Post-Earthquake Fire Spread between Buildings

Estimating and Costing Extent in Wellington

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ABSTRACT

Fires after earthquakes sometimes develop into conflagrations resulting in widespread losses of life and property. A geographic information system (GIS) model linked to property and valuation data is shown to be an appropriate tool for estimating urban fire losses. One approach uses a static buffering technique to define potential burnout zones that are sampled randomly to give estimates of losses. The other uses a dynamic cellular automaton technique for determining both the rate and extent of fire-spread in response to a wide range of factors including wind, radiation, sparking, branding, building separations and building claddings. The dynamic approach uses a set of 'rules' based on fire physics modified by historical data. The model runs in real time for single ignitions. The static method is used to estimate losses assuming a 12m separation will prevent fire spread All buildings are assumed combustible (upper bound case). The dynamic model assuming fire can not spread to buildings with non-combustible claddings and areas of vegetation are not flammable (lower bound case). The resulting losses are between NZ$50M and NZ$500M (excluding building contents), compared with NZ$5,000M for shaking losses for a magnitude 7.3 earthquake and a total building stock of NZ$19,000M.

KEYWORDS

Post-Earthquake Fire, Urban Fire Spread, GIS Models, Expected Losses, Earthquakes

INTRODUCTION

Fire following earthquake is an extremely variable problem. Losses from such fires can vary from insignificant (e.g. Izmit earthquake 1999, Turkey; ChiChi earthquake 1999, Taiwan) to disastrous (e.g. San Francisco 1906, USA; Tokyo 1923, Japan). New Zealand experience, Table 1, mirrors that seen worldwide.

In most cases we found no reports of post-earthquake fires. In one case one house was destroyed and there was minor damage to a few others, and in the second case, Hawke's Bay 1931, there was major conflagration that destroyed most of the business district of Napier City.

Event Name	Date	Magnitude	Locality Affected	Fire Losses
Marlborough	16th Oct 1848	7.8	Wellington [MM8]	None[16]
Wairarapa	21st Jan 1855	8.1	Wellington [MM9]	None[17,18]
Murchison	16th Jun 1929	7.7	Murchison [MM9]	None[12]
Hawke's Bay	3rd Feb 1931	7.8	Napier [MM10]	Conflagration[7,13]
Pahiatua	5th Feb 1934	7.4	Pahiatua [MM8]	None[10]
Wairarapa	24th Jun 1942	7.2	Masterton [MM8]	Minor[11]
Inangahua	23rd May 1968	7.2	Inangahau [MM10]	None[14]
Edgecumbe	2nd May 1987	6.6	Edgecumbe [MM9]	None[6]

Table 1. New Zealand's experience of fire losses following major earthquakes.

Historical information[21] reveals that conflagrations occurred in many New Zealand towns in the late 19th and early 20th centuries, but few details are known. The main causative factors wee timber buildings with timber claddings, lack of building separation, large numbers of ignition sources, and lack of ability to control the fires as a result of damaged water supplies and lack of adequate fire fighting equipment. These factors are also likely to occur post-earthquake; hence conflagrations can be expected in areas of similar buildings that still exist in the inner suburbs of Wellington.

PREVIOUS WORK

Post-earthquake fire spread models have tended to rely on previous data to calculate rates and extent of fire spread. Due to the relatively small number of post-earthquake fire conflagrations the amount of data is small and is dominated by several events with the best data collection. The data are difficult to interpret as the information required relating fire spread rates and minimum firebreak sizes to building sizes and types (including cladding types) and other factors such as wind are not always available.

PART 1 SCOPING THE PROBLEM

Because of the great variability in the potential and extent of post-earthquake fires there is a need for an effective way of screening a city for the potential impact. A method that relies in part on a GIS model of a major New Zealand city, the capital Wellington, to define potential fire "burnout" zones, and in part on random sampling of the burnout zones to construct estimates of losses is described. One desired output of the model is an estimate of the probability of exceedance of various levels of loss as a function of the number of ignitions.

FIRE MODEL

Within the GIS model we input spatial and other data for every building in Wellington City, including the footprints, and estimates of height, floor areas and replacement values. In order to generate potential burnout zones we generate contours or "buffers" of specified width around each building footprint (Figure 2) and then make the assumption that when the buffers from adjacent buildings touch or overlap the fire can spread from one building to another defining "burnout zones" within which all buildings will burn out. The zone is independent of the location of the ignition.

