FIRE FOLLOWING EARTHQUAKE MODELLING, PROBABILISTIC IGNITION MODEL FOR BUILDING STOCK

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ABSTRACT:

Fire following earthquake (FFE), as an indirect seismic hazard involves three main phases: ignition, spread and suppression. Records of historical FFE's shows higher significance for ignitions taken place inside buildings. This paper therefore, focuses on ignition following earthquake (IFE) and introduces a probabilistic algorithm for intra-structure ignition modelling. The occurrence of intra-structure ignitions depends on several parameters such as structural damages, non-structural damages, ground and structural PGA, overturning critical acceleration for building components and equipments, buildings occupancy, building height, building area and earthquake time. A GIS-based computer program has been designed and developed in this work which models probability of ignitions for each building using synthetic earthquake scenarios. Logic tree and Monte Carlo simulation processes are used for combining uncertainties associated with different components controlling intra-structure ignition such as earthquake parameters and building behaviour. The proposed model is based on an analytical methodology which takes into account many effective parameters controlling IFE. The main objective of this study is to develop a methodology to probabilistically convolute different uncertainties associated with factors controlling intra-structure IFE. The approach is introduced as an alternative solution to the statistical ignition model currently being used in many FFE hazard models. However, detailed studies towards quantification and calibration of probability functions used in this study are beyond the scope of this paper and require further statistical data and investigations. The proposed model and the developed computer tool are used to model IFE for a city district in northern Tehran. Ignition probabilities obtained from this model are compared against those estimated by the HAZUS ignition model.

KEYWORDS: Fire following earthquake, seismic hazard, ignition, GIS, logic tree, Monte Carlo

1. INTRODUTION

Fire Following Earthquake (FFE), as an indirect seismic hazard, threats many residential centres and mega-cities all around the world. This phenomenon may consist of many simultaneous fires which are complex, have widespread damages and losses and can spread by time. There are examples of catastrophic fires following earthquakes such as 1906 San Francisco earthquake, 1994 Northridge and 1995 Kobe, representing the importance of further studies and investigations on this phenomenon. Like other fire patterns, the FFE process consists of three main phases; ignition, spread and suppression. Earthquake-related hazards such as seismic ground motions, liquefaction and faulting are considered as the triggering factors for fire following earthquakes. However, the built environment characteristics such as building vulnerability, urban density, utility network, and mitigation efforts are all important factors in controlling ignitions as well as fire spread and effectiveness of suppression measures. For example, for a dense city exposed to high seismic hazards, the existence of timber structures or under-pressure natural gas network, in the absence of proper disaster management measures, are sufficient to highlight the importance of FFE.

Ignitions following earthquake (IFE) are directly related to the built environment and how they respond to earthquake hazards. The ignition models used in many FFE models are based on statistical correlation between mean fire frequency and strong ground motion parameters observed during past earthquakes. Damage patterns seen in the recent FFE cases reveal that most of fires following earthquakes have started from inside buildings. Intra-structure IFE depends on many factors, the most important are strong ground motions and how it shakes buildings and their contents. Various kinds of ignitions can be generated as the results of damage to structural elements, non-structural elements and contents of a building. Strong ground motions result in excessive drift in structural and non-structural elements which could result in abrasion or damage of building utility networks such as electrical wiring and gas pipelines. Certain intra-structure contents are also considered as sources for IFE. The stability of such contents may reduce once they are exposed to seismic acceleration which in turn could result in overturning and therefore, are considered as potential sources of ignitions.

2. PREVIOUS WORKS

With regard to FFE hazard and risk modelling, most of researches in recent years are related to fire spread modelling with less attention paid to modelling sources of ignitions. Statistical correlations made between strong ground motion and ignition frequencies are mostly used as a mean to model this phase of an FFE model. Mizuno et al (1978) developed the first IFE models based on statistical analyses on FFE damage data from earthquakes in Japan. Scawthorn (1986) followed this approach and expanded this concept to develop probabilistic post-earthquake fire ignition and spreading model. Such models have been used to study the FFE pattern in jurisdictional scale and to estimate the aggregated economic FFE-related losses on regional scales. FFE damage data from US earthquakes in 20th century are used to model ignition mean rate as a function of seismic intensity and urban population density. Eidinger (2005) also investigated the effects of gas distribution network on ignition following earthquakes. He stated that 26% of ignitions following Northridge earthquakes happened because of damages to gas distribution network. Studies by Trifunace and Todorovaska (1998) relates the number of ignitions following 1994 Northridge earthquake to MMI, number of breakages in water pipe lines, number of red-tagged buildings, peak ground velocity (PGV) and soil classes. They proposed several empirical relationships for such dependencies.

