984	3 – 4 (confined to buildings of fire origin)
Mexico City, 1985	200 fires reported within 24 hours (confined to buildings of origin).
Edgecumbe, 1987	No fires reported.
Whittier, 1987	58 structure fires (confined to bldg of origin) and 75 gas fires in first 5 hours.
Loma Prietta, 1989	27 in first 2 hours (confined to buildings of fire origin)
Hokkaido Nansei-oki, 1993	Initial fire outbreak immediately developed to a conflagration.
Northridge, 1994	50 structure fires in first 2 hours, and 110 over 6 hours (most confined to bldg)
Kobe, 1995	89 fires in first 14 minutes (about 50% grew to conflagration). 205 fires reported on the first day. 240 fires by four days later.

TABLE 2: Summary of reported fire spread and extent of damage

San Francisco, 1906	Fire spread by direct flame impingement and thermal radiation. Spot ignitions by burning brands. Buildings were 90% wood up to 5 storeys. Problem with wind. 28,000 buildings destroyed over an area of 10 sq km.
Tokyo, 1923	Severe conflagration. Rapid fire spread through closely spaced dwellings. Problem with wind. 450,000 houses destroyed over an area of 38 sq km.
Napier, 1931	Major conflagration destroyed 4 hectares of city buildings. Fire spread by wind-driven flames, flame impingement and burning brands.
Niigata, 1964	Conflagration in high-density residential areas. Burning oil slick on tsunami-driven water.
Managua, 1972	Conflagration in downtown burned for one week. Modern tall concrete buildings were burned out. Fire spread from storey to storey.
Morgan Hill, 1984	Fire spread between structures due to flying brands (wind speed 7 m/s).
Mexico City, 1985	No major conflagrations No wind. No buried gas pipelines. Gas tank fire spread to two adjacent buildings.
Whittier, 1987	No reported fire spread beyond the structures of fire origin.
Loma Prieta, 1989	Fire spread by radiant heat from apartment building fires. No wind.
Hokkaido Nansei-oki, 1993	Conflagration in residential and industrial area. Fire spread by radiant ignition, exterior fuel tanks and flying brands. Metal roofs limited the fire spread. Fire progressed relatively slowly (35 m/hour).
Northridge, 1994	Most fires confined to building of origin due to light winds, good building construction and building separation, and fire fighting. Fire spread between mobile homes by thermal radiation. 110 fires under control within 6 hours.
Kobe, 1995	Severe conflagration. Fire spread by direct flame contact on collapsed wooden buildings. Solvents and plastics assisted fire spread. Cars helped to spread fire across narrow streets . Fire spread via windows. Non-combustible buildings stopped fire spread. Little wind. 69,000 buildings destroyed in 65 hectares.

FIRE SPREAD

Table 2 shows a summary of reported fire spread mechanisms and the extent of fire damage for each earthquake. Fire spread occurs most rapidly where there is a significant wind and where there are continuous sources of combustible fuel. Fire spread within buildings can be reduced by ensuring that passive fire protection systems have sufficient fire and earthquake resistance. Failure of active fire protection systems is discussed later. Local authorities can reduce the probability of conflagration by promoting earthquake-resistant and fire-resistant urban environments with fire-resistant cladding materials and wide roads to reduce fire spread by thermal radiation. Many lessons can be learned from recent conflagrations in modern suburban environments such as the Oakland Hills fire in California in 1991 (Pagni 1993). The fires at Kobe show the extreme need to control the initial outbreak of fire in conflagration-prone areas.

TABLE 3: Damage to buildings and communications, impediments to fire service access