We randomly distribute a desired number of ignitions amongst the buildings assuming each building has the same probability of ignition, and for all zones that are thus ignited, accumulate the total value of the buildings destroyed. Repeating this many times enables us to estimate the probability of exceedance of various levels of loss.

EXAMPLE

As an example we consider the case where a gap of 12m is assumed sufficient to prevent the spread of fire from one building to another. Radiation calculations indicate that fire can not spread more than 12m by spontaneous ignition unless the radiator is very large.

The width of "buffer" space around each building is therefore 6m, and fire spread is possible whenever adjacent buffer zones come into contact as shown in Figure 1. Burnout zones range in size from a single to many buildings. Adjoining vegetation is assumed to be non-combustible.

Figure 1:_ Examples of burn out zones for a mixed residential/commercial area of Wellington City.

Our estimate of the replacement value of all buildings in Wellington City is NZ$19 billion, distributed amongst 76,000 buildings. The 12m critical separation results in the delineation of 3973 burnout zones with replacement values ranging from NZ$0 to NZ$785 million (Table 2). All values in this paper are for building damage and exclude the value of contents.

We then randomly distributed 1, 3, 10, 30 or 100 ignitions over the buildings, accumulating the losses for each trial. This was repeated 10,000 times for each number of ignitions. The results are summarised in Figure 2.

Value within burnout zone ($millions)	Number of burnout zones
0.0 – 2.0	2310
2.1 – 5.0	719
5.1 – 10.0	491
10.1 – 20.0	293
20.1 – 50.0	134
50.1 – 100.0	18
100.1 – 200.0	7
200.1 – 500.0	0
500.1 – 1000.0	1
> 1000.0	0

Table 2: Distribution of the replacement value of Wellington City's buildings amongst burnout zones defined by a 12m wide critical separation between buildings.

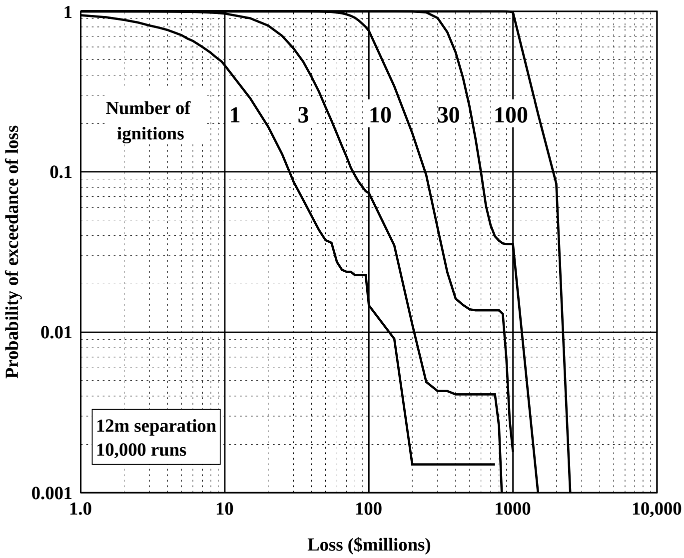

Figure 2: Probability of exceedance of various levels of loss for ignitions randomly distributed amongst the 76,000 buildings of Wellington City.

DISCUSSION

This model includes many simplifying assumptions, however the overall approach of defining a set of loss values by whatever rules are deemed appropriate, and then selecting from that set on a random basis to define the probability of occurrence of various sizes of loss, is a standard loss assessment method.

Two conclusions that can be drawn from Figure 3 are as follows.

1. The 50-percentile loss is roughly proportional to the number of ignitions. It increases from NZ$l0 million for one ignition to about NZ$l billion for 100 ignitions.

2. The uncertainty in the loss decreases with the number of ignitions. With one ignition the loss can vary from NZ$0 to NZ$785 million depending on which burnout zone is selected. With 100 ignitions the loss is relatively invariant at NZ$1 billion to NZ$2.5 billion.

In comparison, the loss due to shaking damage to buildings in a large earthquake on the Wellington fault is likely to be in the region of NZ$5 billion[9,20]. Based on data from post-earthquake fires in the United States about 40 ignitions could be expected in Wellington City following such an earthquake[8], giving a 50-percentile loss of about $500 million. From Figure 3 the extreme range in the fire loss (for 40 ignitions) is approximately 7 to 40% of the size of the shaking loss.

