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Modelling the spread of post-earthquake fire

W.J. Cousins, D.W. Heron & S. Mazzoni

Institute of Geological & Nuclear Sciences, Lower Hutt, New Zealand.

G.C. Thomas & D. Lloydd

Victoria University, Wellington, New Zealand.

ABSTRACT: Post-earthquake fire is a highly variable phenomenon. Fire losses are often zero, but sometimes conflagration can develop with near total destruction of a city. We describe two GIS-based ways of modelling post-earthquake fire in the urban setting, one static and one dynamic. The static approach relies on a buffering technique to define "burn-zones" that are sampled randomly to give estimates of losses. From repeated sampling we are able to model the fire-loss as a function of numbers of ignitions, building separations and building properties. The dynamic approach uses a 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, cladding materials and individual separations of buildings. Using the static model we show that losses due to fire following a major earthquake near Wellington City are likely to be smaller than losses due to shaking, provided the wind at the time is no stronger than a "moderate breeze", but are likely to become severe in gale-strength winds. Creating artificial firebreaks appears not as effective a mitigation measure as minimising the numbers of ignitions and providing buildings with non-flammable claddings.

1 INTRODUCTION

Fire following earthquake is an extremely variable phenomenon. Losses from such fires can vary from insignificant (as in the 1999 ChiChi earthquake, Taiwan) to serious (1995 Kobe earthquake, Japan) to disastrous (1923 Kanto earthquake, Tokyo, Japan). New Zealand's experience is no exception. For most historical New Zealand earthquakes we are aware of no reports of post-earthquake fires. For one, the Wairarapa earthquake of 1942, one house was destroyed by fire and there was minor fire damage to a few others (Downes et al 2001). In one other case, the Hawke's Bay earthquake of 1931, there was major conflagration that destroyed most of the Napier business district (e.g. Wright 2001).

There are two aspects to the variability. One is a high level of variability in the number of ignitions, and the other is a high level of variability in the extent of fire-spread from each ignition. We are modelling just the fire-spread aspect.

Wellington City, which we use as an illustration, has many of the risk factors that together give a high probability of post-earthquake conflagration. It straddles one of New Zealand's most active faults and so is likely to experience severe ground shaking. The main access routes and water supply lines cross the fault. Much of the terrain is steep so that many access routes around the city have the potential to be blocked by landslides. Much of the inner suburban area consists of light timber-clad houses, usually of two storeys, that are close to adjoining houses. The central city is reticulated with natural gas. Wellington City thus has many potential ignition sources and, after a large earthquake, fire spread is likely to be rapid. Fire fighting resources, especially water, will be limited. Indeed the first century of European settlement has seen the burnout of one or more blocks of buildings at least eight times (Monigatti c1966) with estimated losses of up to about $50 million in present day values.

We have developed two GIS-based (Geographic Information Systems) models for simulating the spread of post-earthquake fires. One, a static model, uses a simple buffering technique to define potential "burn-zones", which are then sampled randomly to construct estimates of losses. From repeated sampling we are able to assess the probability of exceedance of various levels of loss as a function of the number of ignitions, the spacing between buildings and the cladding materials. The second is a dynamic model for tracking the rate and extent of fire spread in response to a wide range of factors including wind, radiation, sparking, branding, cladding materials and separations of buildings. It is more realistic than the simple model but runs much more slowly.

The static model can be used to scope the fire-spread problem, to assess the effectiveness of large-scale mitigation measures, and to identify those parts of a city where conflagration could occur and where more detailed modelling would be desirable. The dynamic model is intended for detailed investigation of mitigation measures and for response planning during fire emergencies. Both models are still under development but are showing considerable promise. Below we briefly describe both models and then apply the static model to fire-spread in Wellington.

2 UNDERLYING DATABASE

Both models are supported by a database of spatial information about the fuel (i.e. the buildings). The main database item is the building footprint, and linked to each footprint is information on the number of stories, the floor area, the replacement value, and the cladding materials. Floor areas, numbers of stories, and cladding materials are derived from a property database managed by QuotableValue New Zealand, and replacement values are calculated as a product of floor area and estimated construction cost. The estimated construction costs range from about \$650/m^2 (for low-cost industrial buildings) to \$1800/m^2 (for high quality houses on steep sections). The base costs are derived in part from published cost estimates for construction in Wellington (Giddens 2001). Our estimate of the replacement value of all buildings in Wellington City is \$23.4 billion, distributed amongst 75,800 buildings.

