Fire Following Earthquake

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ABSTRACT

Fires following earthquakes have caused the largest single losses due to earthquakes in the United States and Japan. The problem is very seriously regarded in Japan, but not very seriously considered in the US or other earthquake-prone countries. Yet, the potential for future conflagrations following earthquakes is substantial. Earthquakes in the US in 1983 and 1984 have recently highlighted this problem. The scenario for post-earthquake fire must consider structural and non-structural damage, initial and spreading fires, wind, building density, water supply functionality and emergency response. Each of these factors is reviewed in this paper, and an analytical model and preliminary results for San Francisco, California are presented.

INTRODUCTION

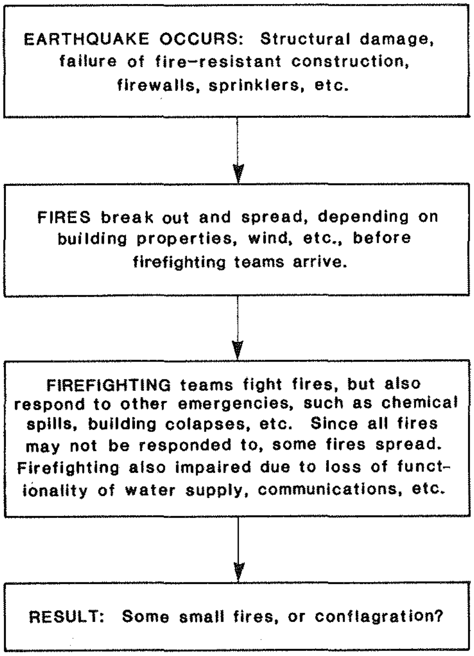
Although many aspects of fire and earthquakes have been investigated in recent years, one aspect that has seen very little treatment has been the subject of fire spread in an urban region following an earthquake, herein termed post-earthquake fire. This problem is important in cities in Japan, the US and other countries which have a large building stock composed primarily of wood. This is true of all Japanese cities, and most cities in the US, especially the seismically active West (e.g., Los Angeles, San Francisco). This hazard also exists with regard to industrial installations, such as oil refineries, large factories, chemical plants and installations dealing with hazardous materials. The problem is an especially complex and challenging one, since an earthquake has the potential for initiating a chain of events involving damage to structures and to lifelines such as water supply, gas, electricity, transportation and communications systems, that can turn a moderately damaging seismic event into a conflagration of disastrous proportions.

In Japan, the problem is very seriously regarded, which is appropriate given the holocaust that occurred in Tokyo on Sept. 1, 1923, as well as Japan's history of conflagrations in general. Indeed, in Japan earthquakes are feared equally for post-earthquake fire, on the one hand, and for shaking, tsunami, liquefaction and landslide damage on the other. However, in the US and most other earthquake-prone countries, the problem is largely ignored, which is strange since in the US as well as in

Japan the single most damaging earthquake of the twentieth century has actually been a post-earthquake fire. This refers, of course, to San Francisco 1906 and Tokyo 1923. In 1906, 80% of the damage in San Francisco was due to fire, amounting to a burnt area of 12.2 sq. km., 28,000 buildings in all. At today's prices, this would be about $3 billion. Little appreciated today is that fires occurred throughout the heavily shaken portions of California, and that the central business district of the city of Santa Rosa was also destroyed by fire in 1906. Tokyo's conflagration in 1923 was much worse, burning 38.3 sq. km. and reaching firestorm proportions, with a tragic death toll of about 140,000.

POST-EARTHQUAKE FIRE CONSIDERATIONS

The post-earthquake fire problem is complex and involves many diverse elements (Figure 1). It begins with the occurrence of the earthquake, which causes structural and non-structural damage to buildings, lifelines, fire stations, communications networks, etc. Structural damage results in the loss of integrity of many of the fire safeguards we rely upon, such as firewalls/stops/doors, etc., fireproof wall and roof coverings (i.e., loss of stucco, brick, etc., wall coverings), sprinkler systems, fire alarms, etc. Additionally, damage occurs to urban lifelines such as water supply, transportation, communications, etc.



EARTHQUAKE OCCURS: Structural damage, failure of fire-resistant construction, firewalls, sprinklers, etc.

FIRES break out and spread, depending on building properties, wind, etc., before firefighting teams arrive.

FIREFIGHTING teams fight fires, but also respond to other emergencies, such as chemical spills, building colapses, etc. Since all fires may not be responded to, some fires spread. Firefighting also impaired due to loss of functionality of water supply, communications, etc.

RESULT: Some small fires, or conflagration?

