Developing a Physics-based Model for Post-Earthquake Ignitions

Selim Serhan YILDIZ
Istanbul Technical University
yildizsel@itu.edu.tr

Himmet KARAMAN
Istanbul Technical University
karamanhi@itu.edu.tr

ABSTRACT

Earthquakes not only cause damages by shaking, but secondary disasters like fire following earthquake (FFE), tsunami, liquefaction, land slide etc. also cause large-scale losses. In some cases, FFEs result in losses more than shaking do as seen in the 1906 San Francisco earthquake and the 1923 Kanto earthquake. FFEs are generally caused by strong ground shakings. Strong shakings damage the structures and infrastructures. As a consequence of earthquake, many ignitions can occur due to damaged gas systems and electrical systems, overturning of electrical appliances and heating equipments and falling of flammable materials from shelves in structures. In addition to interior structure ignitions, damaged infrastructure elements such as gas pipelines and electric transmission lines can also cause ignitions. Some of these ignitions spread due to amount of fuel load (combustible materials), construction material, direction and speed of wind etc. in the environment and they can turn into large urban conflagrations. This paper proposes a physics-based post-earthquake fire ignition model in order to estimate number and location of ignitions in urban areas.

Keywords

Post-earthquake ignition, Fire following earthquake, Physics-Based, Urban.

INTRODUCTION

Earthquakes not only cause damages by shaking, but secondary disasters like fire following earthquake (FFE) and tsunami also cause large-scale losses. In some cases, the losses associated with FFE exceed the losses from direct shaking as seen in the 1906 San Francisco earthquake and the 1923 Kanto earthquake.

The major earthquakes damage lifelines of cities such as water systems, electrical systems and gas systems in addition to the structures. Heavy damage in the electrical and gas systems can result in leakage from gas systems and sparking from electrical systems. These leakage and sparking can cause many simultaneous fire ignitions. These ignitions can turn into large urban conflagrations due to construction material, water capacity, fire fighting capabilities, inadequate number of firebreaks etc. Water capacity and fire fighting capabilities are decelerated because of damaged water pipelines, debris from collapsed buildings onto the road and interruption in communication systems. All of these effects provoke many destroyed buildings, numerous casualties and enormous economical losses.

There were many earthquakes resulted in FFEs that caused significant damages in history such as the 1906 San Francisco, the 1923 Kanto (Tokyo), 1931 Napier, 1948 Fukui, 1964 Niigata, 1968 Tokachi-oki, 1978 Miyagiken-oki, 1983 Nihonkai-chubu, 1989 Loma Prieta, 1993 Hokkaido Nansei-oki, 1994 Northridge, 1995 Hyogo-ken Nambu (Kobe), 1999 Marmara, 2003 Tokachi-oki and 2011 Tohoku earthquakes. The 1906 San Francisco and The 1923 Kanto Earthquakes were the biggest ones because they both resulted in large urban conflagrations. Fire following the 1906 San Francisco earthquake was the most destructive FFE in US history. There were 59 known fires (52 in San Francisco and 7 in other cities) in affected area in the 1906 San Francisco earthquake (Scawthorn and O'Rourke, 1989). There were 300 breaks in local city distribution water mains and 23200 breaks in service lines. The fire lasted for 3 days because of the leak of water caused by damaged water pipelines. Because of highly flammable contruction (wooden buildings), inadequate fire protection and inadequate water supply, ignitions turned into large conflagrations (Scawthorn et al., 2006). Finally, the earthquake and fire ended up with approximately 3000 deaths and 28000 destroyed buildings that 80% of them caused by fires following earthquake (Scawthorn et al., 2005). The 1923 Kanto fire was the largest urban conflagration in history. There were 277 fire outbreaks, about 133 of which spread. 80% of 83600 water services to houses were burned (Scawthorn et al., 2005). The conflagration caused approximately 140000 deaths and destroyed approximately 447000 houses (Hamada et al., 1992).