3 DYNAMIC MODEL

The dynamic model uses a "cellular automaton" technique in which the landscape is modelled as a regular grid of 3m x 3m cells with each cell being assigned a set of states and properties representing the physical environment (e.g. Ball & Guertin 1992). Spread of fire from one cell to another depends on the states, the properties and a set of "rules". Possibilities can include the following:

- state - burning or not, and if burning how fiercely,
- properties - combustible or not, ignitable or not, and
- rules - probability of ignition according to intensity of combustion, distances from burning cells, and biases such as wind and elevation.

The "rules", a crucial element of the model, are derived from a combination of fire physics and historical data. The "properties" are derived from the underlying spatial database by simply laying the grid of cells over the building footprints and assigning to each cell the properties of whatever is beneath it. Any cell that is more than 50% filled with "building" is deemed a building cell and all others are deemed to be empty.

The mechanics of the process is that the entire set of cells is scanned repeatedly, cell by cell, in a raster fashion. During the scanning process cells are "activated" one at a time and, whilst activated, a cell's state is changed according to its current state and properties, 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 which makes it straightforward to model time-variant states such as the build-up and decline of a fire.

The above is only a brief overview of the dynamic model. Details and applications are discussed elsewhere (Cousins et al 2002, Thomas et al 2002).

4 STATIC MODEL

The static “burn-zone” model has two main features. One is the specification of a “critical separation”, which is the maximum distance that a fire can jump from one building to another, and the other is the exclusion of all biasing factors such as wind, ground slope or active suppression. The reasons for not allowing any biasing factors are that the critical separation then is independent of the direction of fire-spread and, consequently, the size and shape of a burn-zone do not depend on which building within the zone is ignited first. In other words, the burn-zones can be defined uniquely by the critical separation alone. Once the critical separation has been selected, the burn-zones are generated within the GIS and summary data are extracted for statistical modelling. The generation of the burn-zones may take some hours of computer processing time for each value of critical separation but the summary data, once available, can be used to carry out many thousands of fire simulations.

To define the burn-zones we draw buffers with width equal to half the critical separation around each building’s footprint, and then group together those buildings whose buffers touch or overlap. Relevant information such as replacement value, numbers of buildings, and numbers of occupants, is then derived by summation over each burn-zone.

Note that we have implicitly assumed that all buildings are combustible and that fire can spread to and from all buildings. Hence the basic model represents a type of worst-case scenario, though not necessarily the worst possible case because vegetation is not yet included in the model.

When the critical separation is 12m, for example, there are 5310 burn-zones in Wellington City. More than half have values below $1 million and probably represent small groups of houses. The largest has a value close to $1 billion and is the block of about 90 commercial buildings bounded by Lambton Quay, Bowen Street, The Terrace, Boulcott Street and Willis Street. The bulk, sixty percent or $14 billion, of the value of Wellington resides within burn-zones having values in the range $5 million to $50 million (Figure 1). If the critical separation is increased to 20m most of the value, sixty-five percent or $15 billion, lies within just 20 burn-zones of $200 million or more.