Figure 1. Simplified Scenario for the Post-Earthquake Fire Problem

Beyond physical damage, the shaking causes fires to break out, due to a variety of causes including overturning of open flames (candles, fireplaces, water heaters), electrical short circuits, arcing of power lines, hot equipment coming into contact with debris, friction or sparking of articles during the shaking itself, etc. Many of these fires can quickly and easily be put out by citizens if the citizens are uninjured, aware of the fire, can get to it and have the means with which to fight it. Experience shows that citizens are capable of doing this in a good percentage of the initial fires (Ref. 1). However, because of people not being aware of some of these fires in the initial stage, or not being able to put a fire out, some fraction of initial fires spread to the stage where they require well-equipped firefighting teams. This fire spread is initially within the compartment, then the building. Fire spreading to neighboring buildings may be gradual or rapid, depending on the spacing and exposure between buildings, the materials of the buildings and their contents, the damage to these materials, the wind and the emergency response. Wind is an especially critical factor since inter-building fire spreading velocity increases exponentially with wind speed.

Historically, this experience has been borne out by several earthquakes:

Earthquake and year		Number of Initial Fire Outbreaks
San Francisco	1906	50
Tokyo (Japan)	1923	129
Fukui (Japan)	1948	24
San Fernando	1971	109
Coalinga	1983	19*

*15 grass fires; 4 buildings

Most recently, the 1983 Coalinga and 1984 Morgan Hill, California earthquakes have pointed out the potential for major post-earthquake fires (Refs. 10, 11). These two events highlighted several lessons, including:

- Fire departments functioned well but were inundated with numerous demands involving not only fire but structural damage, search and rescue, hazardous material incidents and medical aid.

- Communications were seen to be extremely vital but highly vulnerable, especially with regard to reporting initial fires to the fire departments.

- Fire departmental response can be retarded, due to the following factors:

  1. delays in reporting the fires, due to telephone overload
  2. delays in proceeding to the fire, due to rubble-blocked roads, landslides, downed wires, traffic jams, etc.
  3. problems at the scene, including downed wires, collapsed buildings, and especially, lack of water due to damaged mains or, less frequently, insufficient pressure.

Restoration of utilities (gas and electricity) can result in delayed fires, at the time of the service restoration. This can be hours to days after the initial disaster. Restoration needs careful thought as to how and when to reconnect an area. Consideration might be given to not restoring service before individuals are present in every structure (with public officials authorized to enter those structures whose owners are not available in in order to check for fire or gas leaks, and for standby fire units to be in place in the area at the time of utility restoration.

The diversity, significance and complexities of fires following earthquakes are evident. This complexity requires simulation modeling, which has rarely been applied to this problem (Refs. 2-4).

ANALYTICAL MODELING

This section reviews some previous analytical modeling of the author, performed in Japan, and presents some preliminary results of ongoing work.

Scawthorn et al. (Refs. 4,9) presented an analytical methodology for the probabilistic estimation of losses due to fire following earthquake in an urban setting, Figure 2. That work, which was conducted in Japan and utilized the city of Osaka as a case study area, showed that fire following earthquake was related to patterns of overall seismic damage and, under certain circumstances, could be more significant than damage due to general shaking (as indeed it had proven several times historically). Table 1 for example indicates total expected fire and shaking losses for the city of Osaka, Japan under two hypothetical but realistic earthquake scenarios. These losses are for direct structural material losses only, not including any human casualty equivalents or indirect social losses.

TABLE 1: Comparison of Post-earthquake Fire Spreading and Other Losses for Osaka, Japan* (after Ref. 4)

Damage Agent	Losses (US $ millions)		
(low-rise bldgs. only)	Annual	M 6.5 @ 40 km.	M 8.0 @ 160 km.
Fire	45	188	13
Shaking	80	158	17
Liquefaction	20	3.4	0

*(Osaka has a population of 2.8 million people, and an area of 208 sq. km.)

More recently, the author has extended this methodology and is presently employing it to examine the effects of a major earthquake on the city of San Francisco (population 700,000, area 125 sq. km.). Figure 3 shows San Francisco and the distribution of fire stations (symbols) and engine companies (numbers), while Figure 4 shows seismic intensity in the Modified Mercalli Intensity scale (MMI) for San Francisco, given a magnitude 8.3 earthquake on the San Andreas fault similar to the 1906 event. Seismic intensity is determined according to the interaction of intensity of ground shaking (decreasing with distance from an earthquake fault) and local site geologic effects, which may increase or decrease seismic intensity. Note that the city generally sustains about MMI VII+ (significant structural damage) although MMI IX (heavy damage, some collapse) is exceeded, especially in the eastern portion of the city where old marshy areas will experience ground failure.

