Journal of Building Engineering xx (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

# Life risks due to fire in mid- and high-rise, combustible and non-combustible residential buildings

Xia Zhang[a,*], Jim Mehaffey[b], George Hadjisophocleous[a]

[a] Department of Civil and Environmental Engineering, Carleton University, 1125 Colonel By Drive, Ottawa, ON, Canada K1S 5B6
[b] CHM Fire Consultants Ltd., 239 Glebe Avenue, Ottawa, ON, Canada K1S 2C8

ARTICLE INFO

*Keywords:*
Life risk analysis
Fire emergencies
Mid- and high-rise buildings
Residential buildings
Combustible construction
Non-combustible construction

ABSTRACT

CUrisk, a comprehensive model available for assessing fire risks in buildings, is used to assess and compare the life risks due to fires in mid-rise and high-rise residential buildings of non-combustible, light wood frame, and cross laminated timber constructions. The non-combustible buildings and some of the light wood frame buildings are explicitly code compliant designs, while some of the light wood frame buildings and the cross laminated timber buildings are alternative solutions. The computation results show that, the life risks of the simulated buildings are very low due to the installation of sprinkler systems and the risks are limited to the occupants in the rooms of fire origin. The effects of building area and storeys on life risk are minor. However, the area of the room of fire origin affects life risk significantly. Properly designed and protected combustible buildings do not impose higher life risk to occupants than non-combustible buildings. Life safety performance of buildings depends more on the design solutions as a whole rather than the selection of the construction type.

## 1. Introduction

Prescriptive building codes are undergoing transition to performance or objective based codes in many countries. Provisions provided within performance or objective based codes [1] are deemed to be acceptable solutions. Meanwhile, alternative solutions are permitted if they are demonstrated to provide performance equivalent to or better than that of the replaced provision. However, not all proposed buildings can be supported through the codified alternative solution route. For example, the height and area of increasingly desired mid- and high-rise wood buildings in Canada are beyond the limits for combustible buildings permitted by the National Building Code of Canada (NBCC) [1] and the Building Code of British Columbia (BCBC) [2]. To aid in the design and approval of such buildings, FPInnovations recommended in the Technical Guide for the Design and Construction of Tall Wood Buildings in Canada [3], to use fire risk assessment in the development of alternative solutions to demonstrate quantitatively that fire risks produced by alternative solutions are not greater than those associated with the acceptable solutions given in codes.

The effects of construction on fire risk can be due to different fire spread probabilities and fire development characteristics. Type of construction can affect fire development through different heat release contributions made by different construction elements, and different heat losses to wall, floor and ceiling assemblies and walls as a result of different thermal conductivities of these elements.

Unfortunately, quantitative methods for comparing fire risks of the alternative solutions with those of the acceptable solution are not included in codes. While the general principles of fire risk analysis have been contained in guidelines offered by NFPA [4] and SFPE [5], specific details or examples are still not available. CUrisk [6], a comprehensive model developed at Carleton University for assessing fire risk in buildings, can compute fire risk including life risk in buildings and consider the effects of construction on fire risk.

In this paper, CUrisk is used to assess and compare the life risks due to fires in mid-rise and high-rise residential buildings of combustible and non-combustible construction.

## 2. Brief description of the fire risk analysis model CUrisk

CUrisk is a comprehensive fire risk analysis computer model. The model consists of a number of sub-models: system, scenario generation, fire growth and smoke movement, occupant response, fire spread, occupant evacuation and life risk analysis. It predicts two performance parameters that can be used for decision making: expected life risk and fire cost expectation. The expected life risk of any alternative design can be compared to that of a code compliant design to determine the acceptability of the alternative solution, and the fire cost expectation can be used to identify cost effective designs.

* Corresponding author.
*E-mail addresses:* xia.zhang@carleton.ca (X. Zhang), jim.mehaffey@gmail.com (J. Mehaffey), george.hadjisophocleous@carleton.ca (G. Hadjisophocleous).

http://dx.doi.org/10.1016/j.jobe.2016.11.001
Received 22 December 2015; Received in revised form 1 November 2016; Accepted 2 November 2016
Available online xxxx
2352-7102/

The system sub-model controls the operation of the model and outputs the final results based on the intermediate results produced by other sub-models. The scenario generation sub-model converts the user defined scenarios, which are combinations of fire and active and passive fire protection systems of a building, to the format that other sub-models can handle to meet the need for automatic multi-scenario calculation. The fire growth and smoke movement sub-model uses a two-zone approach to predict the hazardous conditions in both zones of each compartment of the building [7–9]. The occupant response sub-model produces the probabilities of occupants starting evacuation to respond to the perception of fire signals and warnings from fire protection systems, other occupants and the fire department [10]. The probabilities are different for occupants in different compartments as the fire signals and warnings they receive are different.

After the occupant response sub-model, Monte Carlo runs are repeated for three sub-models: fire spread, occupant evacuation and life risk analysis. In each Monte Carlo run, the fire spread sub-model calculates the probability of fire spread from the room of fire origin to other rooms [11]. The occupant evacuation sub-model predicts the evacuation process for each occupant, considering the hazardous conditions produced by the fire growth and smoke movement sub-model and the probabilities that occupants start evacuation produced by the occupant response sub-model [12]. The life risk analysis sub-model produces the numbers of injuries and deaths in a fire, based on the fire spread probability produced by the fire spread sub-model, the radiant heat intensity, temperature of hot gases and concentrations of toxic gases produced by the fire growth and smoke movement sub-model, and the evacuation path of each occupant produced by the occupant evacuation sub-model [6].

According to the average numbers of injuries, deaths or casualties of all Monte Carlo runs for a scenario and the scenario composition of a case, the expected risk *ER* of injury, death or casualty of the case can be calculated by using

$$ER = \frac{\sum_{i=1}^{N_S} p_i C_i}{\sum_{i=1}^{N_S} p_i} \quad (1)$$

where $N_S$ is the number of scenarios, $p_i$ the probability of scenario $i$, $C_i$ the consequence, average number of injuries, deaths or casualties, of scenario $i$. All consequences and expected risk are given in persons/fire.

The expected risk of injury, death or casualty of any alternative solution can be compared with that of a code compliant design to determine the acceptability of the solution.