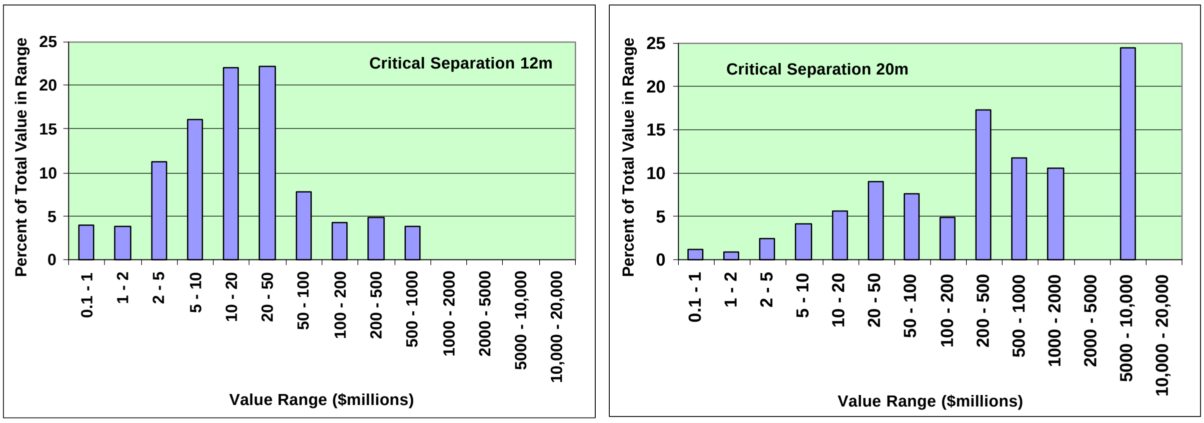

Figure 1. Distribution of the replacement value of Wellington City’s buildings amongst the various sizes of burn-zone defined by critical separations between buildings of 12m and 20m. All buildings are assumed combustible and fire is able to spread to and from all buildings.

5 APPLICATIONS OF THE STATIC FIRE-SPREAD MODEL

5.1 Potential losses when fire can spread to and from all buildings

One important application of the burn-zone model is in assessing the significance of post-earthquake fire. This can be done by randomly distributing ignitions amongst the buildings in an area of interest and, for all burn-zones thus ignited, accumulating the total value of the buildings destroyed. As an example, consider the case of Wellington following a magnitude 7.5 earthquake on the Wellington fault. On average there could be 30 separate ignitions (Cousins et al 1991, Lloyd 2001), but the uncertainty in the number is high and so we randomly distribute 1, 3, 10, 30 or 100 ignitions over the buildings, accumulating the losses for each trial. Repeating this 10,000 times for each number of ignitions, and for a critical separation of 12m gives the results summarised in Figure 2.

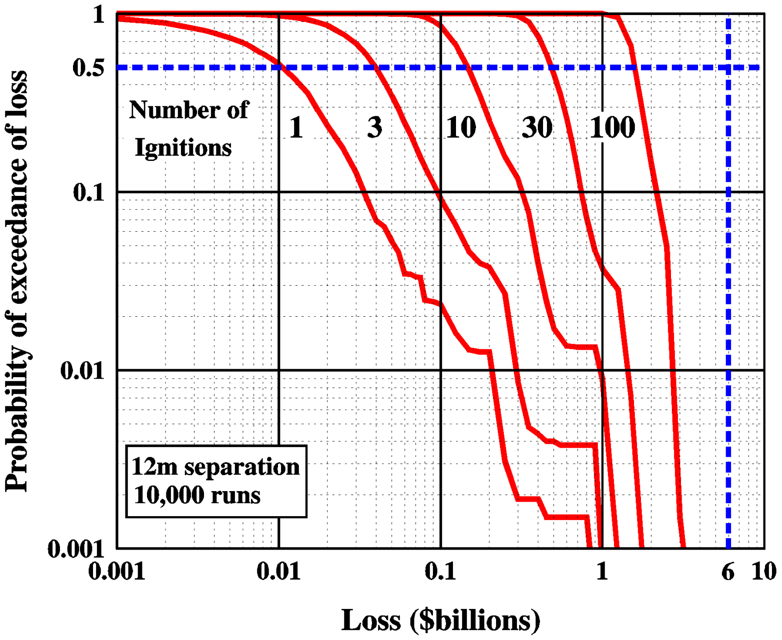

Figure 2. Probability of exceedance of various levels of loss for ignitions randomly distributed amongst the 75,800 buildings of Wellington City after the buildings have been grouped into burnout zones delineated by a critical separation of 12m.

The main features of Figure 2 are as follows:

- Regardless of the number of ignitions, the fire losses are always considerably smaller than the shaking loss ($6 billion, vertical dashed line) expected for a large earthquake on the Wellington fault, given a replacement value of $23.4 billion (Cousins & Heron 2000, Hopkins 1995).
- The 50th percentile loss (shown by the horizontal dashed line) is roughly proportional to the number of ignitions. It increases from about $10 million for 1 ignition to about $1.5 billion for 100 ignitions.
- The uncertainty in the loss decreases as the number of ignitions increases. For 1 ignition the loss ranges from $500 to $900,000,000, a factor of nearly 2 million. For 100 ignitions the range is $1 billion to nearly $3 billion, a factor of only 3.