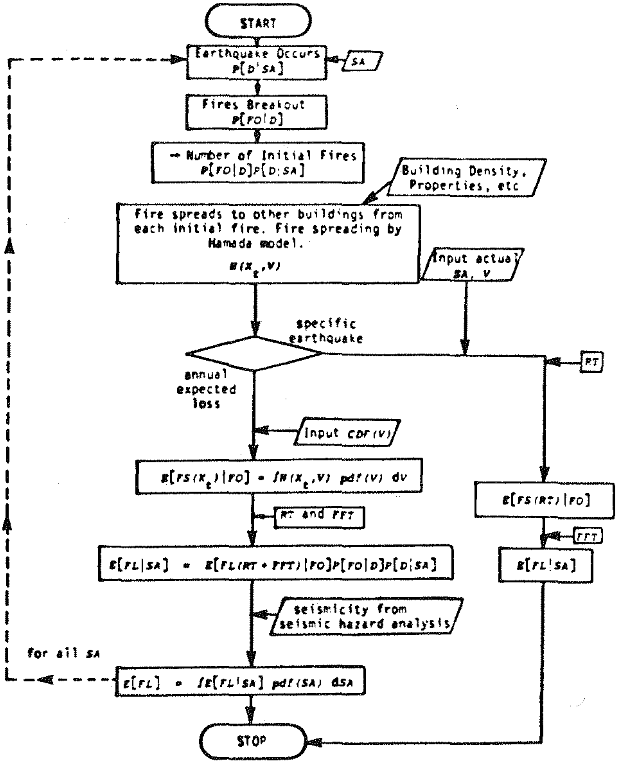


Figure 2 Schematic Diagram of Analytical Methodology (Reference 9)

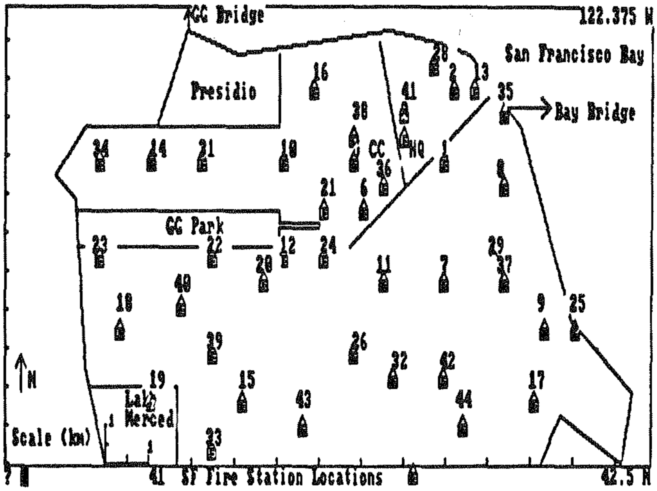


Figure 3 San Francisco Fire Department Fire Station Locations

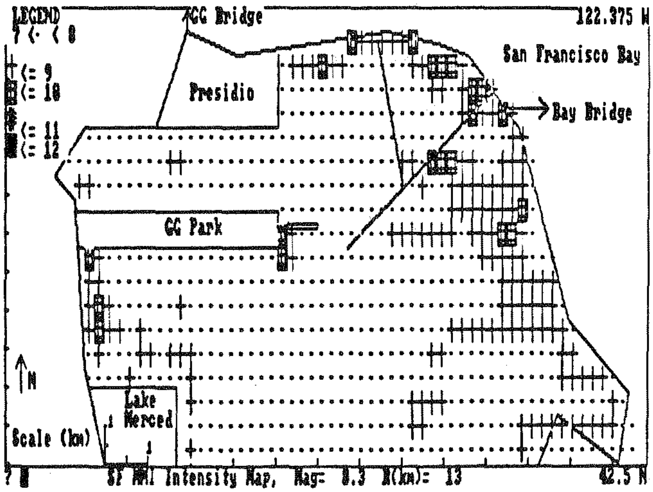


Figure 4 MMI Intensities for San Francisco for a M8.3 on the San Anreas Fault

Initial fire outbreaks are next determined, as a function of seismic intensity, building structural characteristics and occupancy. Initial fire outbreaks are due to a variety of sources, including gas pipe breakage (e.g., overturning water heaters), open flames (e.g., candles), electrical malfunctions (e.g., damaged wires, malfunctioning appliances), reactions of spilled chemicals, etc. We consider fire outbreaks which are not extinguished by local citizens. That is, we only consider fires which grow to considerable size, and require trained firefighting personnel and equipment. While deterministic analyses for initial fire outbreak rate are conceptually possible, present data are insufficient. Instead, based on past US and Japanese earthquake experience, regressions have been performed to determine initial fire outbreak as a function of seismic intensity and occupancy. Employing these correlations together with building and seismic intensity distributions, we see in Figure 5 that about 27 fires will occur. This initiation of fire occurrence is based on a random Poisson process, and is not unique as to specific fire location or total number. Numerous trials have shown that the total number of fires is usually in the range of 25-35, with similar patterns of occurrence.