PART 2: THE DYNAMIC FIRE-SPREAD MODEL

The results given above depend on the assumptions that a separation distance of more than 12m prevents fire spread and all buildings are combustible. Historical data[1] shows that fires will sometimes spread over gaps of more than 12m, and may also be stopped by smaller gaps[19]. In order to more accurately determine distances over which fire spread occurs, the GIS model has been further developed with "rules" governing fire spread.

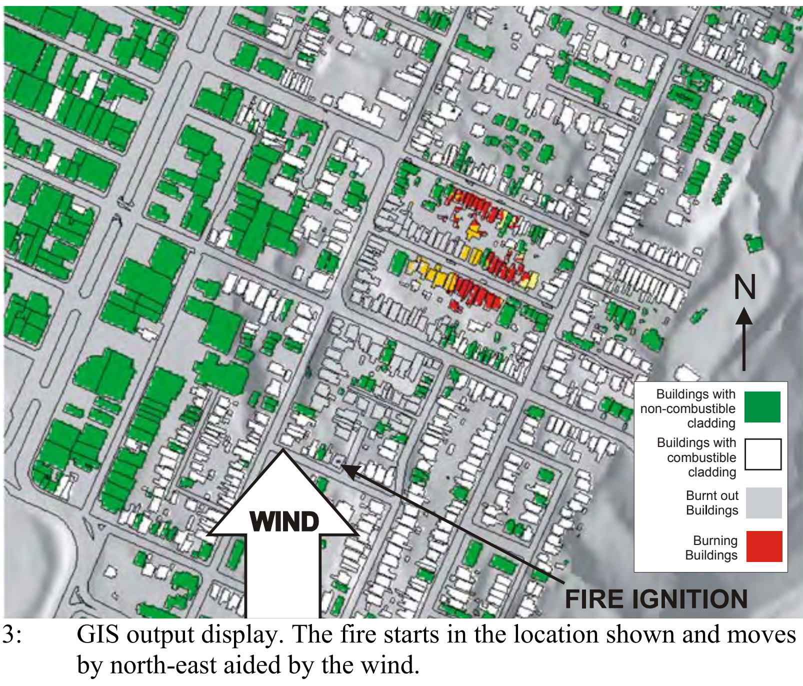

Figure 3: GIS output display. The fire starts in the location shown and moves north by north-east aided by the wind.

The dynamic fire-spread model uses a "cellular automaton" spread technique in which the landscape is modeled as a regular lattice of cells, with each cell being assigned a set of states and values representing the physical environment. The grids size of 3.0m is chosen as a compromise between accuracy and simulation run time. It also corresponds well to a traditional 3.05m (10 feet) separation between timber houses in the outer suburbs. The rectangular grid overlays the building outlines. Any cell which is more than 50% filled with a part of a building is deemed a building cell and all other cells are deemed empty. The building height is taken as 4.5m, a weighted average value for a mixture of 1 and 2 storey residential buildings.

Spread of a factor, in our case fire, from one cell to another depends on the states, the values and a set of "rules". Possibilities can include the following: state (burning or not, if burning how fiercely), values (combustible or not), and rules (probability of ignition according to distances from burning cells, allowing for biases such as wind). The mechanics of the process is that the entire set of cells is scanned repeatedly in a raster fashion. During the scanning process cells are ‘activate’ one at a time and whilst activated a cell's state is changed according to its current state and values, the states of surrounding cells, and the fire-spread rules. Because of the repetitive nature of the scanning process there is a built-in time step and hence it is straightforward to model time variant states such as the build-up and decline of a fire. Results are displayed as images of burnt and burning areas at specified time intervals (Figure 3), and the model considers individual building separations, cladding combustibility, and wind speed and direction.

FIRE SPREAD "RULES"

The fire spread rules govern whether fire is spread from one cell to the next. These rules have been developed using a combination of fire physics and historical data. Given the scarcity of exact historical data a number of assumptions have been made. Generally an attempt has been made to bound the input values by finding a minimum and maximum value and using an intermediate value.

Each cell is given a number of attributes that determine spread. We assume that buildings with non-combustible cladding may spread fire to other cells when ignited internally, but cannot be ignited by other burning buildings. Vegetation is assumed to be non-combustible.