## 3. Buildings and alternative solutions

Six-storey residential buildings of combustible construction are currently permitted by the BCBC [2] and are expected to be permitted by the NBCC 2015. They are typically built of light-frame construction in British Columbia with a maximum permitted building area of 1200 m$^2$. They can also be built of mass timber elements such as glulam beams and columns, and cross laminated timber (CLT) floors and walls. For 6-storey residential buildings of non-combustible construction, the maximum permitted area is 6000 m$^2$.

12-storey residential buildings are required by the NBCC [1] and the BCBC [2] to be of non-combustible construction and are permitted to have an unlimited building area. If built, 12-storey residential buildings of combustible construction would be built of mass timber elements such as glulam beams and columns, and CLT floors and walls.

All of these buildings are required to be sprinklered and to have a maximum travel distance of 45 m from a suite door to an exit, whether they are combustible or non-combustible, 6-storey or 12-storey.

According to these requirements and other code requirements not detailed here, three building layouts were designed. The layouts of the first floors are shown in Figs. 1–3. The other storeys of the buildings have the same plans as the first floors except that staircases on other

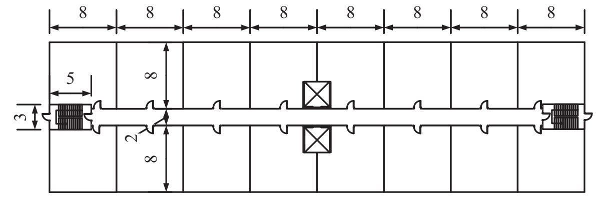


**Fig. 1.** Layout of the first storey of small-area (1152 m$^2$) 6-storey building (small building).

floors have no exits to outside. The 6-storey small-area (1152 m$^2$) building in Fig. 1, the 6-storey large-area (1728 m$^2$) building and the 12-storey large-area (1728 m$^2$) building in Fig. 2 and the 6-storey large-area (1728 m$^2$) building in Fig. 3 are called small, large I, high and large II buildings hereafter for brevity.

For the small, large I and large II buildings, life risks are calculated for non-combustible (NC), light wood frame (LWF) and cross laminated timber (CLT) constructions, and CLT construction with higher reliability sprinklers (CLT-HRS). In the 12 combinations, the small LWF and all NC buildings are explicitly code compliant while the others are alternative solutions. All of these buildings have public doors with fire protection rating of 45 min, suite doors with fire protection rating of 20 min, and no balconies above windows.

For the high building, life risks are calculated for NC and CLT constructions, CLT construction with higher reliability sprinklers (CLT-HRS), CLT construction with balconies above windows (CLT-BCN), and CLT construction with suite doors with fire protection rating of 45 min (CLT-SD45). The NC building is explicitly code compliant and the CLT buildings are alternative solutions. These buildings have public doors with a fire protection rating of 1.5 h, suite doors with fire protection rating of 20 min, and no balconies above windows, unless otherwise specified.

The configurations and fire resistance ratings of the floor and ceiling assemblies and walls of these buildings are summarised in Table 1. In the buildings of non-combustible construction, columns and beams of reinforced concrete provide load-bearing capacity together with the ceiling and floor assemblies. The configurations containing CLT are based on the fire resistance tests performed by National Research Council Canada [13], and other configurations are from NBCC [1] or BCBC [2]. RGB, NLB, and LB in the table denote regular gypsum board, non-loadbearing and loadbearing.

Each suite of the buildings has 3 windows. Partitions inside the suite are neglected for simplicity. This will produce conservative results. The window sizes of the 8 m×8 m suites are 1.5 m×1.5 m and those of the 12 m×8 m suites are 1.5 m×2.25 m, producing the same ratio of opening area to floor area for all suites. The door of each suite and corridor has a width of 0.8 m and a height of 2.03 m. The windows and doors have an initial leakage fraction of 0.15.

For all the buildings, the central alarm is available and connected to the fire department. Sprinklers, smoke alarms and smoke detectors are designed to be present in suites and public corridors, in suites, and in public corridors and exit stair shafts, respectively. The temperature rating and response time index of sprinklers and maximum distance between adjacent sprinklers are taken as 57 °C, 50 m$^{1/2}$ s$^{1/2}$ and 4 m according to NFPA 13 [14].

The number of occupants in each building is the maximum permitted by the codes. Each 8 m×8 m suite has 4 occupants and 12 m×8 m suite has 6 occupants. Occupants are assumed to be healthy and consisting of half adults and half seniors.

The characteristics of all cases are summarised in Table 2. More details are given elsewhere [15].

## 4. Scenarios and case descriptions

The scenarios for each building include the combinations of the

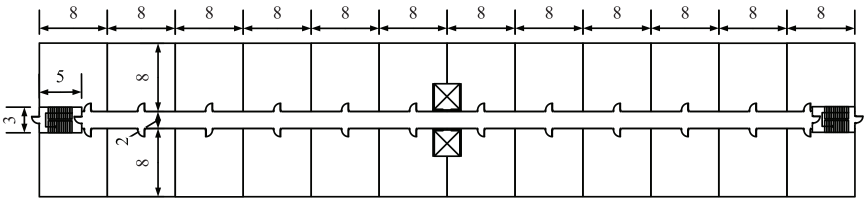

**Fig. 2.** Layout of the first storey of the large-area (1728 m$^2$) 6- and 12-storey buildings (large I and high buildings).

ignition time, activation of sprinklers and response times of the fire department. The reliability of smoke alarms, 0.93 [16], is not explicitly considered in the event tree but accounted for in the response sub-model instead. Thus, each case shown in Table 2 has 8 scenarios as shown in Figs. 4 and 5 for cases with normal reliability sprinklers and higher reliability sprinklers. The probabilities of the scenarios are calculated from statistics [17–19]. The reliability of the higher reliability sprinklers is taken as 2% higher than that of the normal reliability sprinklers. The improvement can be realized through more frequent inspections and better maintenance.

The time delay between the fire initiation and the time the fire department starts to suppress the fire includes the notification time and setup time, in addition to the response time shown in the event trees. The notification time is taken as the minimum of the times at which smoke detectors or sprinklers activate or fire is large enough to be perceived by occupants. The setup time of the fire department is taken as 240 s according to statistics [20].

Fire is assumed to happen in a suite on the first floors close to an exit to produce conservative results. The medium $t^2$ fire is assumed based on the observations of full-size bedroom fire tests [21] and recommendations [22,23]. The fuel load in the buildings is taken as 854 MJ/m$^2$, the 90% percentile of the statistical data for all home types because the number of the apartment suites surveyed was only 6 [24].