REASON OF POST-EARTHQUAKE FIRES

FFEs are generally caused by strong ground shakings. Strong shakings damage the structures and infrastructures. As a consequence of earthquake, many ignitions can occur due to damaged gas systems and electrical systems, overturning of electrical appliances and heating equipments and falling of flammable materials from shelves in structures. In addition to interior structure ignitions, damaged infrastructure elements such as gas pipelines and electric transmission lines can also cause ignitions. Some of these ignitions are put out by occupants and they do not result in significant damages. Some of them spread due to amount of fuel load (combustible materials), construction material, direction and speed of wind etc. in environment and they can turn into large urban conflagrations. The most common FFEs are caused by restoration of electricity in red tagged buildings which are unsafe and no one are not allowed to enter inside. If there is a gas leak in the red tagged building, it will be ignited by restoration of electricity.

According to Mohammadi and Grobbel (1996), FFEs can be caused by gas leaks due to failure of pipes or gas appliances, electrical distribution system problems, flammable material spills and overturning of burning candles, table lamps and gas grills. Actually, equipments like candles and table lamps are not commonly used in present life, so these factors will not be considered in future studies.

PREVENTION AND MITIGATION MEASURES

In order to prevent and counter FFEs, causes should be examined in detail. Indoor elements include gas and electrical systems, electrical appliances, heating equipments and flammable materials. Damaged gas systems can cause gas leaks and these gas leaks can turn into ignitions because of damaged electrical systems, electrical appliances and heating equipments. Flammable materials can also cause spread of fire rapidly. Automatic seismic shut-off valves for gas and electrical systems should be used and heating equipments should be fixed to decrease the ignition probability.

Strong earthquakes can heavily damage main gas pipelines and electrical transmission lines as seen in historical earthquakes. Shaking causes several breaks in gas mains and service lines, and contributing factors like collapsed electrical transmission lines, ignition system of a truck or sparking due to any friction can initially cause ignitions. Spread of these type of ignitions are generally faster than indoor ignitions. They can turn into large urban conflagrations due to diameter and operating pressure of the pipe, construction materials of neighboring structures, wind speed and direction. Gas and electrical networks should be reinforced against a possible earthquake. As mentioned before most fires are occurred because of restoration of electricity in red tagged buildings. Lack of communication between disaster or emergency managers and power companies results in this type of fires. Power companies should keep in contact with emergency managers before any restoration operation.

INDOOR IGNITION MODELING FOR BUILDINGS

The effective and fully deployed FFE model should contain ignition modeling, spread modeling and suppression modeling. The model should be able to estimate number and location of ignitions, spread potential of ignitions by considering the suppression activities. Aim of this study is developing a physics-based indoor ignition model for buildings.

Many of current ignition models calculate the number of ignitions for a particular area by using equations due to Peak Ground Acceleration (PGA) or Modified Mercalli Intensity (MMI) as only input data. They obtained these equations with regression analyses by using historical records. A reliable model should consider the physical factors of ignition and calculate the number of ignitions or ignition probability according to these factors. These type of models are named physics-based ignition models. In physics-based models, aim or problem is defined very similar to the real condition by identifying real components of the problem.

An ignition can be defined as a fire occurred after earthquake that needs fire department response. Fires which are extinguished by occupants are not considered as ignitions in FFE problem. The first step of FFE modeling is modeling the ignitions that means estimating number and location of ignitions. Ignition term can be expressed by different names like fire or fire outbreak in several sources. Occurrence of post-earthquake ignitions can be considered in two different ways. One of them is indoor ignitions caused by damage to buildings and the other one is the outdoor ignitions caused by damaged lifeline systems like main gas pipelines and electric transmission lines.

According to structural damage after an earthquake, ignitions can appear because of damaged building utility systems, heating equipments, cooking equipments and other inflammable or electrical appliances depending on the magnitude of the earthquake. Many scientists made researches to estimate the number of post-earthquake indoor ignitions and they developed different models. Most of these models depend on ground motions. Existing ignition models according to PGA values have big differences in ignition estimation results (Figure 1).