There are four modes of fire spread:-
(i) Spread to a contiguous cell.
(ii) Spread by radiation to a nearby cell, causing spontaneous ignition of the cladding.
(iii) Spread by radiation to a nearby cell, causing piloted ignition of the cladding (sparking).
(iv) Spread by airborne flaming material (flying brands).

Both spark and branding criteria are assigned a probability, allowing the model to be easily modified to allow for different building types, for example the use of timber shingle roofs in buildings in California.

SPREAD TO CONTIGUOUS CELLS

The spread of fire to cells in contact with a burning cell is assumed always to happen. The only parameter is the time taken for fire spread from one cell to the next. The value of 2.5 minutes is based on anecdotal evidence of fire-spread rates throughout a typical New Zealand dwelling.

SPREAD BY RADIATION

Each cell radiates heat flux across the gap between itself and nearby cells. The level of radiant heat flux incident on the nearby cell is due to the radiator temperature and the radiation view factor. The view factor in this case depends on the number of contiguous cells that are alight and their arrangement. The arrangement is dependent on the number of contiguous cells alongside one another.

The temperature of the radiator has a significant effect on the level of radiant heat flux as the heat flux varies with the fourth power of absolute temperature. The *deemed to satisfy* provisions of the New Zealand Building Code[4], uses different values for temperature depending on the fuel load equivalent density. Each level of fuel load is assumed to correspond to a time and hence corresponding temperature on the standard ISO-834 time-temperature curve, which is typically lower in temperature than compartment fires. In a small compartment that has reached flashover, temperatures of 1000-1100˚C are likely[25]. Values of between 800 and 1200ºC are expected in compartment fires[5]. We have assumed a temperature of 1000˚C, which most compartment fires are expected to reach[3].

Reported values of emissivity for fires in the open cover a wide range of values from 0.5 to 1.12[15]. Most of the literature is focused on compartment fires or furnaces where the emissivity values are a combination of emissivity and the absorptivity of bounding surfaces. Other literature[2] reports design methods where the aim is to prevent fire spread and hence a conservative value of 1.0 is used. The value for emissivity used here is 0.9.

SPONTANEOUS AND PILOTED IGNITION CRITERIA

Fire will spread to nearby buildings if the cladding material is heated sufficiently to cause spontaneous ignition or piloted ignition in conjunction with sparks. For simplicity the criteria are based on a single value for received radiation, ignoring the fact that the level of radiant heat flux required for ignition reduces with time of exposure.

Values reported for spontaneous ignition of timber range from 28 kW/m^2[15] to 33.5 kW/m^2[5]. The value used to calculate tables of window sizes and boundary distances in the *deemed to satisfy* provisions of the New Zealand Building code[4], is 30 kW/m^2. The value used in this study is 30 kW/m^2.

Similarly, the value for piloted ignition varies from 10.0 kW/m^2 for long duration exposure as the critical heat flux for timber specimens in a cone calorimeter[24], to 18.0 kW/m^2 for 30 minute exposure in the open as used to calculate tables of window sizes and boundary distances in the *deemed to satisfy* provisions of the New Zealand Building code[4]. The value we use is 12.5 kW/m^2[2].

The model is based on a 3.0m grid, hence sensitivity to values chosen for both the level of heat flux required for ignition and the radiator temperature is less than would be expected for a model using actual separation distances and radiator dimensions.

In the model radiation can "see" through other cells that are on fire, which may cause excessively rapid fire spread across gaps. This effect will be investigated more fully as the project proceeds.

Radiator width (m) / Distance (m)	3	6	9	12	15	18	21	Infinite
3	42.0	64.0	72.9	76.5	78.2	79.1	79.6	80.4
6	14.1	25.5	33.3	38.2	41.2	43.1	44.3	47.1
9	6.7	12.8	17.7	21.6	24.4	26.5	28.0	32.5
12	3.9	7.5	10.8	13.5	15.8	17.6	19.1	24.7
15	2.5	4.9	7.2	9.2	10.9	12.4	13.7	19.9
18	1.8	3.5	5.1	6.6	7.9	9.1	10.2	16.6
21	1.3	2.6	3.8	4.9	6.0	7.0	7.8	14.3
24	1.0	2.0	2.9	3.8	4.7	5.5	6.2	12.5
27	0.8	1.6	2.3	3.0	3.7	4.4	5.0	11.1
30	0.6	1.3	1.9	2.5	3.1	3.6	4.1	10.0

Table 3 Incident radiation in kW/m^2 on external surfaces of exposed buildings at increasing separation distances for varying widths of a 4.5m high radiator.

