Fire risk analysis of a 6-storey residential building using C Urisk

Xiao Li, Xia Zhang, George Hadjisophocleous*

Department of Civil and Environmental Engineering, Carleton University, 1125 Colonel By Drive, Ottawa, Canada. K1S 5B6

Abstract

A quantitative fire risk analysis computer model CUrisk is being developed at Carleton University to evaluate the fire performance of buildings. For different fire scenarios, fire conditions in all the compartments of a building can be predicted by the Smoke Movement and Fire Growth submodels. CUrisk also considers fire spread from the compartment of fire origin to other compartments using the newly developed Fire Spread submodel. The results of these submodels as well as the outputs of the Occupant Response and Evacuation submodels are used by the Life Hazard and Economic Loss submodels to determine the consequences of each scenario in terms of expected number of deaths or injuries and fire losses. CUrisk takes into consideration the effect of different fire protection measures such as sprinkler systems, detectors and alarms and fire department actions. After analyzing all the possible fire scenarios, two final decision making parameters, the Expected Risk to Life and Fire Cost Expectation are calculated. A case-study using a six-storey residential building has been conducted using CUrisk and results are presented and analyzed in this paper.

© 2013 International Association for Fire Safety Science. Published by Elsevier Ltd. All Rights Reserved

Keywords: Fire risk analysis; Multi-storey residential building; Performance based design; Fire spread

1. Introduction

Designs for fire safety are gradually moving from the traditional prescriptive-based approach to performance based. To support performance-based designs, risk analysis guidelines and risk assessment approaches have been developed [1-7]. Furthermore, ISO TC92/SC4 WG10 is preparing documents for international standardization of terminology, concepts, and frameworks of fire risk assessment [8]. A number of fire risk analysis models have been developed based on the concepts of performance based design. CESARE-Risk [9] is a risk assessment model that is used to quantify the performance of a building fire safety system; FIERAsystem [10] (Fire Evaluation and Risk Assessment system) is a computer model to evaluate fire protection systems in industrial buildings, with a primary focus on warehouses and aircraft hangars; CRISP (Computation of Risk Indices by Simulation Procedures) [11] is a tool to assess fire risk based on simulation models and Monte Carlo methods. Chu and Sun [12] proposed a quantitative fire risk assessment framework which utilizes Markov Chain combined with time-dependent event tree techniques to obtain the occurrence probability of fire scenarios and correspondent consequences. A more recent model [13] uses the application of Bayesian Network techniques to assess dwelling fires to minimize fire risk and enhance emergency strategies.

In Canada, a Strategic Research Network called NEWBuildS [14] has been established to promote the use of wood products in mid-rise buildings for residential and non-residential uses. Wood is a combustible material, therefore special attention is given to fire safety. CUrisk is a quantitative fire risk assessment model being developed at Carleton University, and the Network would like to use CUrisk to determine the fire risk and develop design guidelines for mid-rise wood-based buildings or hybrid construction (combination of wood with concrete or steel). The present paper reports on a case study of

* Corresponding author. Tel.: +1 613 520 2600 ext.5801; fax: +1 613 520 3951.
E-mail address: george_hadjisophocleous@carleton.ca.
fire risk analysis of a 6-storey wood-based building, where the fire risk analysis model CUrisk is used to evaluate the fire safety of a proposed building.

2. Description of CUrisk

CUrisk is comprised a system model and sixteen sub-models. The system model deals with the system methodology and the basic structure of the assessment approach, organizes basic functions of each sub-model, relationship of all the sub-models, as well as data input and output of the whole model. As shown in Fig. 1, fire risk analysis begins with the production of all fire scenarios. For each scenario, a design fire is selected and then the Fire Growth sub-model is run to predict the conditions in all the fire compartments. The Smoke Movement sub-model is used to predict the conditions in non-fire compartments. The Boundary Failure and Fire Spread sub-models are used to calculate the probability of fire spread to other compartments and to provide further information on hazardous conditions. The information of the building hazardous conditions is sent to the sub-models of Fire Detection, Occupant Response, Occupant Evacuation, Fire Department Response and Action, Life Hazard and Economic Loss to calculate the consequences in terms of life safety and fire damages of each scenario. After finishing all scenarios, the final two decision-making parameters, the Expected Risk to Life and Fire Cost Expectation are obtained. More detailed description can be found in CUrisk Technical Report [15].