The minimum and maximum numbers of Monte Carlo runs for the fire spread, evacuation and life risk analysis sub-models are set to be 1000 and 8000 for each scenario. When Monte Carlo runs reach the maximum number or the changes of the mean numbers of injuries and deaths compared to their previous values are both lower than 0.1%, the calculation for a scenario stops and that for next scenario starts.

## 5. Results and discussion

### 5.1. Development of hazardous conditions

The model predicts life risks based on fire spread probabilities, hot gases and concentrations of toxic gases. The buildings with sufficient fire resistance ratings contain fire in the room of fire origin. Compartmentation of the buildings controls the movement of smoke. In the rooms of fire origin, the hazard of toxic gases is much weaker than that of hot gases. Therefore, the computation results show that hot gases are the only hazard leading to life risk for the simulated cases.

Figs. 6–9, Figs. 10–13 and Figs. 14–17 show temperature development for scenarios S4 and S8 for the small, large I, high and large II buildings, for the rooms of fire origin, for the corridors close to the rooms of fire origin, and for the staircases close to the rooms of fire origin. In these scenarios, sprinklers fail to activate. The difference between scenarios S4 and S8 is ignition time, which does not affect fire development while they affect evacuation results.

Hot gases below 120 °C do not endanger occupants because fractional effective dose (FED) due to high temperature is not significant when the temperature is below 120 °C. For the cases that the concentration of toxic gases is also not high enough, the time corresponding to 120 °C is called the available safe evacuation time hereafter. After this time, occupants could be injured or killed as further temperature rise can hurt occupants.

Figs. 6–9 show that, for all layouts, the temperature difference among the rooms of fire origin of different constructions is very small before flashover and increases slightly after flashover. The rooms of fire origin of the small, large I and high buildings have the same available safe evacuation time, 238 s, and the same temperature development due to the same area, while those of the large II buildings have an available safe evacuation time of 274 s and a lower temperature due to the larger area, allowing relatively longer available safe evacuation time.

Fig. 10 shows that, for the corridors of the small buildings, the available safe evacuation times are 1242 s for the LWF and CLT buildings and 1328 s for the NC building.

Fig. 11 shows that, for the corridors of the large I buildings, the available safe evacuation times are 1266 s for the LWF and CLT buildings and 1358 s for the NC building, 24 s and 30 s longer than those for the small buildings. The smoke temperatures are lower than those in the small buildings. These differences are attributable to the different areas of the corridors.

Fig. 12 shows that, for the corridors of the high NC and CLT buildings, the available safe evacuation times and smoke temperatures are the same as for the large I NC and CLT buildings, due to the same layout. For the corridor of the high CLT-D45 building, the available safe evacuation time is 1800 s, about 9 min longer than that of the high CLT building as a result of the fire protection rating of 45 min of the suite doors, 25 min longer than that of the regular doors. The late failure of the door of the room of fire origin results in a lower temperature in the corridor of the CLT-D45 building compared to that of the CLT building.

Fig. 13 shows that, for the corridors of the large II buildings, the available evacuation times are 1404 s for the LWF and CLT buildings and 1494 s for the NC building, 138 s and 136 s longer than for the large I buildings. The smoke temperatures are lower than those in the large I buildings. These differences are due to the lower temperatures in the rooms of fire origin of the large II buildings, which is resulted from the larger areas of the rooms of fire origin.

The life risk due to fire is determined by the exposure dosage and depends on exposure time and intensity of the fire conditions. The corridors in the large I and high buildings provide slightly longer available safe evacuation times and lower temperatures compared to

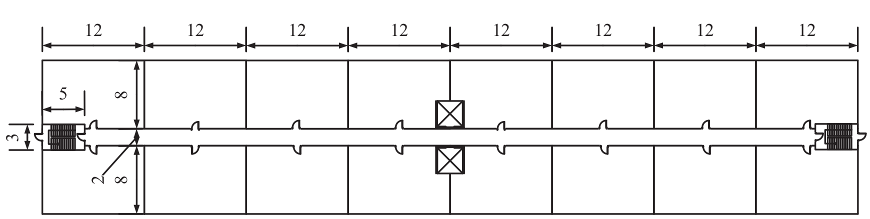

**Fig. 3.** Layout of the first storey of the large-area (1728 m$^2$), 6-storey building (large II building).

**Table 1**
Configurations and fire resistance ratings of floor and ceiling assemblies and walls.

| Construction/Storeys | Floor and ceiling assemblies | Staircase walls | Exterior walls | Corridor walls | Walls between suites |
|---|---|---|---|---|---|
| Non-combustible/6 | F1c<br>1 h LB | S14a<br>1 h NLB | S10a<br>1 h NLB | S14a<br>1 h NLB | S6e<br>1 h NLB |
| Light wood frame/6 | F10f<br>1 h LB | W6d<br>1 h LB | EW1a with 38 mm×140 mm studs<br>1 h LB | W6d<br>1 h LB | W6d with 38 mm×140 mm studs<br>1 h NLB |
| Cross laminated timber/6 | 12.7 mm RGB +105 mm CLT<br>1 h LB | 12.7 mm RGB+105 mm CLT+12.7 mm RGB<br>1 h LB | 105 mm CLT+12.7 mm RGB<br>1 h LB | 12.7 mm RGB+105 mm CLT +12.7 mm RGB<br>1 h LB | W6d with 38 mm×140 mm studs<br>1 h NLB |
| Non-combustible/12 | F1b<br>2 h LB | S6a<br>2 h NLB | S2d<br>1 h NLB | S6e<br>1 h NLB | S6e<br>1 h NLB |
| Cross laminated timber/12 | 12.7 mm RGB +175 mm CLT<br>2 h LB | 12.7 mm RGB+175 mm CLT+12.7 mm RGB<br>2 h LB | EW1a with 38 mm×140 mm studs<br>1 h NLB | W6d with 38 mm×140 mm studs<br>1 h NLB | 12.7 mm RGB+175 mm CLT +12.7 mm RGB<br>2 h LB |

that in the small buildings, indicating a better safety margin, which could be counteracted by the longer travel times. The corridors of the large II buildings have the longest available safe evacuation times and lowest temperatures among all the buildings and provide the best safety margin. However, the effect of corridors on life risk is not obvious because the hazard of smoke in the corridors is much lower than that in the rooms of fire origin due to the much lower temperatures and toxic gas concentrations.