From the assumptions regarding temperature and emissivity of the radiator, incident radiation can be calculated. At this stage the building height parameter in the computer model has not been implemented and 4.5m has been used. Flame height has been ignored as the flames cool rapidly with height and the flames above building will not significantly increase the level of radiation. The results of this calculation are shown in Table 3. The darker and lighter shaded areas show combinations where the radiation required for spontaneous and piloted ignition respectively occur.

SPREAD BY RADIANT IGNITION

Fire spread by this mode always occurs in the model when received radiation exceeds 30 kW/m^2. It is independent of both wind speed and direction.

SPREAD BY PILOTED IGNITION

Fire spread by this mode is dependent on the distance sparks can spread and on having a minimum level of incident radiation of 12.5 kW/m^2. Burning cells produce sparks from 5 to 25 minutes after ignition. It is assumed that sparks spread further downwind in a 90° arc and at wind speeds higher than 20 km/hr. The spread distance of sparks as a function of wind speed is shown in Table 4.

Wind Speed	Calm	20 km/hr	30 km/hr	50 km/hr
Spread Distance Downwind (m)	9	12	18	21
Spread Distance Cross and Upwind (m)	9	9	9	9

Table 4: Spark Spread Distances as a Function of Wind Speed.

The distances in Table 4 were derived from the areas of loss compared with wind speed derived by Scawthorne[23]. This derivation was performed on a trial and error basis by running the model with various values and comparing the total burnt out area with Figure 11 of his report[23]. We have ignored the low values between 10 and 30 km/hr wind speed from the San Francisco 1906 post-earthquake fire, as it appears that wind had no effect on the speed of fire spread. This may have been due to several factors such as low local wind speeds (wind speeds may have been measured elsewhere) and lack of spark production. Incorporating these low values would result in a counter-intuitive prediction that spread rates increase with wind speed until a wind speed of 20 km/hr, and then reduces between 20 and 30 km/hr and then increases again after 30 km/hr.

SPREAD BY FLYING BRANDS

Spread by flying brands is assumed to occur only in winds higher than 30 km/hr after which fire spread and losses increase rapidly[26]. Some branding occurred in Kobe after the Great Hanshin-Awaji earthquake in 20 km/hr winds[19], but this was not apparent after other earthquakes. The model is tested for brand propagation from a burning cell between 5 and 25 minutes after ignition.

Brands are assumed to propagate in a 45° arc downwind and may spread up to 45m. This is slightly more than the 38m that fire spread across Van Nees Avenue in the 1906 San Francisco Earthquake, when the wind speed was about 40 km/hr. The likelihood of brands being a means of rapid fire spread is less in Wellington than regions such as southern California because the majority of roofs in Wellington are corrugated steel and flat roofs are relatively uncommon. A brand is more likely to cause ignition if it lands on a combustible surface such as timber roof shingles and on a sloped roof is more likely to fall off. There is the possibility of ignition of vegetation adjacent to buildings and debris accumulated in roof gutters.

RESULTS AND DISCUSSION

The model was run, randomising the ignition locations for four wind scenarios, with 27 ignitions in each case. This is the mean number of expected ignitions based on historical data[1]. The results for the four scenarios are shown in Table 5, showing the number of buildings burnt, floor area lost and the value of buildings lost (excluding value of building contents).

Wind Speed	Calm	20 km/hr	30 km/hr	50 km/hr
No. Buildings Burnt	235	263	272	1122
Area of Buildings Burnt (1000 m^2)	37	39	39	97
Total Value of Loss (10^6 NZ$)	46	51	52	200

Table 5: Results from the four wind scenarios.

The total losses vary from 0.2 to 1.1% of a total exposure of NZ$19 billion and are significantly less than a previous study[8] in Wellington of 1.6% of total exposure in calm to moderate winds. This previous study included fire spread between buildings with non-combustible claddings and was based on 40 ignitions. The total loss is more than that predicted by Hopkins[20]; however his study simply assumed fire losses of 1% of shaking losses. The impact of wind speed is much greater than expected. The effect of allowing for piloted (spark) ignition of buildings further downwind is minimal as shown by the small increase in total loss between the calm and 20 and 30 km/hr scenarios.