A scenario is composed of a number of clearly defined events. In the Fire Scenario sub-model, the event tree is composed of the following events: room of fire origin, selection of design fire, fire states, door states, weather conditions, sprinkler suppression, detectors and alarms, fire fighting, and boundary types. This sub-model will produce the number of fire scenarios, and the probability of occurrence of each scenario.

The Smoke Movement sub-model is a two-zone model and is used to predict conditions of the fire origin compartment and all the non-fire compartments in the building [16, 17] as a result of fire development in the fire compartment. For each fire scenario, only a single fire ignition source is used. The output of this sub-model includes smoke temperature, species concentration, depth of the smoke layer, radiation flux to its boundaries, and smoke obscuration in each compartment, based on the fire origin location, type and speed, building geometry and dimensions, properties of boundary materials, ventilation system, and environmental condition.

The Fire Growth sub-model uses the same module as the Smoke Movement sub-model. It goes through all the compartments separately, each of which is treated as a standalone fire compartment, to predict the fire and smoke conditions of those compartments. Then based on the results of the Fire Spread sub-model, the damages will be calculated by the Economic Loss sub-model. Both of the two sub-models take data from the Design Fire sub-model and export data to the Economic Loss sub-model.

The Fire Spread sub-model is a probabilistic model using the Bayesian Network approach and probability theory [18, 19]. This sub-model is used to calculate the probability of fire spread not only across rooms horizontally on the same floor but also vertically across different floors throughout the building at different simulation times. The results reflect the
combination of fire development process and boundary failure process. The cumulative probability of boundary failure is calculated based on the equivalent failure time in a real fire to the fire resistance rating of the building components. The probability of fire growth to a fully-developed fire depends on several factors, the fuel load, the geometry of the compartment and its ventilation conditions, and the availability of fire suppression systems.

The Occupant Response sub-model [20, 21] is used to predict the response of occupants. This model is developed based on the concept of a PIA process, i.e., perception, interpretation, and action. Occupants are separated into three groups: occupants in the fire compartment (OFC), in adjacent compartments (OAC), and in other compartments (OOC). Occupant response begins from the time of receiving cues of fire or smoke.

The Occupant evacuation sub-model [22] begins from the time when an occupant decides to evacuate. There will be different routes for them to select and different speeds for them to move based on their moving and judging ability as well as their familiarity with the building. Each exit is given a probability of being used. When an occupant has reached a doorway, a possibility of queuing is checked based on the density at the doorway. Movement speed is adjusted based on levels of smoke and population density within a given compartment.

The Life Hazard sub-model [15] is used to calculate the number of occupants killed and injured in each fire scenario. The total probability of death, at a given compartment and a given time is calculated using the union of the individual probabilities of death from being exposed to toxic gases, hot gases, heat fluxes, and fire spread. The overall probability of death of an occupant at a given time can be obtained by keeping track of the evacuation route of the occupant.

The Building Cost sub-model [23] can calculate the capital cost of the building components and building construction (i.e., the cost of building), passive and active fire protection systems and the maintenance cost of the active fire protection systems. It takes input data directly from users. The Economic Loss sub-model calculates the economic loss of each fire scenario. It takes the output data of the Hazardous Conditions sub-model and Building Cost sub-model, and uses damage criteria of building components, fire protection systems and contents from users to estimate the economic loss.

The Expected Risk to Life (ERL) is one of the two final decision-making parameters, defined as the expected death frequency per year per individual of a building, which is calculated by Eq. (1) [15], Expected Risk of Injury (EROI) can also be obtained using a similar equation by submitting the number of injuries for each scenario.

\[ ERL = \frac{F}{POP} \sum_{i=1}^{K} P_i N_i \]  

where \( F \) is the annual fire frequency of the building; \( P_i \) is the probability of scenario \( i \); \( N_i \) is the number of deaths of scenario \( i \); \( K \) is the number of scenarios; \( POP \) is the population of the building. A similar method is also used in [12].