The Scawthorn approach was later adopted by HAZUS (1999) program in the United States to model fire following earthquake losses. This model consists of all three main phases, *i.e.* ignition, spreading and suppression. The ignition mean rate used in the HAZUS model is estimated by an empirical relationship which relates ignition mean frequency normalized by urban area to peak ground acceleration (PGA). The HAZUS approach models the ignition rate independent of other controlling factors and only based on regional built environment data. Therefore, borrowing such empirical functions to estimate ignition rates for other regions seems inadequate since the built environment setting changes from one region to another. Besides, in a given built environment, ignition rate is highly dependent on building vulnerability, building occupancies and urban density, none of which addressed by the HAZUS model. Earthquake time and date are also the controlling factors which are not addressed in the HAZUS model. There have been other attempts to relate IFE to other controlling factors. For example using statistical data, Tokyo Fire Department developed some curves showing ignition mean rates as functions of PGA and based on buildings occupancy, building materials and earthquake time and date.

3. INTERNAL IGNITION FOR BUILDING STOCK

In this paper, an analytical approach is proposed for modelling ignition following earthquake (IFE). The controlling factors for IFE, such as strong ground motions, building vulnerability, content characteristics and utility damage are modelled probabilistically in order to estimate the overall ignition probability inside a building. To estimate IFE probability for each building, a scenario-based probabilistic approach is developed which is briefly discussed here. Detailed discussions on this methodology are beyond the scope of this paper and are available in Zolfaghari *et al* (2008). A building exposed to strong ground motions, depending on its structural and occupancy type, could generate various potential sources of ignitions. In this paper, the intra-structure ignitions are grouped in three main categories as shown in Figure 1:

- Damages to building utility networks such as gas and power networks due to structural damage or excessive structural deformation
- Disruptions and damages to ignitable non-structural component and braced contents and equipments such as boilers and fireplaces due to structural damages. Automobiles parked in parking could also be categorized in this group
- Overturning of flammable and ignitable unbraced hazardous contents and equipments such as TVs and heaters due to seismic ground and structural acceleration

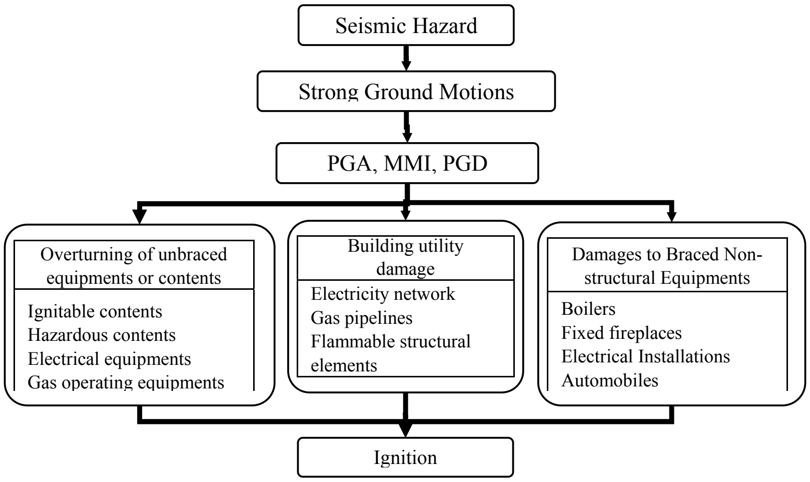


Figure 1: Major sources of intra-structure ignition following earthquake

The first two cases mostly depend on overall building response with regard to strong ground shaking. Therefore, seismic vulnerability and degree of structural ductility are the controlling factors for these types of ignitions. The last type, however, is less dependent on building damage but mainly controlled by the level of acceleration received by contents.

In this work an event tree approach is used to model uncertainties associated with ignition sources and to develop a probabilistic ignition following earthquake model. For example, Figure 2 shows the conceptual relationship between structural damage and utility-related ignitions. The “AND” and “OR” operators in this figure represent the product and summation of probabilities respectively.