The lower level of loss in calm conditions may be attributed to the relatively large road widths in Wellington[22]. In the outer suburbs road reserves are of the order of 20m wide, with town planning requirements prohibiting building within 3.0m of the front boundary. This creates a gap of 26m between buildings. In the inner suburbs road reserves are smaller, however timber buildings (mostly dwellings) tend to be built back from the boundaries. The separation distances across streets are rarely less than 15m, which in the model prevents spread, except, in the downwind direction. Fire spread between buildings with non-combustible cladding has been ignored, but will sometimes occur, particularly when the cladding is damaged[19].

FUTURE DEVELOPMENTS OF THE MODEL

A Monte Carlo simulation of ignition locations will be carried out to reduce uncertainty in the results due to the location of the ignitions. An increase in the values of losses is expected. Two identical trials with randomised ignitions have given two very different values of losses of NZ$70M and NZ$191M.

The model will be developed to take into account actual building heights and sloping topography. Fire spread up and down slopes is expected to be highly dependent on wind speed and direction. The probability of fire spread between damaged and destroyed buildings will be allowed for by a set of "rules" that are dependent on types of building construction and the code of practice each building was designed to. This information is held in the database attached to the model.

Sensitivity studies will be carried out to determine the effect on the final result of varying various parameters including fire temperature, emissivity and critical heat flux for piloted and spontaneous ignition. The model will then be applied to the post earthquake fires after the Hawkes Bay Earthquake of 1931 for validation.

The model will be further developed to better estimate fire-spread within the commercial areas of Wellington that contain mostly buildings with non-combustible claddings. The existing model allows for little or no fire spread within this area of high property values. The model grid may have to be refined to a smaller grid of probably 1.0m for the likely fire spread mechanisms to be adequately modelled.

The effect of vegetation between buildings and large areas of sometimes highly flammable vegetation close to buildings will be taken into account.

CONCLUSIONS

The GIS model and database containing materiality, cost and other information is a suitable tool for determining post earthquake fire spread using two modelling techniques. The buffer model described in Part 1 gives two findings that may be generally applicable:-

(i) the 50th percentile loss is roughly proportional to the number of ignitions and

(ii) The uncertainty in loss decreases as the number of ignitions increases.

The dynamic spread technique is more comprehensive and allows for the estimation of the extent and rate of fire spread allowing for a wide range of factors such as wind speed and direction, branding, building separation, sparks and the combustibility of building claddings.

The effect of wind on post-earthquake fire spread in Wellington appears to be more pronounced than previous experience would suggest, however this is probably due to the wide gaps between buildings across streets.

There are several factors such as fire spread between damaged and destroyed buildings with non- combustible cladding and spread between larger non-combustible buildings in the CBD which may lead to an under prediction of the total loss in Part 2. Trial runs indicate a large variation in total loss depending on the ignition location. Comparisons of two identical runs with highly variable losses lead to the expectation that the average loss will increase. The assumption in Part 1 that all buildings within a certain separation distance burn may lead to an over prediction of the loss.

The expected loss is between about NZ$50 million for moderate wind speeds found in Part 2 and NZ$500 million found in Part I, compared with a probable loss of NZ$5 billion for shaking damage and a total exposure of NZ$19 billion, excluding the value of building contents in each case.

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REFERENCES:

1. Botting, R., "The Impact of Post-Earthquake Fire on the Urban Environment," Fire Engineering Research Report 98/1, School of Engineering, University of Canterbury, Christchurch, 1998, 240 p.
2. Buchanan, A. H. (ed.),, *Fire Engineering Design Guide, (2nd Ed)*, Centre for Advanced Engineering, Christchurch, 2000, pp. 78-81.
3. Buchanan, A. H., "Structural Design for Fire Safety," John Wiley and Sons, Chichester, 2001, p. 67.
4. Building Industry Authority, "Approved Document for New Zealand Building Code Fire Safety Clauses," Wellington, 2000, p. 168.
5. Butcher, E. G. and Parnell, A. C., *Designing for Fire Safety*, John Wiley and Sons, Chichester 1983, p. 49.
6. Butcher, G., Andrews, L. and Celand, G., "The Edgecumbe earthquake, a review of the 2 March 1987 Eastern Bay of Plenty earthquake," Centre for Advanced Engineering, University of Canterbury, Christchurch, 1998, 120 p.
7. Conly, G., *The Shock of '31, The Hawke's Bay Earthquake*, A,H, & A,W, Reed Ltd, Wellington, Sydney, London, Auckland, , 1980, 234 p.
8. Cousins W. J., Dowrick D. J., Sritharan S., "Fire following earthquakes", Proceedings, Institution of Fire Engineers Conference, New Plymouth, 26-29 August 1991, pp 65-80.
9. Cousins, W. J., and Heron, D. A., "Integrated risk assessment model for Wellington City Council - Phase 2", Institute of Geological & Nuclear Sciences, Client Report 1998/135, Lower Hutt, January 2000, 101 p.