Figs. 14–17 show that the temperatures in the staircases are always lower than 120 °C for all the four buildings, regardless of construction type. Therefore, occupants on the floors different from the rooms of fire origin will not be endangered by the fire.

Similar analysis can be made for scenarios S3 and S7, which are different from scenarios S4 and S8 in the response time of the fire department.

Figs. 18–21 show temperature development in the rooms of fire origin for scenarios S2 and S6 for the small, large I, high, and large II buildings. The temperatures in the rooms of fire origin in these scenarios are always lower than 120 °C, and those in the corridors and staircases are even lower. These temperatures are much lower than those of scenarios S3, S4, S7 and S8 because of the activation of sprinklers. For scenarios S1 and S5, a similar temperature development was predicted. No injuries or deaths are expected for these scenarios.

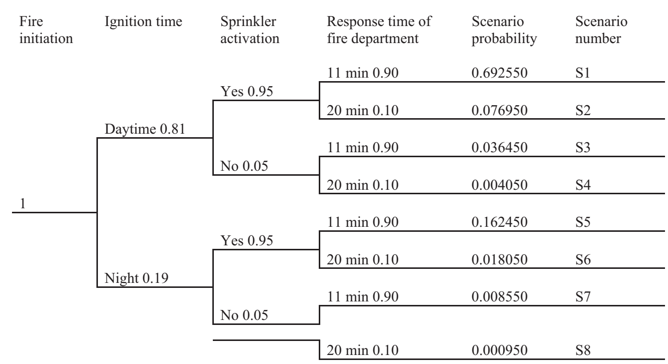


**Fig. 4.** Event tree for the cases with normal reliability sprinklers.

### 5.2. Occupant evacuation

Figs. 22–26 show the maximum and minimum remaining occupants as a percentage of the total occupants in the evacuation processes in all Monte Carlo runs for night scenario S8 for the small NC, LWF and CLT buildings and those for daytime scenario S4 and night scenario S8 for the small, large I, high, and large II NC buildings. The range between the minimum and maximum remaining occupants reflects the randomness of the evacuation processes produced by the Monte Carlo simulations.

All evacuation processes consist of three stages. In the first stage, occupants in the room of fire origin evacuate and the evacuation rate is

**Table 2**
Characteristics of cases.

| No. | Layout | Construction | Building area (m×m) | Suite size (m×m) | Size of 3 windows (m×m) | Suites | Occupants | Fire protection rating of public doors | Fire protection rating of suite doors | Balconies | Reliability of sprinklers |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Small | NC | 18×64 | 8×8 | 1.5×1.5 | 96 | 384 | 45 min | 20 min | No | Regular |
| 2 | Small | LWF | 18×64 | 8×8 | 1.5×1.5 | 96 | 384 | 45 min | 20 min | No | Regular |
| 3 | Small | CLT | 18×64 | 8×8 | 1.5×1.5 | 96 | 384 | 45 min | 20 min | No | Regular |
| 4 | Small | CLT-HRS | 18×64 | 8×8 | 1.5×1.5 | 96 | 384 | 45 min | 20 min | No | High |
| 5 | Large I | NC | 18×96 | 8×8 | 1.5×1.5 | 144 | 576 | 45 min | 20 min | No | Regular |
| 6 | Large I | LWF | 18×96 | 8×8 | 1.5×1.5 | 144 | 576 | 45 min | 20 min | No | Regular |
| 7 | Large I | CLT | 18×96 | 8×8 | 1.5×1.5 | 144 | 576 | 45 min | 20 min | No | Regular |
| 8 | Large I | CLT-HRS | 18×96 | 8×8 | 1.5×1.5 | 144 | 576 | 45 min | 20 min | No | High |
| 9 | High | NC | 18×96 | 8×8 | 1.5×1.5 | 288 | 1152 | 1.5 h | 20 min | No | Regular |
| 10 | High | CLT | 18×96 | 8×8 | 1.5×1.5 | 288 | 1152 | 1.5 h | 20 min | No | Regular |
| 11 | High | CLT-SD45 | 18×96 | 8×8 | 1.5×1.5 | 288 | 1152 | 1.5 h | 45 min | No | Regular |
| 12 | High | CLT-BCN | 18×96 | 8×8 | 1.5×1.5 | 288 | 1152 | 1.5 h | 20 min | Yes | Regular |
| 13 | High | CLT-HRS | 18×96 | 8×8 | 1.5×1.5 | 288 | 1152 | 1.5 h | 20 min | No | High |
| 14 | Large II | NC | 18×96 | 8×12 | 1.5×2.25 | 96 | 576 | 45 min | 20 min | No | Regular |
| 15 | Large II | LWF | 18×96 | 8×12 | 1.5×2.25 | 96 | 576 | 45 min | 20 min | No | Regular |
| 16 | Large II | CLT | 18×96 | 8×12 | 1.5×2.25 | 96 | 576 | 45 min | 20 min | No | Regular |
| 17 | Large II | CLT-HRS | 18×96 | 8×12 | 1.5×2.25 | 96 | 576 | 45 min | 20 min | No | High |