The Fire Cost Expectation (FCE) [15] is the other final decision-making parameter computed by the model. FCE is defined as a vector with four components: \( COST_{Fixed} \), the capital cost of the passive and active fire protection systems; \( COST_{Maintain} \), the annual maintaining cost of the active fire protection systems; \( COST_{Loss} \), the expected annual loss as a result of all probable fire incidents in the building; and \( COST_{Total} \), the total cost in the time span of the design life of the building.

\[ AFL = COST_{Loss} = F \cdot \sum_{i=1}^{K} P_i C_D \]  

The \( COST_{Loss} \) is the Annual Fire Loss (AFL) which is calculated by Eq. (2); \( P_i \) is the probability of scenario \( i \) occurring; \( C_D \) is the total cost of damage to the entire building in scenario \( i \) ($); \( k \) is the number of scenarios.

3. Case study description

3.1. Building layout

A simple six-storey wood constructed residential building is used to perform the fire risk analysis case study. As shown in Fig. 2(a), the layout of each floor is identical and each floor of the building has 6 two-bedroom apartments (8.0 m × 8.0 m), a corridor (24.0 m × 1.5 m), 2 stair shafts (3.0 m × 5.5 m), 2 elevator shafts (3.0 m × 5.4 m) and 2 public zones (3.0 m × 6.6 m). There are only 2 main doors to the outside on each side of the first floor (2.0 m × 2.0 m). The corridor on each floor is connected to the common area by two doors (0.9 m × 2.0 m).
All the apartments in the building are assumed to be identical. Each apartment has 5 rooms, 5 doors and 2 windows. On each floor only the first apartment (top left on Fig. 2(a)) is divided into 5 compartments ranging from R1 to R5 (see Fig. 2(b)), and all other five apartments are considered as one compartment (R6 to R10). This is done to reduce the simulation time and avoid computational problems caused by having too many compartments. Elevator shafts are not considered as compartments as it is assumed that they are not used in case of fire. Therefore, on each floor there are 15 compartments giving 90 compartments in the building. Apartment rooms are numbered first (R1 to R60); for example, R11, R35 and R57 means living room of the first apartment on second floor, kitchen of first apartment on fourth floor and top right apartment on sixth floor. All other compartments (as common areas, stairways) are numbered from R61 to R90.

3.2. Input data

The compartment fire development is assumed to be \( t \) square fires. Growth speed [24] and maximum heat release rates are: R1, Medium fire, max heat release rate (MHRR) 6 MW; R2 and R3, Slow fire, MHRR 5 MW; R5, Fast fire, MHRR 2 MW; R6 to R10, Medium fire, MHRR 12 MW. Similar data are used on all floors. Note that non-apartment compartments such as elevator shafts, stair shafts, corridors and public zones are not considered to have enough fire loads to support fire growth and fire spread, but smoke can spread to those areas through openings. The maximum heat release rate can be estimated by the fuel type and ventilation conditions, \( Q_{\text{max}} = 1518.4 \sqrt{H} \) [24]. The actual heat release rates of the design fires will be limited by the ventilation conditions and have smaller values than the MHRR.

All main doors of the apartments (doors to the corridors), building entrances are set to 20% open, and all the corridor doors and doors inside the apartments are set to 50% open, and all the windows are set to break at 300 °C [25].

Table 1. Five different fire resistance rating (in minutes) options of building components

| Options | Wall | Door | Ceiling/floor | Window |
|---------|------|------|---------------|--------|
| 1       | 30   | 10   | 30            | 3      |
| 2       | 45   | 20   | 45            | 3      |
| 3*      | 60   | 30   | 90            | 5      |
| 4       | 90   | 40   | 90            | 8      |
| 5       | 120  | 50   | 120           | 10     |