To model this process, sources of sparks and fuels need to be modelled first. The gas and electrical network are the main sources of utility-related ignitions in a building which provide necessary spark and fuel sources. Building damage or intensive structural ductility could result in brakeage and damage to gas and power network in a building and therefore, they are the deriving factors for such ignitions. Other flammable structural and non-structural components may also provide the necessary fuel needed for ignitions. For building-specific ignition modelling, it may be possible to quantify damages and disruptions to different utilities using structural analysis. However, such analyses are beyond the scope of this research and more regional-scale solutions are considered here. For simplicity, it was assumed that a direct relationship exists between structural damage stage (damage ratio) and utility damage. Damaged gas pipelines may or may not lead to gas leakage. Similarly, damaged power lines may or may not cause sparks. Using such algorithm, probabilities of ignition from different building or content sources are convoluted in order to estimate probability of at least one or more ignitions inside buildings.

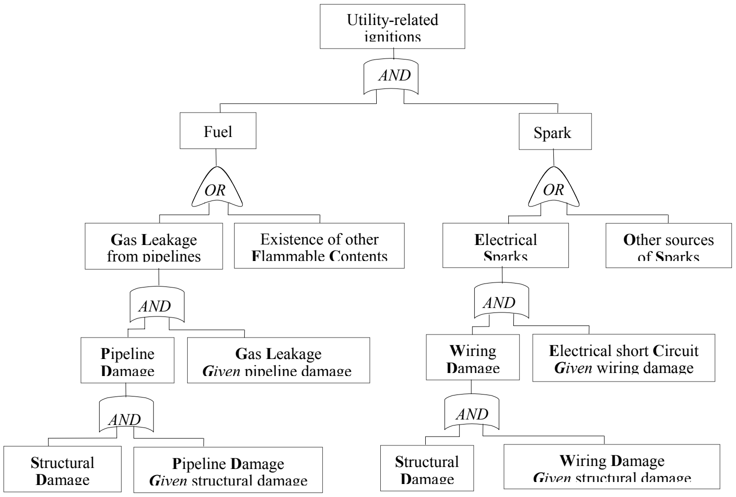


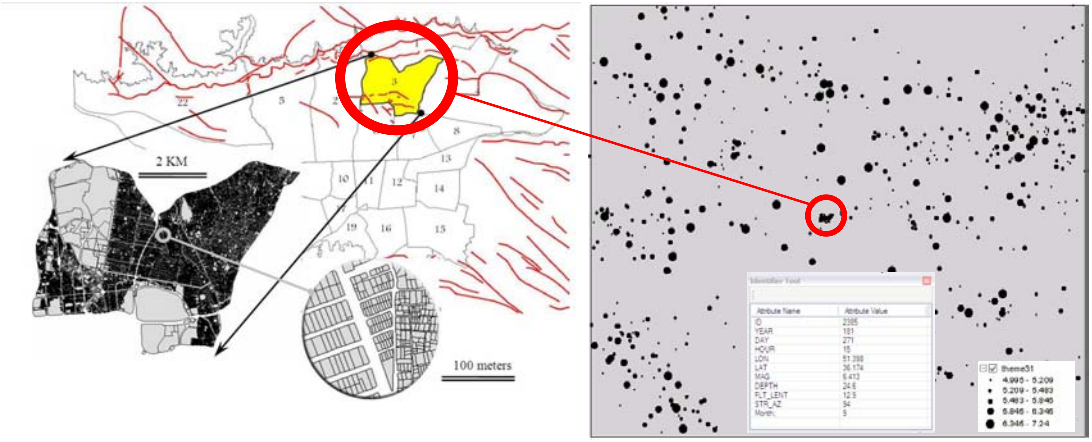
Figure 2.Combination of major components and their relationships with regard to utility-related ignitions

In this research a scenario-based earthquake hazard model is used in order to eliminate the correlation effect while convoluting ignition probability from different sources. In order to estimate IFE probability for each building, probabilistic distribution of seismic ground motion (MMI, PGA) generated by earthquake scenarios are calculated using attenuation functions and earthquake source parameters such as magnitude and source-to-site distances. Ground motion values are used to estimate the distributions of overall damage to building as well as lateral forces to unbraced contents. The earthquake scenario could be the reoccurrence of a given historical earthquake selected from regional earthquake catalogue. Alternatively, a deterministic earthquake scenario using regional seismotectonic sources may be assessed.