Earthquake	Reported damage	Fire service access
San Francisco, 1906	Fire alarm receiving office destroyed. Telephone system failed over wide area. Fire stations damaged but all fire vehicles went into service.	Many unsuccessful attempts to send alarms.
Tokyo, 1923	Fire station damage prevented the use of some fire vehicles and equipment.	Access blocked by collapsed buildings, bridges, and damaged roads.
Napier, 1931	Fire Station destroyed and fire engines buried.	Rubble and downed power lines blocked streets.
San Fernando, 1971	Parts of telephone system disrupted due to physical damage, power cuts, and overloading.	Difficulty contacting the fire department.
Managua, 1972	Telephone equipment damage at several exchanges. Three fire stations collapsed. Some portable equipment salvaged. Serious lack of resources.	Narrow streets blocked with debris. Fire department could not be contacted.
Morgan Hill, 1984	Telephone overloading but no damage.	Significant delays. Citizens drove to fire stations to report incidents.
Mexico City, 1985	Telephone system seriously damaged. Main exchange building collapsed and many others severely damaged. Earthquake damage to Fire Department.	Fire department could not be contacted. No reported access problems.
Whittier, 1987	Telephone system remained serviceable although saturated with calls.	Some delays due to difficulties in dispatch and travelling to fires.
Loma Prieta, 1989	Fire Dept dispatch computer overloaded after 5 minutes. Radio communications overloaded. Old equipment, insufficient reserve apparatus, hose fittings and fuel. Poor co-ordination.	Fire units manually dispatched until the call volume subsided. No reported access problems.
Hokkaido Nansei-oki, 1993	The two fire trucks were undamaged but only 25% of the fire fighters were available.	Access to fire was blocked by debris in narrow streets.
Northridge, 1994	Significant disruption to telephone and other communications systems. Loss of standby power and computer-aided dispatch. Minor damage to fire stations.	Degraded emergency response but no serious access problems.
Kobe, 1995	Command centre unable to receive calls immediately after the earthquake due to major damage and overloading. Earthquake damage affected fire stations and fire-fighters.	Fire department could not be contacted. Control of operations transferred to fire stations. Access to sites limited by narrow, rubble-strewn streets, congested with pedestrian and vehicle traffic.

FIRE SERVICE OPERATIONS

Earthquakes can cause damage to many facilities, including most lifelines. The survey shows that delays in reporting fires often results from earthquake damage to communications equipment and buildings. Even if adequate reporting of fires occurs, fire services often have great difficulty getting to the fires for many reasons, including inadequate resources, damaged fire stations, and blocked streets, as summarized in Table 3. The importance of earthquake resistant fire stations and buildings for other essential facilities cannot be over-emphasised.

Table 4: Cause and extent of water supply failure system.

Earthquake	Cause and Extent of Supply Failure	Consequences of Supply Failure
San Francisco, 1906	Complete water failure in most of city. Three major water lines failed in marshy ground. Widespread damage to distribution system.	Absence of water seriously disrupted response. Fires quickly grew to conflagration, driven by persistent wind and wind changes.
Tokyo, 1923	Complete water supply failure.	Water failure caused massive fire spread.
Napier, 1931	Complete water supply failure. Fractures in cast iron water pipes. Reservoir damaged and water tower overturned.	Improvised water supplies allowed the fire-fighters to stop fire spread along three streets.
Long Beach, 1933	Underground water main breakage, particularly in filled ground.	No other details reported.
Niigata, 1964	Underground water pipes broken.	No other details reported.
San Fernando, 1971	The water supplies devastated. Wells ruptured and reservoirs cracked. Pumping stations inoperative due to electricity failure.	No serious spread of fire occurred. Water used from swimming pools.
Managua, 1972	Underground water system badly damaged in poor ground and across earthquake faults. Many breaks in street mains.	Absence of water severely hampered fire-fighting.
Morgan Hill, 1984	Large water losses due to breaks in two transit lines. Many connection failures.	Adequate water to contain and suppress the few major fires.
Mexico City, 1985	Area of water pipe damage much larger than area of structural damage. Shear failures in large pipes, telescopic failures in smaller pipes.	Lack of water adversely affected fire-fighting ability.
Edgecumbe, 1987	Underground asbestos-cement pipes failed in shear. Steel and PVC pipes behaved well.	
Whittier, 1987	Water supplies performed well. Peak water pressure only 50% of normal for two days.	Some areas without water for a few hours, but no major problems.
Loma Prieta, 1989	Water mains broke in areas of soft soil. 69 breaks in water mains affected a 44 square block area.	Severe water shortage. Fire confined to one block with seawater pumped by fireboat.
Northridge, 1994	Water loss from many pipe breaks. Pumping stations and tanks damaged.	Low water pressure. Water from swimming pools.
Kobe, 1995	Most hydrants unserviceable. Many breaks in piping. Water from cisterns, but many damaged. Small fire trucks had limited water capacity.	The lack of water allowed rapid fire spread. Water tankers could not navigate the narrow streets.

Fire services face immense challenges immediately after a major earthquake because they are expected to cope with earthquake-relates fires, and non-earthquake-related fires, and they will be subjected to a massive influx of requests for many other forms of assistance. Off-duty personnel may have difficulty getting to work, and some fire fighters will have earthquake damage to their own property or families.