* Code-Compliant, except the data of window

To demonstrate the performance of the Fire Spread sub-model, five different options as shown in Table 1 are compared. Option 3 follows the National Building Code of Canada 2010 (NBCC 2010) [26]. The fire resistance ratings of windows are from the engineering judgment based on experimental findings [27].
The time of Fire department action is divided into notification time, response time and setup time, which are set to be 30 s, 360 s, and 120 s, respectively. For the Response and Evacuation sub-models, 144 occupants are distributed in the building with 4 people at each apartment (2 in the living room, 1 in the master bedroom and 1 in the small bedroom), 50% male and 50% female occupants, and 50% young and 50% adult occupants. For the Building Cost sub-model and Economic Loss sub-model, six input data fields are needed, including the cost of building components, the cost of active and passive fire protection system, the cost of emergency systems, the cost of building contents and some general input data, such as inflation rate, interest rate, and downtime cost.

To calculate the final two decision making parameters Expected Risk to Life and Fire Cost Expectation, the annual fire frequency, design life of the building, fire scenarios and their probabilities should be assigned. The Ontario (a province in Canada) statistical data shows the residential fire ignition frequency to be $2.61 \times 10^{-3}$ per unit per year [28], therefore, the annual fire frequency of the 36-apartment building can be estimated to be $9.396 \times 10^{-2}$ per year. The design life of the building is set to be 50 years. Four fatal scenarios of fire origins and their probabilities are identified according to a study of the Ontario Fire Statistics data [29], and fires are set to start in 4 different rooms on different floors, living room (R1), master bedroom (R2), small bedroom (R3) and kitchen (R5), with probabilities 0.24, 0.12, 0.1, and 0.54, respectively. In this case study, sprinklers, fire department and alarms are chosen to be fire protection options. According to statistics [30] and engineering judgment, the operation reliabilities of fire department action, sprinklers operation, and alarms operation are taken as 0.6, 0.95, and 0.9, respectively.

### 3.3. Fire scenarios and design options

The event trees of three design options are illustrated in Fig. 3 and Fig. 4. These figures graphically illustrate the dependence of events and are used to calculate the scenario probabilities. Note that probability of fire occurrence on each
floor is considered to be the same (1/6), thus the event trees only show the scenario structures of one floor, and the total number of scenarios should be multiplied by 6. Similarly, all the apartments on each floor are considered to have the same fire occurrence probability, which can significantly reduce the number of fire scenarios, although a side apartment (as First Apartment, R7, R8 and R10 in Fig. 2(a)) may have different fire consequences comparing with middle apartments (as R6 and R9 in Fig. 2(a)). The fire resistance ratings used are those of the code-compliant Option 3 shown in Table 1, and all other inputs are as stated earlier. The simulation time for all the scenarios is 1800 s, with a time step of 2 s.

4. Results and discussion

4.1. Fire and smoke

Figure 5 illustrates the fire conditions in compartments when the fire is originated in the living room R11 on the 2nd floor. For this case it was assumed that there are no fire protection measures such as sprinklers or fire department. Doors inside the fire apartment are all 50% open, thus smoke can spread from the living room to bedrooms, bathroom and kitchen through the doors, which measure 0.9 m wide by 2 m high.

![Fig. 5. Fire conditions in the fire origin apartment; fire origin room: R11. (a) CO concentration vs. time; (b), radiation vs. time; (c), smoke layer temperature vs. time; (d), occupant evacuation time vs. occupant ID.](image)

Figure 5(a) shows smoke layer temperatures, which reach more than 900 °C in the fire origin room and as high as 400 °C in other rooms in the same apartment. The heat release rate and radiation in the fire origin room are shown in Fig. 5(b). This graph shows that the heat release rate of the fire starts to decrease at around 400 s because oxygen in the room is insufficient to support continuous combustion. At about 900 s, however, it starts to increase due to the window breaking (300 °C), and then it remains steady. The variation of radiation, temperature and smoke layer interface height and level of CO also confirm this point, and indicate the transition from fuel controlled fire to ventilation controlled fire limited by opening conditions, e.g. doors and windows. CO concentrations and smoke layer interface heights are shown in Fig. 5(c).