To derive full probabilistic results, the model is designed to calculate potential ignition probabilities using a synthetic earthquake catalogues, consisting of many small to large earthquakes in a given region. Such algorithm facilitates independent consideration of earthquake location, size, time and also ground motion variations. Logic tree and Monte Carlo simulation process are used in order to combine uncertainties associated with seismic hazard and built environment response (Peyghaleh 2008). The use of scenario-based earthquake hazard allows the probabilistic convolution of ignition sources and their uncertainties with no or negligible correlation effect. In this work, it is assumed that seismic ground motions could generate three sources of ignitions in a building as stated earlier.

4. GIS-BACED SOFTWARE AND PILOT STUDY RESULTS

The proposed methodology is used to design and implement a GIS-based hazard software. This analytical tool is well designed inside an open-source GIS platform which provides powerful spatial analyses as well as effective visualization capabilities. This software is capable of running one or many earthquake scenarios versus built environment data for a given region. As a pilot study, the built environment data for District 3 in northern Tehran is used (Figure 3a). From socioeconomic point of view, the district accommodates mostly middle to high class citizens with many newly developed apartment blocks. In this database, each building or block of apartment is represented by one parcel. The building stock provides number of building parcel by occupancy, building structural type, building square area and number of storey. To derive number of dwelling units, a conversion table based on data statistic and engineering judgment is used. The model is and pilot data are tested against deterministic single earthquake scenario as well as probabilistic earthquake catalogue. Figure 3b shows geographic distribution of earthquakes form a 1000 year- synthetic catalogue (Zolfaghari 2008). Attenuation relationships of Ambraseys1995 and Zare1999 are used for PGA estimation. ATC-13 failure matrices were used for structure vulnerability curves. In order to estimate structural peak acceleration at different storey, equivalent static analytical method proposed by Iranian seismic design code (Standard Code 2800) is used. Figure 4 shows the analysis results for a scenario earthquake of Mw=7.0 at a distance of 10 km form the district centre. The probability of occurrence of at least one ignition per buildings is shown on this map. Figure 5 shows the variation of probability of at least one ignition versus PGA, number of apartment units, building structural type and building occupancy.



Attribute Name	Attribute Value
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YEAR	181
DAY	271
HOUR	15
LON	51.398
LAT	36.174
MAG	5.413
DEPTH	24.6
FLT_LENT	12.9
STR_AZ	94
Month	9

(a) (b)

Figure 3. a) Tehran city district map and major tectonic faults b) 1000 year synthetic earthquake catalogue

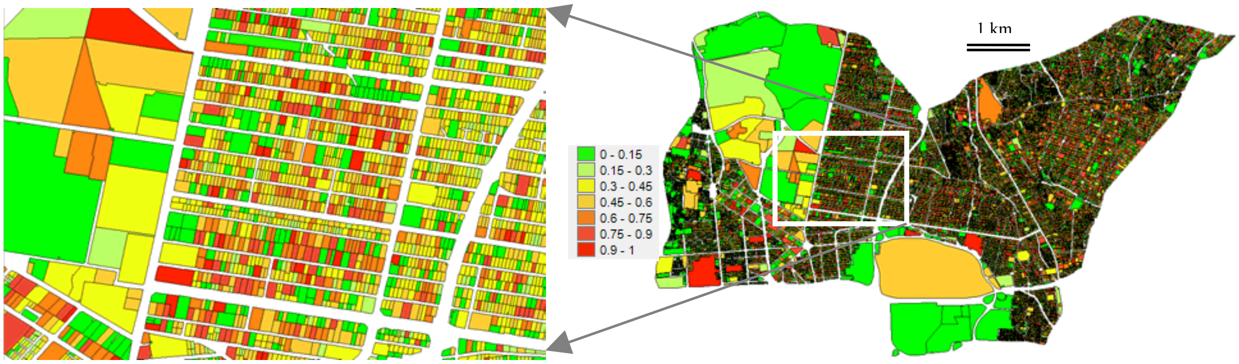

Figure 4. Map of Tehran District 3 showing probability of at least one ignition.

For comparison, the HAZUS approach is used to estimate ignition rate for the same pilot area in northern Tehran. Figure 6 shows the geographical variation of ignition mean rate obtained from the HAZUS approach. The HAZUS model reveals a more uniform rate of ignitions for the study area and the ignition rates presented in this map show less dependency with many of the controlling factors described in this paper. In other words, the HAZUS approach fails to specifically address other controlling factors such as natural gas network, built environment characteristics and earthquake time and date, which all lead to high degree of variations and uncertainties in ignition frequencies.