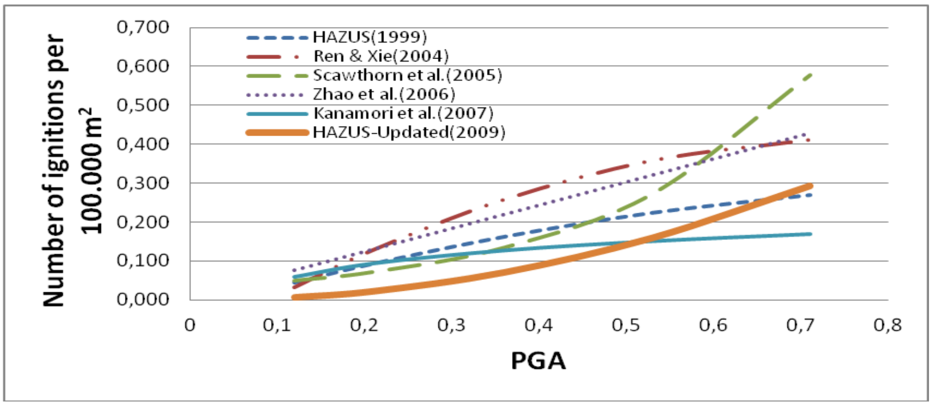

Figure 1. Comparison of Existing PGA-depended Ignition Models

There were some researches about multi-parameter ignition modeling which were studied in the last couple years. Table 1 shows the variables, covariates and equations of different indoor ignition models.

Model (Year)	Outcome (y)	Input variable (x)	Equation
Kawasumi (1961)	rate of ignitions (%)	rate of collapsed wooden buildings	$\ln y = 0.684\ln(x) - 5.807$
Mizuno (1978)	rate of ignitions (%)	rate of totally collapsed households	$\ln(-\ln(1-y)) = 0.606\ln(-\ln(1-x)) - 6.149$
Kobayashi (1984)	number of ignitions per 10000 m^2	building collapse ratio	$y = 0.00356x + 0.00031$ $y = 0.00056\ln(x) + 0.00275$
Chaloner and Duncan (?)	ignition frequency	ratio of destroyed buildings	$\log y = -3.13 + 0.54 \log x$
Li et al. (2001)	incidence of post-earthquake fire	average incidence of civil fires in a city (ρ_c), average incidence of civil fires in the predicted zone of the city (ρ), density of fire (μ_m), area with moderate damage and above of buildings (A_m)	$\lambda_f = (\rho/\rho_c) * \mu_m A_m + \rho A$
Trifunac and Todorovska (1998)	number of ignitions per 25 km^2	MMI	$y = -37.94 + 5.37x$
HAZUS (1999-2009)	number of ignitions per million sq ft of building floor area	PGA	$y = -0.025 + (0.592x) - (0.289x^2)$ $y = (0.581895x^2) - (0.029444x)$
URAMP (2002)	Ignitions per million sq ft	MMI or PGA, and occupancy type	Table 4–10 in Scawthorn et al., 2005
Cousins and Smith (2004)	mean number of ignitions per millions of m^2 of floor area	MMI	$y = x - 8.5$
Ren and Xie (2004)	number of fire sites per 100000 m^2	PGA	$y = -0.11749 + 1.34534x - 0.8476x^2$
Scawthorn et al. (2005)	number of ignitions per thousand SFED number of ignitions per 1000000 square feet of building floor area	MMI PGA	$y = 0.015x^2 - 0.185x + 0.61$ $y = 0.028\exp(4.16x)$
Zhao et al. (2006)	number of ignitions per 100000m^2 building floor area	PGA	$y = 0.0042 + 0.5985x$
Kanamori et al. (2007)	number of ignitions per 100 hector (ha)	PGA	$y = 0.6078\ln(x) + 1.887$
Davidson (2009)	number of ignitions per census tract	Instrumental intensity (x_{ii}), percentage of land area that is commercial, industrial, or transportation (x_{CIT}), total building area in m^2 (x_{tbldg}),percentage of building area that is URM ($x_{\%URM}$) people per km^2 (x_{dens})	$y = -15.42 + 1.13x_{ii} -32.48x_{CIT} + 0.85\ln(x_{tbldg}) + 27.70x_{\%URM} + 0.0000453x_{dens}$
Zolfaghari et al.(2009)	probability for a certain number of ignitions to happen per building	Building utility damage, Damages to braced non-structural equipments, Overturning of unbraced equipments or contents	N/A

Table 1. Characteristics of Existing Post-earthquake Ignition Models

FUTURE STUDIES

Aim of this study is developing a model for indoor ignitions according to building utility systems, hazardous equipments and less hazardous equipments. In addition to these components, occurrence time and day of earthquake are very important parameters. Usage of some equipments changes due to time and day. Heating equipments are not used in summer season and daily cooking equipments like cooking stoves are used mostly in lunch and dinner times.