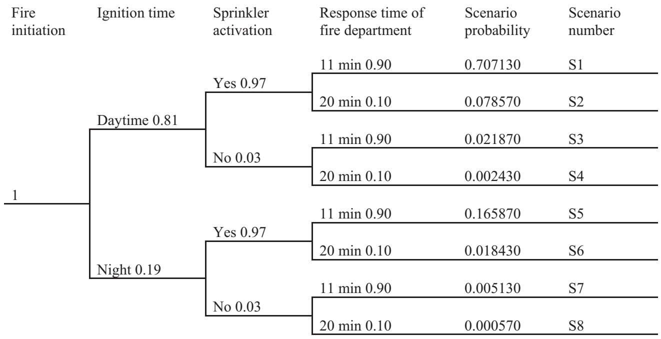


**Fig. 5.** Event tree for the cases with higher reliability sprinklers.

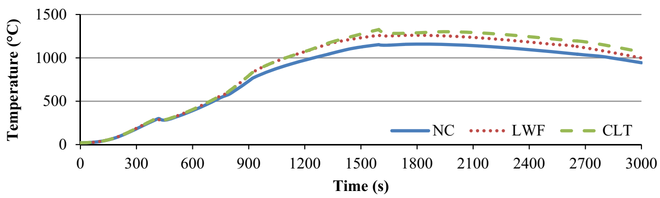


**Fig. 6.** Upper layer temperatures in rooms of fire origin for scenarios S4 and S8 for the small buildings.

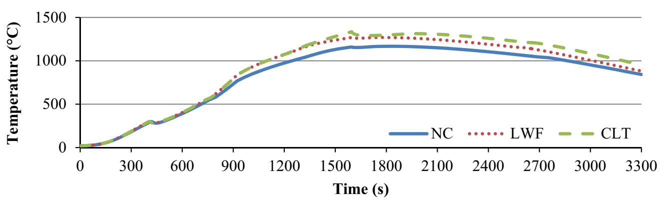


**Fig. 7.** Upper layer temperatures in rooms of fire origin for scenarios S4 and S8 for the large I buildings.

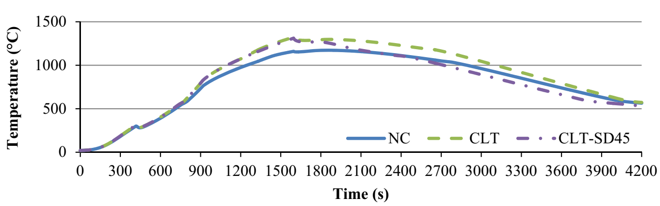


**Fig. 8.** Upper layer temperatures in rooms of fire origin for scenarios S4 and S8 for the high buildings.

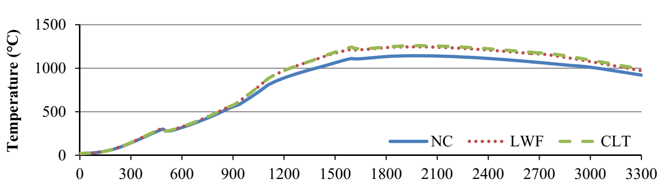


**Fig. 9.** Upper layer temperatures in rooms of fire origin for scenarios S4 and S8 for the large II buildings.

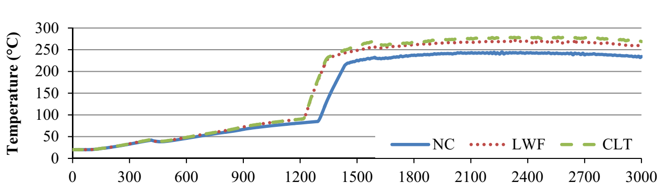


**Fig. 10.** Upper layer temperatures in corridors close to the rooms of fire origin for scenarios S4 and S8 for the small buildings.

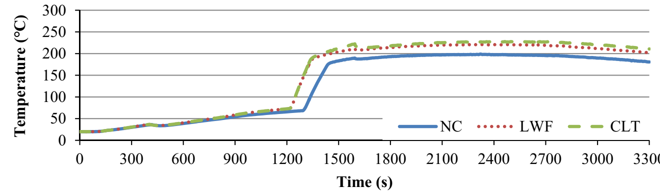


**Fig. 11.** Upper layer temperatures in corridors close to the rooms of fire origin for scenarios S4 and S8 for the large I buildings.

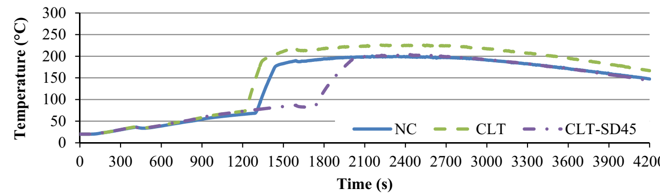


**Fig. 12.** Upper layer temperatures in corridors close to the rooms of fire origin for scenarios S4 and S8 for the high buildings.

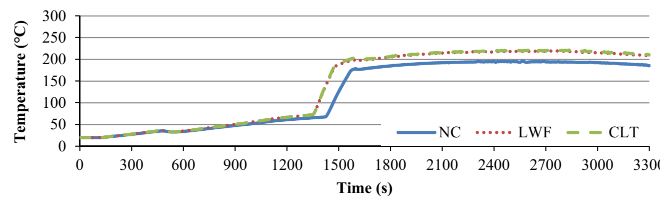


**Fig. 13.** Upper layer temperatures in corridors close to the rooms of fire origin for scenarios S4 and S8 for the large II buildings.

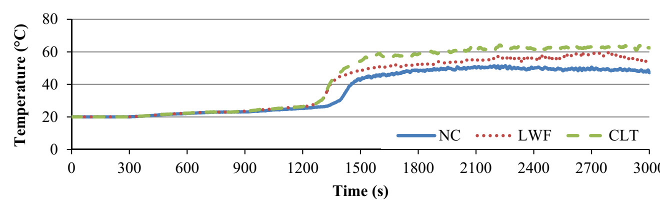


**Fig. 14.** Upper layer temperatures in staircases close to the rooms of fire origin for scenarios S4 and S8 for the small buildings.

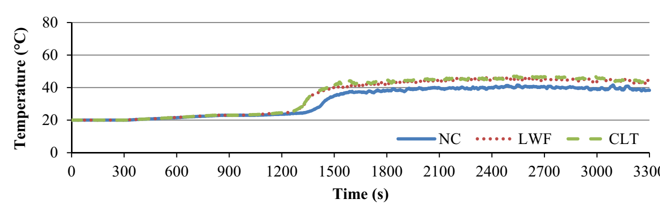


**Fig. 15.** Upper layer temperatures in staircases close to the rooms of fire origin for scenarios S4 and S8 for the large I buildings.

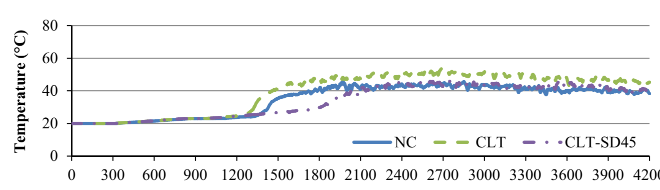


**Fig. 16.** Upper layer temperatures in staircases close to the rooms of fire origin for scenarios S4 and S8 for the high buildings.

governed by the response times and travel speeds of these occupants. In the second stage, occupants with normal response time and travel speed evacuate and the evacuation rate is governed by the maximum traffic capacities of exits. In the third stage, occupants with longer response time and slower travel speeds evacuate and the evacuation

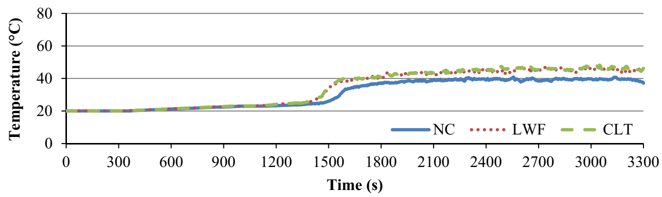


**Fig. 17.** Upper layer temperatures in staircases close to the rooms of fire origin for scenarios S4 and S8 for the large II buildings.