10. Downes, G. L., Dowrick, D. J., Smith, E. G. and Berryman, K. R., "The 1934 Pahiatua earthquake sequence: analysis of observational and instrumental data", *Bulletin of the New Zealand National Society for Earthquake Engineering*, 32(4): 221-245, (1999).
11. Downes, G. L., Dowrick, D. J., Van Dissen, R. J., Taber, J. J., Hancox, G. T. and Smith, E. G. C., "The 1942 Wairarapa, New Zealand, earthquakes: analysis of observational and instrumental data", *Bulletin of the New Zealand National Society for Earthquake Engineering*, 34(2): 125-157, (2001).
12. Dowrick, D. J., "Damage and intensities in the magnitude 7,8 1929 Murchison, New Zealand, earthquake", *Bulletin of the New Zealand National Society for Earthquake Engineering*, 27(3): 190-204, (1994).
13. Dowrick, D. J., "Damage and intensities in the magnitude 7,8 1931 Hawke's Bay, New Zealand, earthquake", *Bulletin of the New Zealand National Society for Earthquake Engineering,* 31(3): 139-163, (1998).
14. Dowrick, D. J., Rhoades, D. A. and Davenport, P. N., "Damage ratios for domestic property in the 1968 Inangahua, New Zealand, earthquake", *Bulletin of the New Zealand National Society for Earthquake Engineering*, 34(3): 191-213, (2001)
15. Drysdale, D. D., *An Introduction to Fire Dynamics*, John Wiley and Sons, Chichester, 1986, p.214.
16. Eiby, G. A., "The Marlborough earthquakes of 1848," Department of Scientific and Industrial Research, DSIR Bulletin 225, Wellington, 1980, 80 p.
17. Grapes, R., *Magnitude eight plus*, Victoria University Press, Wellington, 2000, 208 p.
18. Grapes, R., and Downes, G., "The 1855 Wairarapa, New Zealand, earthquake – analysis of historical data", *Bulletin of the New Zealand National Society for Earthquake Engineering,* 30(4): 271-368, (1997).
19. Hokugo, A., "The Performance of Fire Protection of Buildings against the Fires Following the Great Hanshin-Awaji Earthquake," Fire Safety Science—Proceedings of the Fifth International Fire Safety Symposium, Melbourne, 1997, pp 947-958.
20. Hopkins, D. C., "Wellington after the Quake, the Challenge of Rebuilding Cities", Earthquake Commission, Wellington, 1995, pp 111-120/284..
21. McLean, G., *New Zealand Tragedies, Fires and Firefighting*, Grantham House, Wellington, 1992.
22. pers comm, Mclndoe, G, Lecturer in Urban Design and Planning, School of Architecture, Victoria University of Wellington, 2001.
23. Scawthorne, C., "Fire Following Earthquake, Estimates of the Conflagration risk to Insured Property in Greater Los Angeles and San Francisco," All Industry Research Advisory Council, Oak Brook II, 1987.
24. Tewarson, A., "Generation of Heat and Chemical Compounds in Fires," *The SFPE Handbook of Fire Protection Engineering, (2nd Ed),*DiNenno P.J. (ed.), National Fire Protection Association, Quincy MA 02269, 1995, p. **3**/58.
25. Thomas, G. C., "Fire Resistance of Light Timber Framed Walls and Floors,", School of Engineering, University of Canterbury, Fire Engineering Research Report 97/7, Christchurch, 1997, pp145-156/318.
26. Todd, D. et al, "1994 Northridge Earthquake, Performance of Structures, Lifelines and Fire Protection Systems," National Institute of Standards and Testing, NIST SP 862, Gaithersburg, MD, 1994, 186 p.