Each of these fires requires response by at least one of San Francisco's 41 fire engines. There are insufficient engines to respond to each fire under standard procedures and, if we assume that at least one engine responds to each fire, we can estimate engine arrival time at each fire under post-earthquake conditions, Table 2. We see that several of the fires can be suppressed but that many of the fires are multi-alarm in nature, requiring several or more engines and other resources. Alternatively, if normal multi-engine response procedures are employed, then some fires cannot be responded to. Note that ordinary mutual-aid assumptions will be inappropriate in this situation, since neighboring jurisdictions will have their own problems. This example is for a 10 mph wind from the west. Under such a scenario we can see that one or more large spreading fires are likely. These results are preliminary, and studies are being performed to simulate subsequent fire department response, fire development, and water supply damage.

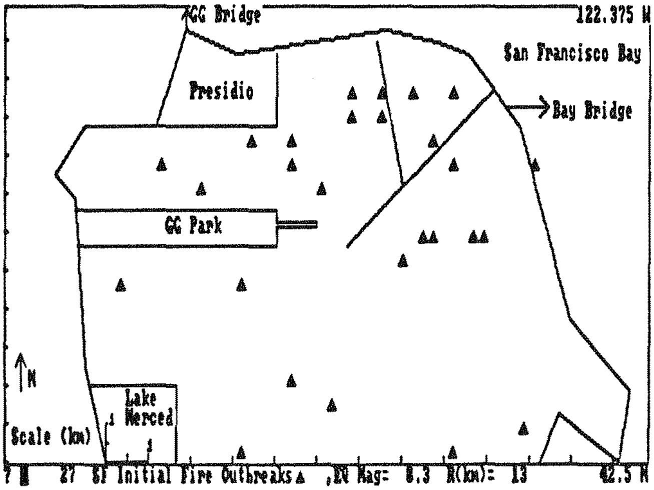


Figure 5 Initial Outbreak of Fires for MMI Distribution in Figure 4

Table 2 Magnitude 8.3 San Andreas Event Scenario,
San Francisco: Initial Fire Department Response and Demand

Wind velocity 10 mph from azimuth 270 INITIAL RESPONSE

Fire	T(arrival) (mins)	Fire Vel. (ft/min)	A(Burnt) (acres)	No. Burnt Bldgs	Loss ($mil)	FFlow (Mgpm)	No.Engs. Reqd.	No.Pers. Reqd.
1	10.5	9.2	0.2	2.2	0.2	1.3	2	11
2	6.2	7.6	0.1	1.6	0.1	1.0	1	8
3	8.1	8.4	0.1	2.8	0.2	1.7	2	14
4	7.4	8.1	0.1	1.1	0.1	0.6	1	5
5	8.5	8.5	0.1	1.3	0.1	0.8	1	7
6	19.9	11.4	0.8	18.7	1.4	11.1	15	93
7	21.8	11.7	1.0	22.9	1.7	13.6	18	113
8	6.2	7.6	0.1	1.6	0.1	1.0	1	8
9	15.2	10.6	0.4	3.8	0.3	2.3	3	19
10	8.1	8.4	0.1	2.8	0.2	1.7	2	14
11	11.6	9.6	0.3	2.4	0.2	1.4	2	12
12	9.7	9.0	0.2	10.0	0.7	5.9	8	49
13	8.1	8.5	0.1	6.4	0.5	3.8	5	32
14	15.6	10.4	0.6	26.0	2.0	15.5	21	129
15	7.4	8.2	0.1	5.0	0.4	2.9	4	25
16	10.5	9.2	0.2	2.2	0.2	1.3	2	11
17	10.5	9.2	0.2	10.0	0.7	5.9	8	49
18	15.2	10.3	0.5	22.8	1.7	13.5	18	113
19	8.5	4.9	0.1	2.5	0.2	1.5	2	12
20	12.4	9.7	0.3	14.4	1.1	8.6	11	71
21	5.0	6.2	0.1	5.6	0.4	3.3	4	28
22	6.2	4.7	0.0	1.5	0.1	0.9	1	8
23	9.3	8.8	0.1	1.3	0.1	0.8	1	7
24	14.7	10.7	0.3	1.6	0.1	1.0	1	8
25	9.3	8.7	0.1	0.6	0.0	0.3	0	3
26	9.3	8.8	0.1	1.3	0.1	0.8	1	7
27	11.6	9.7	0.2	1.0	0.1	0.6	1	5
			6.6	173.5	13.0	103.04	137	859

CONCLUDING REMARKS

Large post-earthquake fires are a low probability, high consequence event. The largest fires in the US and Japan in this century have been due to post-earthquake fire. Adequate preparation and response for fire following earthquake is extremely difficult but is aided by analytical modeling as presented herein. This modeling shows that, on average , post earthquake fire spreading is less of a problem than direct structural damage due to shaking, but that there exist situations where this may be reversed.

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