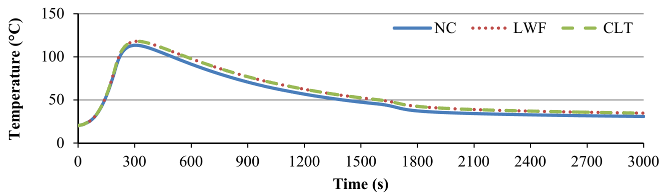


**Fig. 18.** Upper layer temperatures in rooms of fire origin for scenarios S2 and S6 for the small buildings.

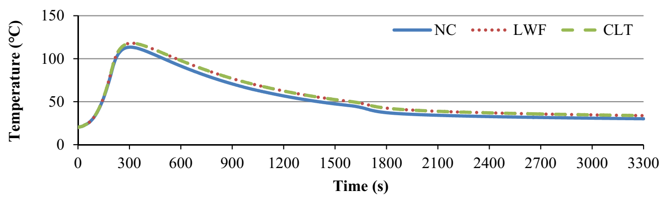


**Fig. 19.** Upper layer temperatures in rooms of fire origin for scenarios S2 and S6 for the large I buildings.

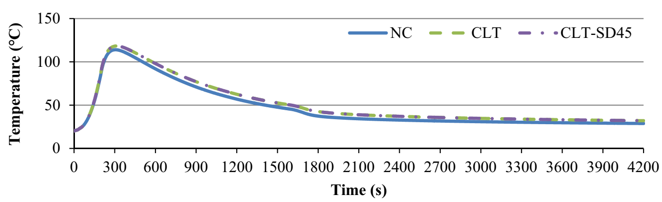


**Fig. 20.** Upper layer temperatures in rooms of fire origin for scenarios S2 and S6 for the high buildings.

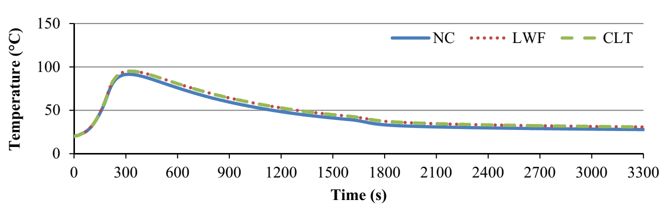


**Fig. 21.** Upper layer temperatures in rooms of fire origin for scenarios S2 and S6 for the large II buildings.

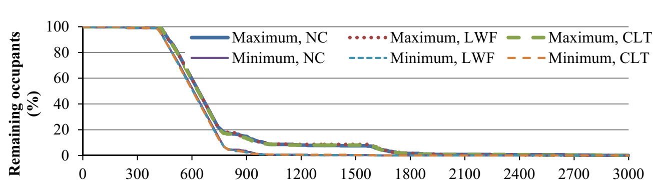


**Fig. 22.** Maximum and minimum remaining occupants as a percentage of total occupants for scenario S8 for the small buildings.

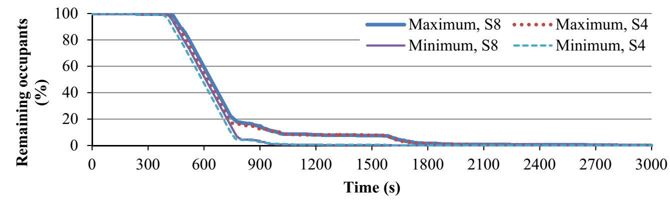


**Fig. 23.** Maximum and minimum remaining occupants as a percentage of total occupants for scenarios S4 and S8 for the small NC building.

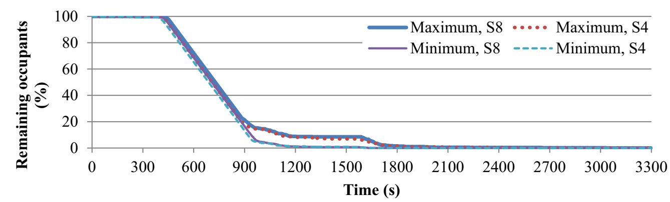


**Fig. 24.** Maximum and minimum remaining occupants as a percentage of total occupants for scenarios S4 and S8 for the large I NC building.

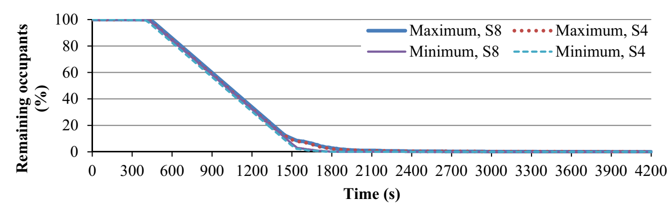


**Fig. 25.** Maximum and minimum remaining occupants as a percentage of total occupants for scenarios S4 and S8 for the high NC building.

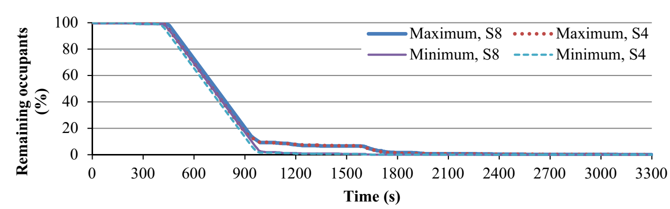


**Fig. 26.** Maximum and minimum remaining occupants as a percentage of total occupants for scenarios S4 and S8 for the large II NC building.

rate is significantly slower and more scattered compared to that of the second stage.

Fig. 22 shows that the time at which 90% of occupants evacuate the buildings is 994 s. The maximum and minimum remaining occupants change very slightly with the construction type due to the similar fire development and occupant distribution in the three buildings. Therefore, the discussion about evacuation will be limited to the NC buildings.

Fig. 23 compares the maximum and minimum remaining occupants for the daytime scenario S4 and night scenario S8 for the small NC building. The time at which 90% of occupants evacuate the building for the daytime scenario S4 is 1006 s, similar to that for the night scenario S8. The similarity is a result of the dominant role of smoke alarms in both scenarios.