Figure 5(d) provides an evacuation time comparison of a fire scenario and fire drill mode. For the fire scenario, fire starts in room R21 without any operation of fire protection measures such as detectors, alarms or fire department. In the fire drill
mode, only the Evacuation sub-model is run, which means there is no fire in the building and all occupants start immediate evacuation with no delay or response time. The occupant evacuation times in fire scenarios are much higher than in fire drill mode, and some occupants even fail to receive fire signals and remain trapped in their original location until the end of the simulation. This graph demonstrates the integrated effects of response time and fire conditions in compartments on occupant evacuation.

4.2. Fire spread

Five fire resistance rating options are compared as shown in Table 1. Option 3 is code-compliant with walls 60 minutes, floors/ceilings 90 minutes, and doors 30 minutes. The fire resistance ratings are increased in order from Option 1 to Option 5. Fig. 6 shows the probability of fire spread of all the compartments (considered for fire spread) at the end of the simulation time of 1800 s, when fire starts in the living room (R1) on the first floor with no fire protection systems such as fire department or fire sprinklers. Fig. 6 clearly demonstrates the effect of fire resistance on fire spread showing that a low fire resistance rating produces high probabilities of fire spread and vice versa. For example, fires are only constrained in the fire apartment with Option 5 while spread up to the fourth floor with Option 1. Fire spread across floors is based on floor failure and external flame spread through windows, with the later being dominant in the vertical fire spread process.

![Fig. 6. Probability of fire spread at the end of simulation time of 1800 s with 5 different fire resistance rating options; fire origin room: R1.](image)

4.3. Fire protection options

Figure 7 demonstrates the effects of 4 different options on smoke layer temperature and carbon monoxide concentration. Both the smoke temperature and CO concentration begin to drop after the fire department action or sprinkler operation. Because the fire department action time, which includes notification time, response time and setup time, is generally longer than the sprinklers operation time which is based on fire conditions, the sprinklers operate very early in the fire while fire department action starts to take effect after 510 s.

In addition, fire damages and life risk are compared using eight different fire protection options. The 8 options are, 1) No active systems; 2) Only alarms; 3) Only fire department; 4) Alarms and fire department; 5) Only sprinklers; 6) Sprinklers...
and alarms; 7) Sprinklers and fire department; 8) Fire department, sprinklers and alarms. Fig. 8 shows the results when fire occurred on the 4th floor living room (R31). For those runs it is assumed that all the fire protection measures are 100% reliable, for example, sprinklers will function normally and control the fire. Fig. 8(a) shows that deaths and injuries only occur when there are no fire protection options. From Fig. 8(b) it is found that the fire department arrival can significantly decrease the damages, as Option 3 and Option 4. And when fire sprinklers are installed in the building, the losses are minimized, as Option 5 to Option 8.

![Fig. 8](image)

Fig. 8. (a) Deaths and injuries, and (b) total damages to the building due to 8 different fire protection options; fire origin room: R31.

### 4.4. Design options

The Expected Risk to Life (ERL), Expected Risk of Injury (EROI) and Expected Annual Fire Loss (AFL) for three different design options are shown in Table 2. From the table, the fire performance of 3 design options can be compared. When both the sprinklers and alarms are installed (Option 1) in the building, the fire risk and damages are lower than Option 2 and Option 3. Furthermore, the differences between the results of Option 2 and Option 3 indicate that the ERL and EROI are lower when alarms are available, but the existence of alarms does not affect the level of AFL.

The fire casualty data of recent five years obtained from Office of Fire Marshal in Ontario, Canada [31], are shown in Table 3. It is found that the results of CUrisk are comparable to those data. Interestingly, the death rate (same meaning as ERL) of Option 2 of CUrisk results is very close to the average Ontario fire death rate, but the fire injury rate (same meaning as EROI) is somewhat lower than the Ontario injury rate. It should be noted that the Ontario fire statistics are based on residential units, most of which are actually lower than 6 storeys. Thus, the comparison here may not be completely appropriate.