Repeating the entire procedure for critical separations of 10, 12, 14, 16, 18, 20, 22, 24, 30 and 48m, and 30 ignition points, gives the results shown by the upper band in Figure 3. The results show quite clearly that the fire losses remain significantly smaller than the large event shaking loss provided the critical separation is no more than about 15m.

5.2 **Buildings with non-flammable cladding**

The assumption that fire can spread to and from all buildings is unduly severe because many buildings have non-flammable claddings. In a real post-earthquake fire situation we could, for example, expect many concrete-clad buildings to be resistant to fire-spread. Some would be sufficiently damaged by earthquake shaking to lose their inherent protection and others would already have sufficient unprotected openings to be vulnerable. Similarly, some iron-clad and some brick-clad buildings would be resistant to fire-spread and some would not.

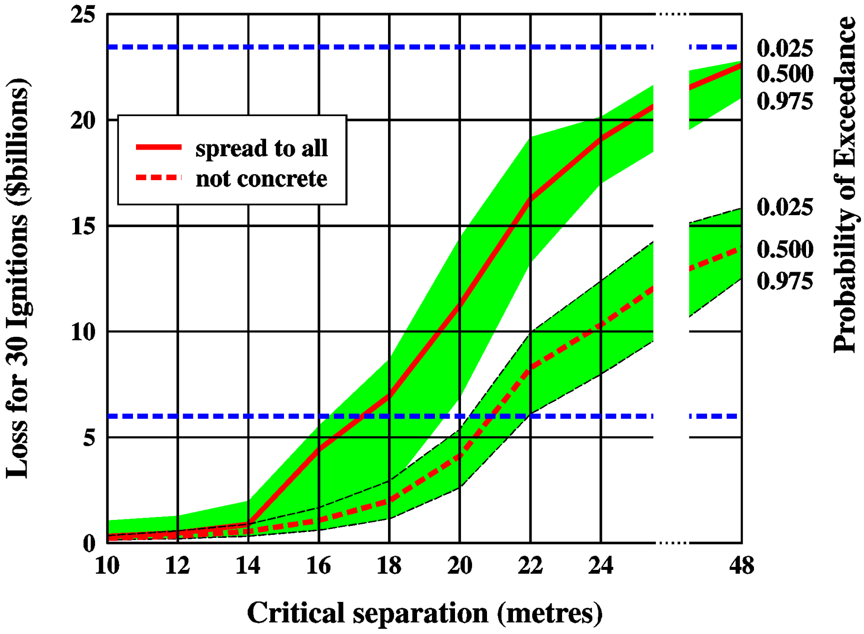

Figure 3. Effect of critical separation on estimated losses from 30 ignitions in Wellington City. The 50th percentile losses are shown by the heavy lines, and the 95% confidence intervals by the shaded bands. The upper band is for the case where fire is assumed able to spread to and from all buildings, and the lower band for the case where fire is unable to spread either to or from concrete-clad buildings. The upper dashed line shows the total replacement value of all buildings in Wellington City. The change in horizontal scale between 24 and 48m is simply to compress the graph in a region where there is relatively little variation in loss.

In order to simulate a more realistic situation with our model we assume that fire is unable to spread either to or from concrete-clad buildings. This is implemented by removing all such buildings from the database prior to the buffering process and then reinstating them at the end as “single-building” burn-zones. Treating all concrete-clad buildings as being resistant to fire-spread, and all other buildings as not, is a crude, but easily implemented way of simulating the overall resistance to fire-spread.

There are 7430 concrete-clad buildings with a total value of $7.5 billion in Wellington City. Isolating them from the fire-spread simulation roughly halves the fire losses and, perhaps more significantly, increases the critical separation at which the fire losses start to become serious from about 15m to 20m (Figure 3).

5.3 **Urban firebreaks**

An intuitive way of minimising fire-spread is the creation of firebreaks. As a somewhat arbitrary simulation of the effect of creating additional firebreaks throughout Wellington the burn-zones were subdivided. Two examples were considered. First, just the largest value burn-zones were each subdivided into three equal portions. For critical separations of 10-14m the top 30 zones were subdivided, for 16-20m the top 20, for 24m the top 10, for 30m the top 4, and for 48m the top 2. Second, all burn-zones were subdivided into two equal portions.