WATER SUPPLY FAILURES

Inadequate supply of reticulated water is the largest single reason for post-earthquake fire damage. This results mainly from damage to the underground pipe distribution network, but also pump failure and damage to tanks. Of the thirteen events shown in Table 4, only one appears to have no major damage to water supply systems. This is a major area of concern for designers and providers of infrastructure. For cities upgrading reticulated water supplies, enhanced seismic protection can be provided using flexible pipe materials resistant to brittle fracture or joint failure, redundant pipe networks and seismic shut-off valves at strategic locations. Seismic shut-off valves must be accessible for rapid re-instatement of water for fire fighting purposes. Fire services and city administrations in seismic areas should develop facilities for providing emergency fire fighting water from alternative supplies such as the sea, lakes, rivers and even swimming pools.

DAMAGE TO FIRE PROTECTION SYSTEMS

Reported earthquake damage to fire protection systems is shown in Table 5. Earthquakes with no reported damage are not shown. This list reports remarkably little damage, which may be inadequate reporting rather than lack of damage. In order to provide fire safety after earthquakes, both active and passive fire protection systems must have adequate earthquake resistance. There are many potential causes of damage to active systems, including loss of water or electricity, or damaged pipes or wires. The Long Beach earthquake was the first major instance of reported performance of sprinkler systems during an earthquake, which led to the development of earthquake bracing standards for tanks and pipes, now included in many sprinkler standards. Structural design of sprinkler restraints is discussed by Botting and Buchanan (1998) who show that many building codes specify inadequate design forces for design of seismic restraints to automatic sprinkler systems and other active fire protection systems. Seismic restraints to active systems are often not properly checked because they are not in the brief of the structural engineers and seismic behaviour is beyond the area of expertise of most fire protection engineers.

TABLE 5: Earthquake damage to fire protection systems in buildings

San Francisco, 1906	Water supplies to sprinkler disrupted by pipe damage.
Long Beach, 1937	No reported damage to detection or alarm systems. Of 500 sprinkler systems, 80% remained operable and 20% suffered damage or water loss. Most repaired within 72 hours.
San Fernando, 1971	No information on damage to detection or alarm systems. About 4% of sprinkler systems damaged and 3% leaked. Some broken hangers or braces.
Morgan Hill, 1984	No reported damage to detection or alarm systems. Sprinkler damage included broken couplings due to hanger failure or impact by other services.
Edgecumbe, 1987	No information on damage to detection or alarm systems. Severe damage to sprinkler systems due to lack of adequate bracing and rupturing of pipes with differential movement.
Whittier, 1987	No information on damage to detection or alarm systems Several leaking sprinkler pipes, or operation of sprinkler heads.
Loma Prieta, 1989	Most fire protection systems not damaged. Good behaviour in sprinklered buildings due to earthquake bracing and little structural damage.
Northridge, 1994	No information on detection or alarm systems. Many sprinkler systems remained intact. Some sprinkler pipes broken by differential movement or inadequate bracing. Sprinkler heads damaged by ceilings.
Kobe, 1995	No information on damage to detection or alarm systems. Sprinklers did not control fires because of damage and lack of water.

Structural design for fire following earthquake includes seismic resistance of passive fire protection, seismic restraint of sprinkler systems, seismic design of water supplies and tanks, and allowance for flexible piping across seismic gaps between or within buildings. Seismic gaps within or between buildings must have the capacity to prevent fire or smoke spread before and after earthquakes.

As new buildings are designed with increasingly sophisticated active fire protection systems, the potential vulnerability for failure in an earthquake increases. The response to this threat must be an increased reliance on passive fire protection systems. The provision of hand-held devices such as fire extinguishers also has a role in preventing small fires getting out of control. Robertson and Mehaffey (1999) suggest a quantitative risk-based technique for fire design of buildings based on the likelihood of impaired lifeline services and reduced fire service response following earthquake.

Passive fire protection systems consist of fixed items in the building, designed to protect structural members and provide containment for fire and smoke without having to be activated by a detection system. This includes non-structural walls, ceilings and other barriers designed to prevent spread of fire and smoke, all of which must have seismic resistance to allow them to function after an earthquake. Structural design for fire following earthquake also includes protecting the fire escape routes from the building, one of the most important components being the provision of earthquake-resistant stairs. Earthquake-induced loss of stairs in a tall building could result in a death trap in fire following earthquake.

MITIGATION

The main lessons learned in the paper are summarised in Table 6, with three lists of recommended priorities, for building owners, territorial authorities and the fire services. The prevention of serious fire after earthquake depends on the provision of excellent earthquake resistance, excellent fire protection, and co-ordination to ensure that both active and passive fire protection remains functional after a major earthquake.