Fig. 24 compares the maximum and minimum remaining occupants for the daytime scenario S4 and night scenario S8 for the large I NC building. The evacuation process for the large I NC building is longer than for the small NC building due to the high occupant load. For scenarios S4 and S8, the times at which 90% of occupants evacuate the building are 1106 s and 1148 s, 100 s and 154 s longer than for the small NC building.

Fig. 25 compares the maximum and minimum remaining occupants for the daytime scenario S4 and night scenario S8 for the high NC building. The evacuation process for the high building is longer than that for the large I building. For scenarios S4 and S8, the times at which 90% of occupants evacuate the buildings are 1484 s and 1502 s, 378 s and 354 s longer than for the large I building due to the higher occupant load.

Fig. 26 compares the maximum and minimum remaining occu-

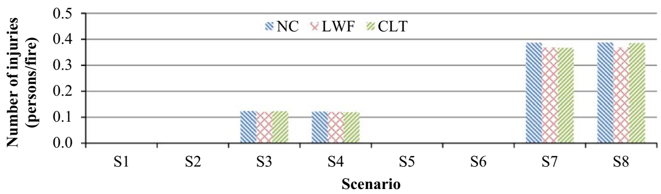


**Fig. 27.** Average number of injuries in the small buildings.

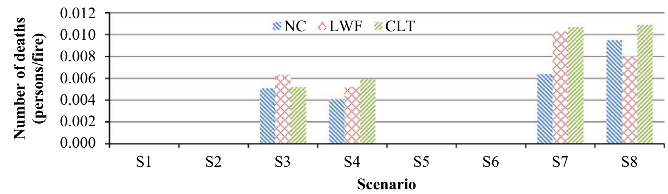


**Fig. 29.** Average number of deaths in the small buildings.

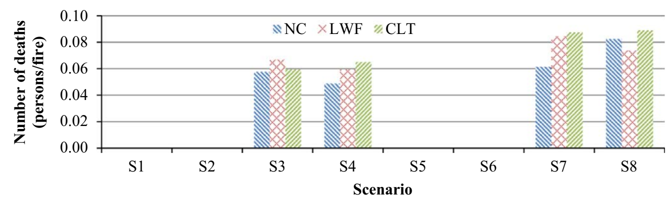


**Fig. 30.** Standard deviation of deaths in the small buildings.

pants for the daytime scenario S4 and night scenario S8 for the large II NC building. For scenarios S4 and S8, the times at which 90% of occupants evacuate the buildings are 976 s and 982 s, 130 s and 166 s shorter than for the large I building, due to the higher probability of occupants starting evacuation as a result of higher occupant load in each suite especially in the room of fire origin. The higher probabilities are produced by the occupant response sub-model [10], which assumes that the action probabilities of occupants in a compartment are the unions of the independent action probabilities of all occupants in the compartment.

Evacuation results for more combinations of scenarios and buildings are not given here for simplicity.

### *5.3. Life risk of scenarios*

Figs. 27–30 show the average numbers and standard deviations of injuries and deaths for different scenarios for the small buildings. For the scenarios with injuries and deaths, the average numbers of deaths are much lower than those of injuries. The standard deviations are on the same order of magnitude as or one order of magnitude higher than the average values for injuries and deaths, respectively. These indicate that death occurs in much fewer fires than injury and the fluctuation of the numbers of deaths is much stronger than those of injuries. In order to avoid misunderstanding incurred by the fluctuation of deaths, life risk is given in the number of casualties, which is the sum of the numbers of injuries and deaths.

Figs. 31–34 show the average numbers of casualties for different scenarios for the small, large I, high, and large II buildings. The effect of the building area and storeys on the number of casualties is small as seen by comparing the numbers of casualties for the small, large I and high buildings. This is because injury and death are limited to the occupants in the rooms of fire origin for the simulated cases. Due to the same reason, the area of the room of fire origin does affect the number of casualties significantly, which is seen by comparing the numbers of casualties for the large II and the other buildings. The numbers of casualties in the large rooms are smaller than those in the small rooms because the temperature and toxic gas concentrations in the large rooms are lower than in the small rooms.

A comparison between the results of different scenarios shows that sprinklers can make a large difference. For the scenarios with activated sprinklers (S1, S2, S5 and S6), no casualty is predicted as a result of fire suppression. This is in good agreement with the statistics for 2006–2010 US home (including apartments) fires that the presence of sprinklers cuts the fire death rate by 83%, from 0.0073 persons/fire to 0.0013 persons/fire [19].

The numbers of casualties for the daytime scenarios S3 and S4 and night scenarios S7 and S8 are of the same order of magnitude as the