The reductions in losses from the extra “firebreaks”, Table 1, were not always as large as might have been expected. In both cases the reductions in loss were small for critical separations of 20m and above. This probably was a result of the large number of ignitions. Even after the subdivision much of the value remained concentrated in a small number of large zones and, given 30 ignitions, the probability that all were ignited remained high.

The reductions in loss were small also, when only the largest burn-zones were subdivided, for critical separations of 10 to 14m. A likely reason for this was that the bulk of the value and the bulk of the loss were in burn-zones smaller than the ones that were subdivided.

Table 1. Effect of creating additional urban firebreaks on losses from 30 ignitions.

Critical Separation (m)	50th Percentile Loss ($millions) for 30 fires			Reduction over base case (%)	
	Base case	Large burn-zones subdivided into 3 parts	All burn-zones subdivided into 2 parts	Large burn-zones subdivided into 3 parts	All burn-zones subdivided into 2 parts
10	$310	$290	$160	7	48
12	$490	$420	$250	14	49
14	$890	$630	$450	29	49
16	$4,400	$2,000	$2,300	55	48
18	$7,000	$3,300	$3,900	53	44
20	$11,000	$6,800	$8,600	38	22
22	$16,000	$13,000	$14,000	19	19
24	$19,000	$16,000	$17,500	16	8
30	$21,000	$19,000	$19,500	10	7
48	$22,600	$22,500	$21,800	0.4	4

5.4 Potential losses from a single ignition

The cost of not fighting fires under normal (i.e. non-earthquake) conditions can be estimated by randomly locating single ignition points many times and averaging the losses. Results of such a simulation are given in Table 2.

Table 2. Estimated 50th percentile losses from one ignition and various critical separations.

Critical Separation (m)	50th Percentile Loss ($millions)	
	Fire Spreads to and from All Buildings	No Spread to and from Concrete-Clad Buildings
10	$7	$5
12	$11	$8
14	$15	$11
16	$27	$16
18	$60	$31
20	$280	$70
22	$1,300	$400
24	$1,600	$700
30	$1,900	$1,300
48	$15,000	$1,700

6 DISCUSSION AND CONCLUSIONS

Before any use can be made of the above results there needs to be a link made between the critical separation and environmental factors, particularly wind speed. From a combination of fire physics and historical data the following relationship, Table 3, was obtained for the effect of wind speed on the size of gap a fire could cross through a combination of radiation, piloted ignition and branding (Cousins et al 2002, Thomas et al 2002).

Table 3. Spark spread distance as a function of wind strength.

Wind strength (and approximate speed)	**Calm**	**Moderate Breeze (20 km/h)**	**Fresh Breeze (30 km/h)**	**Near Gale (50 km/h)**
Spread distance downwind (m)	12	15	21	45
Spread distance cross and upwind (m)	12	12	12	12

Referring back to Figure 3, the spread distances of Table 3 imply that for wind conditions from “calm” to “moderate breeze”, post-earthquake fire is a relatively minor problem in comparison to shaking and other earthquake-related losses, even when fire can spread to and from all buildings regardless of cladding materials. For winds stronger than “moderate breeze” the fire losses are serious. When concrete-clad buildings are removed from the spread process wind stronger than “fresh breeze” is required before the post-earthquake fire losses exceed the shaking losses.

The cost of not fighting fires is significant even under normal conditions when there is just one ignition at a time. For single ignitions the 50th percentile loss varies from about $10 million in “calm” or “moderate breeze” conditions to more than $1 billion for “near gale” conditions (Tables 2 and 3).

Neither of the fire-spread models is yet fully developed. Two important features remaining to be incorporated are the effects of ground slope and vegetation. Bearing that in mind, some tentative conclusions that may be derived from the applications of the static model as outlined above are as follows:

Losses due to fire following a major earthquake centred on Wellington City are likely to be smaller than losses due to shaking, provided the wind at the time is no stronger than a “moderate breeze”. However, fire losses could greatly exceed shaking losses for “near gale” and stronger winds.

The first assertion, that fire losses are likely to be relatively small under low-wind conditions, is probably quite sound. It is derived from a “worst case” application of the static model in which all building claddings are assumed to be combustible and the necessary condition that the fire can spread uniformly in all directions is achievable.