TABLE 6: Suggested priorities for post-earthquake fire damage mitigation

Building owners	**Territorial authorities**	**Fire services**
1. Control ignition sources and fuel by providing lateral restraint.	1. Strengthen under-ground and above-ground water pipes and facilities. Plan alternative water sources.	1. Maintain operational preparedness for a major earthquake.
2. Provide hand-held fire-fighting equipment and operator training.	2. Check seismic restraints to fire protection equipment, ignition sources and fuel in building permit applications and routine inspections.	2. Ensure earthquake resistance of fire stations and command facilities.
3. Ensure seismic resistance of pipework and water supplies.	3. Develop emergency response plan for essential lifeline services.	3. Plan for alternative water supplies in the event of street mains failure.
4. Prevent spread of fire and smoke by passive fire-resisting construction.	4. Plan for controlled re-instatement of electricity and gas after earthquake.	
5. Provide seismic resistance to smoke control systems and seismic gaps.	5. Promote fire-resistant urban environments with controls on claddings and vegetation. Provide wide roads.	
6. Commission assessment of seismic performance and fire protection systems. Enhance where necessary.	6. Undertake an Engineering Lifelines study to identify mitigation strategies likely to increase the survivability of metropolitan areas against fire	

Recommendations for building owners are in two categories; those which can be implemented immediately include lateral restraint of hazardous items and provision of first-aid firefighting equipment, and a larger list of more expensive structural measures which will require the support of professional engineering consultants. The most important item on the long list of recommendations for territorial authorities is strengthening of water supply networks. This and other related lifeline problems are currently being addressed in many New Zealand cities (eg, Lifelines, 1991). The fire services must work with territorial authorities on protection of public water supplies, and develop their own alternative strategies in the event of possible failure of the public water supply system. Seismic resistance of fire stations and other essential buildings has already been discussed.

The risk of widespread fire in an earthquake prone metropolitan city following damage to engineering lifeline services could be investigated using the structured and systematic approach of an Engineering Lifelines study. Factors to be considered would include:

The extent that building earthquake design and fire protection design have been adequately co-ordinated in selected important buildings, and the extent that the benefits from this are appreciated and can be implemented.

The performance requirements of municipal water supplies to ensure serviceability following a major earthquake, the benefits of establishing dedicated emergency supplies well distributed and independent of the existing distribution networks, and the extent that these schemes can be implemented.

The adequacy of existing transportation routes following a major earthquake for fire and other emergency services vehicles, the benefits of establishing redundancy in route selection within a city, and the extent that these schemes can be implemented.

The extent that the collapse of seismically vulnerable buildings is likely to affect transportation routes, and the benefits of building code enforcement particularly for buildings in the vicinity of major transportation routes.

The extent that building density and materials of construction are likely to support conflagration conditions within the city.

The extent of operational preparedness (ie, likely availability and effectiveness) of the New Zealand Fire Service for response to a major earthquake under a large population centre.

CONCLUSIONS

Fire after earthquake is a very serious threat. The risk is difficult to quantify because of large uncertainties about earthquake occurrence and even more uncertainty about the likelihood of fire after earthquake. This paper has made recommendations for reducing the risk of fire after earthquake, based on a systematic historical review of recent earthquakes. Building owners, territorial authorities and fire services can all reduce the risk of serious post-earthquake fires by implementing a co-ordinated disaster plan for such emergencies.

The major recommendations are:

- Provision of excellent earthquake resistance and excellent fire protection for all buildings.
- All active and passive fire protection systems to be provided with earthquake resistance.
- Earthquake resistant water supplies within cities and inside buildings.
- Seismic restraint of potential ignition items and liquid fuels.
- Reliability of stairs and escape routes for both earthquake loading and fire safety.
- Earthquake resistant fire stations and communications facilities.
- Co-ordinated planning for assessment of essential lifelines and emergency response.

REFERENCES

Botting, R. (1998). The Impact of Post-Earthquake Fire on the Built Urban Environment. *Fire Engineering Research Report* 98/1, University of Canterbury, New Zealand.

Botting, R and Buchanan, A.H. (1998). Structural Design for Fire after Earthquake. *Proceedings, Second Australasian Structural Engineering Conference,* Auckland. pp529-534.

Lifelines (1991). Lifelines in Earthquakes - Wellington Case Study. Project Report. Centre for Advanced Engineering, University of Canterbury.

Pagni, P.J. (1993). Causes of the 20 October 1991 Oakland Hills Conflagration. *Fire Safety Journal*, 21, 4, pp 331-340.

Robertson, J. and Mehaffey, J. (1999). Accounting for Fire Following Earthquake in the Development of Performance Based Building Codes. *Proceedings, Interflam'99 Conference,* Edinburgh. pp273-284.