| Design option # | Sprinklers | Alarms | ERL (per Y.P.)* | EROI (per Y.P.)* | AFL (k$/per Y.) |
|-----------------|------------|--------|-----------------|-----------------|-----------------|
| 1               | Y          | Y      | $3.02 \times 10^{-7}$ | $9.63 \times 10^{-7}$ | 2.7             |
| 2               | N          | Y      | $6.04 \times 10^{-6}$ | $1.93 \times 10^{-5}$ | 27              |
| 3               | N          | N      | $6.04 \times 10^{-5}$ | $2.40 \times 10^{-5}$ | 27              |

*per Y.P. means per year per person

| Year | 2006 | 2007 | 2008 | 2009 | 2010 | Average |
|------|------|------|------|------|------|---------|
| Fire death rate ($\times 10^{-6}$ per Y.P.)* | 5.9  | 6.5  | 6.5  | 5.8  | 5.3  | 6.0     |
| Fire injury rate ($\times 10^{-5}$ per Y.P.)* | 3.254 | 3.414 | 2.628 | 3.664 | 3.348 | 3.262   |
| Ontario population ( million) | 12.2 | 12.8 | 12.9 | 13.1 | 13.2 | 12.84   |

*per Y.P. means per year per person

### 5. Conclusions

As a quantitative fire risk analysis model, CUrisk can effectively predict the fire conditions in a building using a two-zone model. Based on these results, and also the results from the Fire Spread, Building Cost, Occupant Response and Evacuation sub-models, CUrisk can evaluate the fire performance of buildings, not only in terms of performance of fire
protection measures, but also in terms of the expected life risk and fire losses during the building design life. The results of CUrisk may not produce exactly the same values as the fire statistical data, due to the uncertain factors in both CUrisk results and statistical data, however, it can generate Expected Risk to Life comparable to fire statistical data.

Acknowledgements

The authors would like to thank Natural Sciences and Engineering Research Council of Canada (NSERC), FPInnovations and all other sponsors of NEWBuildS network for their funding support of this work, and thanks are also given to all the colleagues who have contributed to the development of CUrisk.