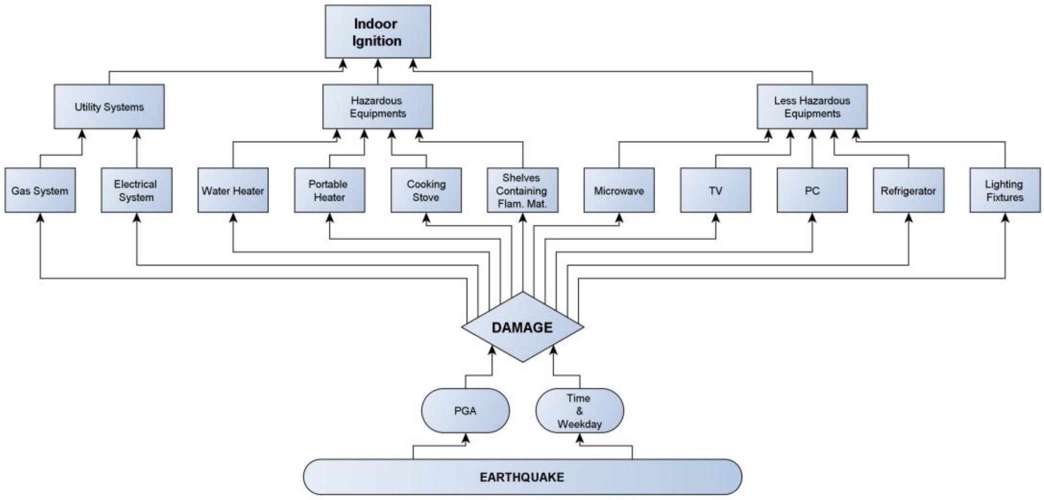

Figure 2. Structure of Post-earthquake Indoor Ignition Models

Figure 2 shows the structure of proposed indoor ignition model. A specific earthquake damages components due to PGA, time and day. Damaged gas system and electrical system can cause gas leakage and sparking that cause ignition. Overturning of hazardous and less hazardous equipments also cause leak of flammable materials and these leakage can result in ignitions by sparking from electrical equipments.

The first phase of study will be determination of ignition probabilities of each component according to a scenario earthquake. Then, indoor ignition probability will be calculated in a hierarchical system. The next step of the study will be estimating spread of these ignitions by considering suppression operations, but spread is not included in this paper.

In order to make the results of the model meaningful and consistent, a threshold ignition probability will be produced. This threshold value will be calculated by using records from past earthquakes. Number of ignitions can be obtained from the ignition probabilities by using this threshold value. This study will make the model more reliable. Most of current models calculate number of ignitions for a particular area, but proposed model will calculated the ignition probability and occurrence of ignition for each building.

CONCLUSION

Fire following earthquake (FFE) is one of the most important secondary disasters and it can cause large amount of losses. These losses can sometimes exceed the losses caused by shaking. Estimating the number and location of potential post-earthquake ignitions strengthen the mitigation and response efforts. Spread of fires can be prevented according to these estimations. A powerful ignition model must include different parameters like damaged utility systems and household equipments. This paper proposes a probabilistic physics-based post-earthquake fire ignition model in order to estimate number and location of indoor ignitions in urban areas depending on building utility systems, hazardous household equipments and less hazardous household equipments.

REFERENCES

1. Cousins, W. and Smith, W. (2004) Estimated losses due to post-earthquake fire in three New Zealand cities, *Proceedings of New Zealand Society of Earthquake Engineering Conference*, paper 28.