The model was also run against a 1000 year synthetic earthquake catalogue. Mont Carlo simulation process is used for this calculation. Figures 7 show geographic distribution of ignition probability for buildings in this region. In these figures, the probability of at least one ignition with annual mean recurrence rate of 0.01 (100 year return period) is shown.

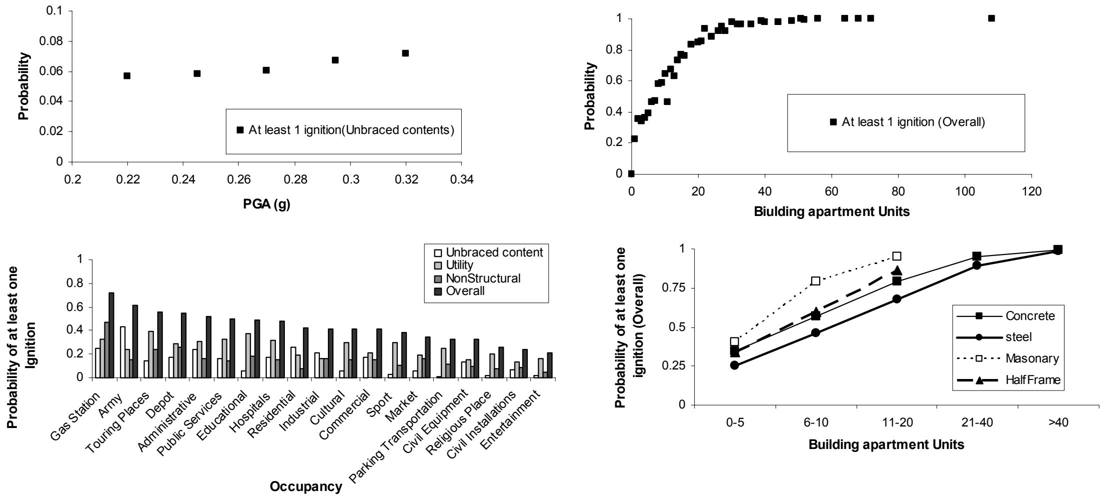

Figure 5. Sensitivity of the analysis results to controlling parameters

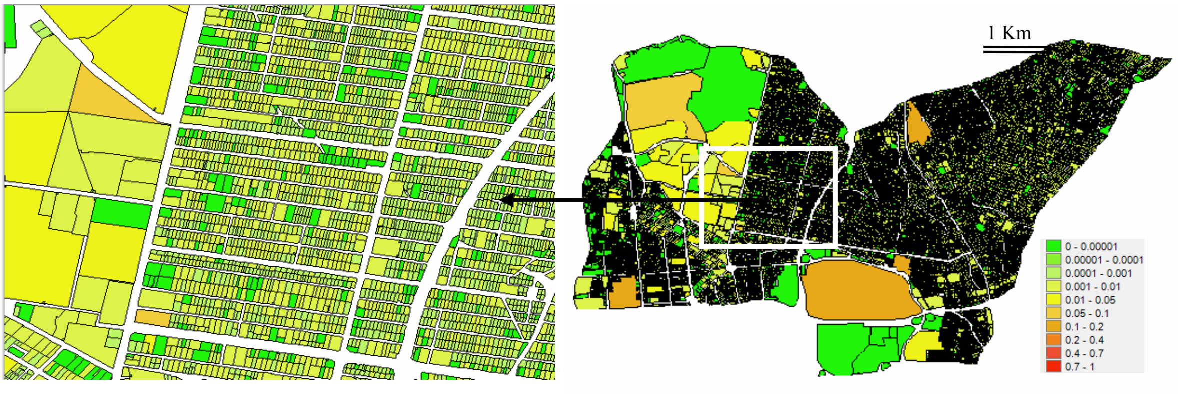

Figure 6.Distribution of mean ignition frequencies by parcel unit (HAZUS Methodology)