References

[1] SFPE Risk Task Group. 2005. SFPE Engineering Guide to Application of Risk Assessment in Fire Protection Design, Society of Fire Protection Engineers, Bethesda, MD, USA.
[2] Yung, D., 2008. Principles of Fire Risk Assessment in Buildings, John Wiley & Sons, Ltd, United Kingdom.
[3] Hasofer, A. M., Beck, V. R., Bennetts, I. D., 2007. Risk Analysis in Building Fire Safety Engineering, Elsevier Ltd, Oxford, UK.
[4] Beck, V. R., 1991. “Fire Safety System Design using Risk Assessment Models: Developments in Australia,” Fire Safety Science - Proceedings of the 3rd International Symposium, International Association for Fire Safety Science, pp. 45-59.
[5] Magnusson, S. E., 1997. “Risk Assessment,” Fire Safety Science - Proceedings of the 5th International Symposium, International Association for Fire Safety Science, pp. 41-58.
[6] Sekizawa, A., 2005. “Fire Risk Analysis: its Validity and Potential for Application in Fire Safety”. Fire Safety Science - Proceedings of the 8th International Symposium, International Association for Fire Safety Science, pp. 85-100.
[7] Fleischmann, C. M., 2011. “Is Prescription the Future of Performance based Design?” Fire Safety Science - Proceedings of the 10th International Symposium, International Association for Fire Safety Science, pp. 77-94.
[8] ISO 16732-1:2012: Fire safety engineering -- Fire Risk Assessment -- Part 1: General. International Organization for Standardization, Fribourg, Switzerland, 2012.
[9] Beck, V. R., 1997. “Performance-based Fire Engineering Design and its Application in Australia,” Fire Safety Science - Proceedings of the 5th International Symposium, International Association for Fire Safety Science, p. 23.
[10] Hadjisophocleous, G. V., Bénichou, N., Torvi, D. A., Reid, I., 2000. “Evaluating Compliance of Performance-based Designs with Fire Safety Objectives”, Proceedings of the 3rd International Conference on Performance-Based Codes and Fire Safety Design Methods, Lund, Sweden, pp. 307.
[11] Fraser-Mitchell, J. N., 1994. “An Object-oriented Simulation (CRISP II) for Fire Risk Assessment”, Fire Safety Science - Proceedings of the 4th International Symposium, International Association for Fire Safety Science, Ottawa, Canada, pp. 793-804.
[12] Chu, G., Sun, J., 2008. Quantitative Assessment of Building Fire Risk to Life Safety. Risk Analysis 28, p. 615.
[13] Matellini D. B., Wall A. D., Jenkinson I. D., Wang J., Pritchard R., 2011. “Bayesian Network Modelling for Fire Safety Assessment: Part I—a Study of Human Reaction during the Initial Stages of a Dwelling Fire”, In Advances in Safety, Reliability and Risk Management, Ed. Berenguer, Grall and Guedes Soares, Proceeding of 2011 Annual European Safety and Reliability Conference (ESREL), Troyes, France, pp. 626-633.
[14] http://newbuildscanada.ca/
[15] Hadjisophocleous G., Fu, Z., Li, X., 2011. Technical Report on CUrisk: A Fire Risk Analysis Model. Carleton University Internal Report, Ottawa, Canada.
[16] Fu, Z., Hadjisophocleous G., 2001. FIERAsystem Theory Documentation: Smoke Movement Model. Nation Research Council Canada Internal Report, Ottawa, Canada.
[17] Fu, Z., Hadjisophocleous G., 2000. A Two-zone Fire Growth and Smoke Movement Model for Multi-compartment Buildings, Fire Safety Journal 34, p. 257.
[18] Cheng, H., 2010. Modeling of Fire Spread in Buildings and Modeling of Fire Spread from the Fire Building to Adjacent Buildings. Ph.D thesis. Carleton University.
[19] Cheng, H., Hadjisophocleous, G., 2011. Dynamic Modeling of Fire Spread in Building, Fire Safety Journal 46, p. 211.
[20] Proulx, G., and Hadjisophocleous, G., 1994. “Occupant Response Model: A Sub-Model for The NRCC Risk-cost Assessment Model,” Fire Safety Science - Proceedings of the Fourth International Symposium, International Association for Fire Safety Science, pp. 841-852.
[21] Hadjisophocleous, G., Fu. F. 2003. Carleton University Internal Report: Occupant Response Model, Ottawa, Canada.
[22] Gruchy, D., 2004. Modelling Occupant Evacuation during Fire Emergencies in Buildings. M.A. Sc. Thesis. Carleton University.
[23] Esposito, D. C., 2004. Economic Impact of Fires in Buildings. M. A. Sc. thesis. Carleton University.
[24] Karlsson, B., Quintiere, J. G., 2000. Enclosure Fire Dynamics. CRC Press, Washington, D.C., United States, p. 130
[25] Babrauskas, V., 1998. Glass Breakage in Fires, The Fire Place (Washington Chapter IAAI Newsletter), p. 15-18.
[26] The Canadian Commission on Building and Fire Codes, 2010. National Building Code of Canada 2010. National Research Council (Canada), Canada.
[27] Skelly, M. J., Roby, R. J., Beyler, C. L., 1991. An Experimental Investigation of Glass Breakage in Compartment Fires. Journal of Fire Protection Engineering 3, pp. 25-34.
[28] Gaskin, J. and Yung, D., 1993. Canadian and USA Fire Statistics for Use in the Risk-Cost Assessment Model. Institute for Research in Construction, Canada.
[29] Juneja, C. S., 2004. Analysis of Ontario Fires and Reliability of Active Fire Protection Systems, Master of Applied Science Thesis, Department of Civil Engineering, Carleton University, Ottawa, Canada.
[30] Bukowski, R. W., 2002. “Estimates of the Operational Reliability of Fire Protection Systems”, Fire Protection Strategies for 21st Century Building and Fire Codes Symposium. Extended Abstracts. Proceedings. Society of Fire Protection Engineers and American Institute of Architects, Baltimore, MD, pp. 111-124.
[31] http://www.ofm.gov.on.ca/en/Media%20Relations%20and%20Resources/Statistics/default.asp.