2. Davidson, Rachel A. (2009) Modeling Postearthquake Fire Ignitions Using Generalized Linear (Mixed) Models, *Journal of Infrastructure Systems*, 15 (2009): 351-360.
3. Federal Emergency Management Agency-FEMA (1999) HAZUS99 Technical Manual, Developed by the Federal Emergency Management Agency through agreements with the National Institute of Building Sciences, Washington DC, 732 pp.
4. Hamada, M., Wakamatsu, K. and Yasuda, S. (1992) Liquefaction-Induced Ground Deformations during the 1923 Kanto Earthquake, *in Case Studies of Liquefaction and Lifeline Performance during Past Earthquakes*, Vol. 1, Japanese Case Studies, M. Hamada and T.D. O'Rourke, Eds., NCEER Technical Report NCEER 92–0001, National Center for Earthquake Engineering Research, State University of New York, Buffalo, NY.
5. Kanamori, T., Shimodaira, S. and Koike, T. (2007) An evacuation plan from a fire following earthquake, *Application of Statistical and Probability in Civil Engineering*, Tokyo, Japan.
6. Kobayashi, M. (1984) Urban post-earthquake fires in Japan, *Proceedings of the Eight World Conference on Earthquake Engineering*, Prentice-Hall, Englewood Cliffs, New Jersey.
7. Lee, S., Davidson, R., Ohnishi, N. and Scawthorn, C. (2008) Fire Following Earthquake-Reviewing the State-of-the-Art of Modeling, *Earthquake Spectra*, Volume 24, No. 4, pages 933–967.
8. Li, J., Jiang, J. and Li, M. (2001) Hazard analysis system of urban post-earthquake fire based in GIS, *Acta Seismologica Sinica*, 14, 448–455.
9. Mohammadi, J. and Grobbel P. (1996) An investigation of post earthquake fire hazard in urban areas, *Proceedings of 11th World Conference on Earthquake Engineering*, Acapulco, Mexico.
10. Okamoto, S. (1984) Introduction to Earthquake Engineering, University of Tokyo Press, Tokyo.
11. Oppenheim, I. J. (1984) Modeling earthquake-induced fire loss, *Proceedings of Eighth World Conference on Earthquake Engineering*, vol. VII, San Francisco, pp. 777–784.
12. Ren, A. and Xie, X. (2004) The simulation of post-earthquake fire-prone area based on GIS. *Journal of Fire Sciences*, 22, 421–439.
13. Scawthorn, C. and O'Rourke, T.D. (1989) Effects of Ground Failure on Water Supply and Fire Following Earthquake: The 1906 San Francisco Earthquake, *Proceedings of 2nd U.S.–Japan Workshop on Large Ground Deformation*, July, National Center for Earthquake Engineering Research, Buffalo, NY.
14. Scawthorn, C., Eidinger, J. M. and Schiff, A. J. (2005) Fire Following Earthquake, *Technical Council on Lifeline Earthquake Engineering Monograph No. 26*, American Society of Civil Engineers, Reston.
15. Scawthorn, C., O'Rourke, T. D. and Blackburn, F. T. (2006) The 1906 San Francisco Earthquake and Fire-Enduring Lessons for Fire Protection and Water Supply, *Earthquake Spectra*, 22(S2), S135-S158.
16. Scawthorn, C. (2009) Enhancements in HAZUS-MH, Fire Following Earthquake Task 3: Updated Ignition Equation, *SPA Project (No. 10010-01-07-01) prepared for PBS&J and the National Institute of Building Sciences*, 16 April 2009.
17. Sekizawa, A. (1997) Post-Earthquake Fires and Firefighting Activities in the Early Stage in the 1995 Great Hanshin Earthquake, *Proceedings of Thirteenth Meeting of the UJNR Panel on Fire Research and Safety*, vol. 2, pp. 289–302.
18. Trifunac, M. D. and Todorovska, M. I. (1998) Northridge, California, earthquake of 1994: Fire ignition by strong shaking, *Soil Dynamics and Earthquake Engineering*, 17(3), 165-175.
19. Zhao, S., Xiong, L. and Ren, A. (2006) A spatial-temporal stochastic simulation of fire outbreaks following earthquake based on GIS, *Journal of Fire Sciences*, 24, 313–339.
20. Zolfaghari, M. R., Peyghaleh, E. and Nasirzadeh, G. (2009) Fire Following Earthquake, Intra-structure Ignition Modeling, *Journal of Fire Sciences*, 27, pp. 45-79.