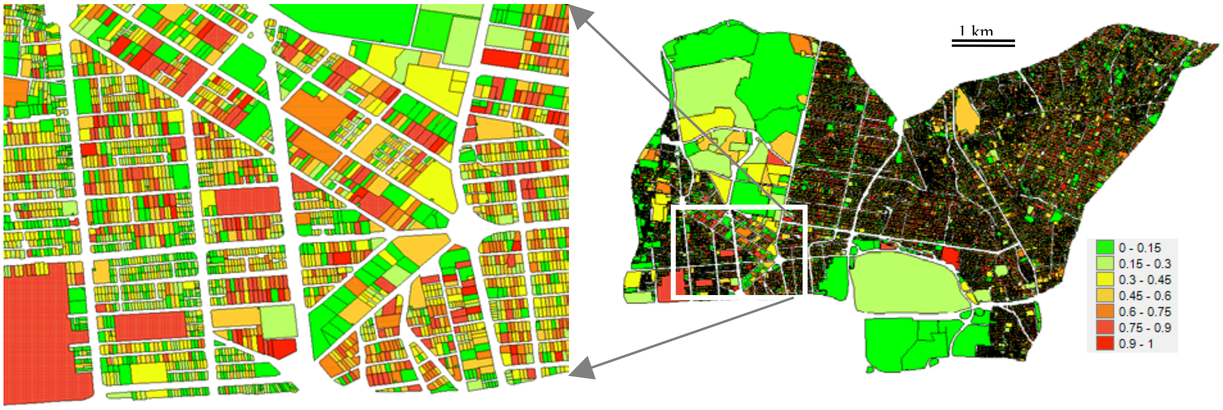

Figure 7. Map of Tehran District 3 showing probability of at least one ignition with 100 year return period using Monte Carlo simulation approach

CONCLUTION

In this paper, an analytical methodology is proposed to estimate the occurrence probability of intra-structure ignitions following earthquake. In this model, effective factors controlling intra-structure ignitions such as seismic ground shaking, building size, building structural system, building occupancy, building contents and earthquake time are considered in order to model ignition probabilities. A computer code is developed based on the proposed method to simulate intra-structure ignitions following earthquake. This analytical tool is well designed inside an open-source GIS platform which provides powerful spatial analyses as well as effective visualization capabilities. The proposed method is presented as an alternative to the statistical models currently being used for FFE models. As a pilot study, the inventory of building stock for a district in northern Tehran is used here. Preliminary results showing probability of at least one ignition from a deterministic earthquake scenario as well as probabilistic synthetic earthquake catalogue are shown for this region. The paper in particular shows how uncertainties from many sources of ignition following earthquake can be combined. The main objective of this study is to develop a methodology to probabilistically convolute different sources of uncertainties associated with factors controlling intra-structure IFE. However, detailed studies towards quantification and calibration of probability functions used in this study are beyond the scope of this paper and require further statistical data and investigations.

REFERENCES

Chen, W. and Scawthorn, C. (2003). Earthquake Engineering Handbook, CRC Press, Boca Raton.

Federal Emergency Management Agency (FEMA). (1985). ATC-13, Earthquake damage evaluation data for California, FEMA, Washington D.C.

Federal Emergency Management Agency (FEMA). (1999). HAZUS99-SR2 Technical Manual, FEMA, Washington D.C.

Johnson, G. (1999). Seismic Reliability Assessment of Critical Facilities, A Handbook, Supporting Documentation, and Model Code Provisions, Technical Report MCEER99-0008, Oakland, California.

Mizuno, H. (1978). On Outbreak of Fires in Earthquakes, Dissertation, Department of Architecture, Kyoto University, Kyoto, Japan.

Peyghaleh , E. (2008). Fire following earthquake risk analysis, a pilot study for the city of Tehran, Dissertation, Department of Civil engineering, Kntu University, Tehran, Iran.

Scawthorn, C. (1986). Simulation Modelling of Fire Following Earthquake, Proc., U.S. National Conference on Earthquake Engineering, Charleston, South Carolina, 1675-1685.

Scawthorn, C., Eidinger, J. M. and Schiff, A. J. Edited by Scawthorn, C., Eidinger, J. M. and Schiff, A. J. (2005). Fire Following Earthquake, ASCE, USA.

Trifunace, M. D., and Todorovaska, M.I. (1998). The Northridge, California, earthquake 0f 1994: fire ignition by strong shaking, Soil Dynamics and Earthquake Engineering 17, 165-175, Elsevier Science Ltd.

Zolfaghari, M., Peyghaleh , E. (accepted paper for publication 2008). Fire following earthquake, Intra- structure ignition modelling . Journal of fire science.