The second assertion, that fire losses could greatly exceed shaking losses for high-wind conditions, needs more investigation. According to the static model, fire losses exceed shaking losses when the fire is able to jump gaps of about 17 to 21m (Figure 3). For this to occur the fire would need to be wind-driven, in which case the assumption of uniform spread in all directions is not necessarily valid. However maps of the large burn-zones show that many have a very distinct north-south elongation, which is almost certainly a result of the strongly linear ridge-valley topography of Wellington. Thus complete burnout of many of the large burn-zones remains possible provided that the ignitions are suitably placed. All that is changed is that the probability is reduced.

“Across-road” separations between buildings in Wellington are rarely less than 15m, often more than 20m. Thus fires are unlikely to cross roads unless wind driven.

Added firebreaks appear not to be an effective way of minimising fire losses when there are multiple (30 or so) ignitions. Very large numbers of firebreaks could make a worthwhile difference to losses in low-wind conditions when fires are not able to jump gaps of 20m or more, but the cost of creating them would be very high. Simply providing buildings with fire-resistant claddings may be a much more cost-effective way of achieving the same result.

For “calm” to “fresh-breeze” conditions, the fire loss is roughly proportional to the number of ignitions. Thus preventing ignitions is a very good mitigation measure, as is the immediate containment of any fires that do start.

Development of the fire-spread models is continuing. Features being added include vegetation, ground slope, and improved modelling of the typically closely-spaced highly-valued buildings of a central business district. Probabilistic approaches will allow for the variability and uncertainty associated with phenomena such as size and location of earthquake, shaking attenuation, season and wind speed.

7 ACKNOWLEDGEMENTS

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REFERENCES:

Ball, G.L. and Guertin, D.P. 1992. “Improved fire growth modelling”. *International Journal of Wildland Fire*, 2(2): 47-54.

Cousins W.J., Dowrick D.J., Sritharan, S. 1991. “Fire following earthquakes”. *Proceedings, Institution of Fire Engineers Conference*, New Plymouth, 26-29 August 1991: 65-80.

Cousins, W.J., and Heron, D.A. 2000. *Integrated risk assessment model for Wellington City Council - Phase 2.* Client Report 1998/135, Institute of Geological & Nuclear Sciences, Lower Hutt.

Cousins, W.J., Thomas, G.C., Heron, D.W., Mazzoni, S. & Lloydd, D. 2002. “Modelling the spread of post-earthquake fire in Wellington City”. *Proceedings, 2002 Technical Conference and AGM*, New Zealand Society for Earthquake Engineering, 15-17 March 2002, Napier, Paper No. 5.4.

Downes, G.L., Dowrick, D.J., Van Dissen, R.J., Taber, J.J., Hancox, G.T. and Smith E.G.C. 2001. “The 1942 Wairarapa, New Zealand, earthquakes: analysis of observational and instrumental data”. *Bulletin of the New Zealand Society for Earthquake Engineering,* 34(2):125-157.

Giddens, C. 2001. (Ed) *Rawlinsons 2001 – New Zealand Construction Handbook*. Rawlinson Media Ltd. Auckland.

Hopkins, D.C. 1995. “Assessment of resources required for reinstatement”, pp 111-120, in *Wellington after the Quake, the Challenge of Rebuilding Cities*, Earthquake Commission (Wellington) 284p.

Lloydd, D. 2001. *The Risk of Post-Earthquake Fire in Wellington*. BBSc (Hons) Report, School of Architecture, Victoria University of Wellington. 125p.

Monigatti, R. (Ed.) 1966 (approx). *From Bells to Blazes. The Story of the Wellington Fire Brigade 1865 to 1965*. A.B.D. Clark Ltd., Wellington.

Thomas, G.C., Cousins, W.J., Lloydd, D., Heron, D.W. and Mazzoni, S. 2002. “Mitigation of post-earthquake fire. Estimating and costing extent of fire in Wellington”. *Seventh International Symposium on Fire Safety Science*, Massachusetts, USA,16th – 22nd June 2002. International Association for Fire Safety Science.

Wright, M. 2001. *Quake - Hawke’s Bay 1931.* Reid Publishing (NZ) Ltd, Auckland. 158p.