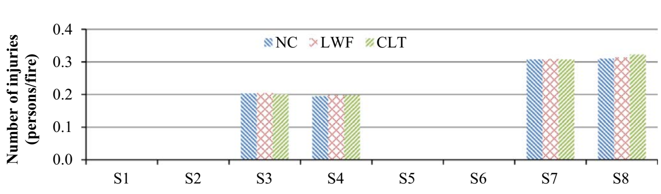


**Fig. 28.** Standard deviation of injuries in the small buildings.

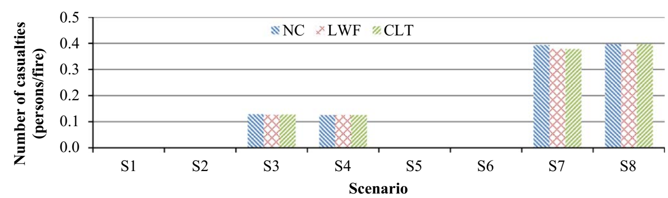


**Fig. 31.** Average number of casualties in the small buildings.

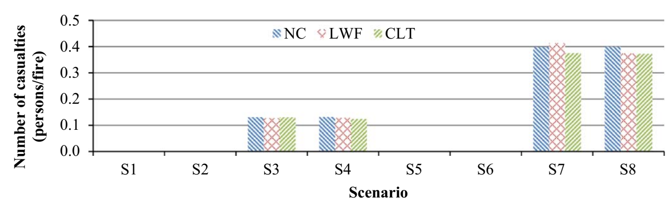


**Fig. 32.** Average number of casualties in the large I buildings.

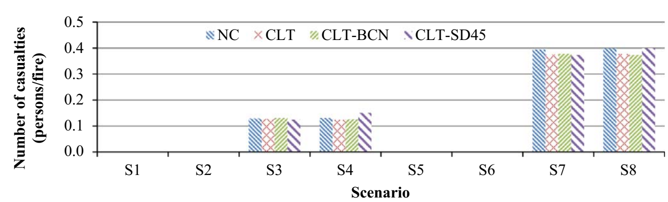


**Fig. 33.** Average number of casualties in the high buildings.

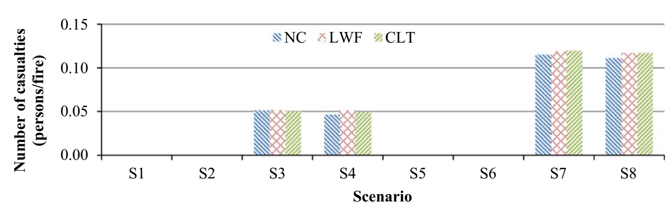


**Fig. 34.** Average number of casualties in the large II buildings.

statistics for 2006–2010 fires of US apartments with smoke alarms [17]. Between the scenarios in the case study and the homes (including apartments) investigated in the statistics, there are slight differences, i.e., sprinklers fail to activate in the scenarios while 4.4% of the homes had activated sprinklers in 2009 [19]. However, this slight difference does not affect the comparison.

Comparisons between scenarios S3 and S4, and S7 and S8 show that the response time of the fire department does not affect the number of casualties, which could be due to the adoption of long response times, 11 and 20 min, in the simulation.

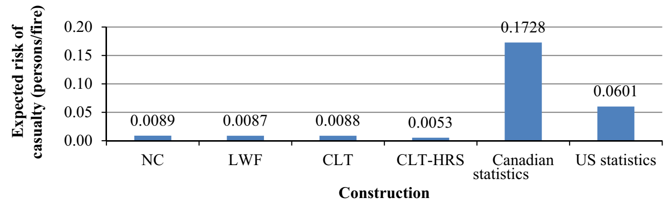


**Fig. 35.** Expected risk of casualty for the small buildings.

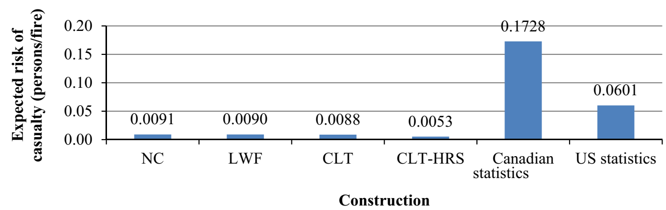


**Fig. 36.** Expected risk of casualty for the large I buildings.

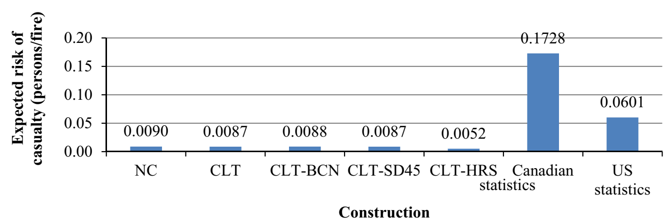


**Fig. 37.** Expected risk of casualty for the high buildings.

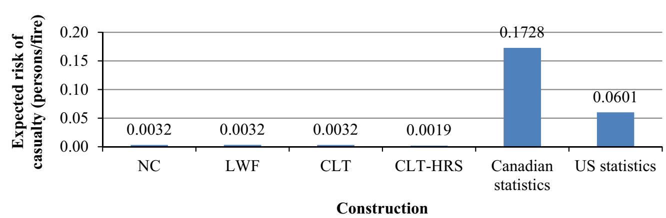


**Fig. 38.** Expected risk of casualty for the large II buildings.

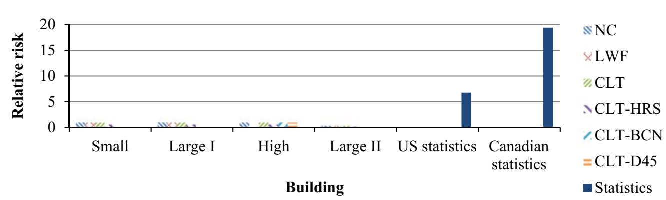


**Fig. 39.** Relative risk of casualty for buildings compared to the small non-combustible building.

For each combination of the building and scenario, the numbers of casualties are similar between the different constructions due to the similar fire conditions, occupant distribution, and evacuation process.

### *5.4. Expected life risk*

Figs. 35–38 show the expected risks of casualty for the small, large I, high, and large II buildings. The expected risks of casualty are between 0.0087 persons/fire and 0.0091 persons/ fire for the small, large I and high buildings with normal reliability sprinklers. These values equal to only 5% of the statistics for the 2002 Canadian apartment fires [25], and 15% of the statistics for the 2007–2011 US apartment fires [16]. The expected risks of casualty for the large II buildings with normal reliability sprinklers, 0.0032 persons/fire, are only 37% of those for the small, large I, and high buildings. The significantly lower risks of all the buildings compared to the statistics are due to the adoption of sprinklers in the modelled buildings. When the reliability of sprinklers is improved, the risks are lowered further.

Fig. 39 shows the relative risks of casualty for all buildings compared to the small NC building. The relative risks are from 0.98 to 1.02 for the small, large I, and high buildings with normal reliability sprinklers and 0.35–0.36 for the large II buildings with normal reliability sprinklers, regardless of the construction type, building area and height. This indicates that these variables are not critical factors affecting life risk. Instead, the area of the room of fire origin affects life risk remarkably. The adoption of higher reliability sprinklers reduces life risk further. The relative life risks of these buildings, regardless of normal or high reliability sprinklers, are much lower than the US [16] and Canadian [25] statistics.

The present paper compares the life risks between residential buildings of different constructions. For the same building, performance of fire protection systems significantly affects life risks due to fire. The effects have been addressed elsewhere [26].

## 6. Conclusions

CUrisk, a comprehensive model developed at Carleton University for assessing fire risks in buildings, has been used to assess and compare life risks due to fires in mid-rise and high-rise residential buildings of non-combustible, light wood frame, and cross laminated timber constructions. The non-combustible buildings and some light wood frame buildings are explicitly code compliant designs, while the other light wood frame buildings and the cross laminated timber buildings are alternative solutions.

The computation results show that, life risks of the simulated buildings are very low due to the installation of sprinkler systems. The casualties are limited to occupants in the rooms of fire origin. The effects of building area and storeys on life risk are very small. However, the area of the room of fire origin affects life risk significantly. Properly designed and protected combustible buildings do not impose higher life risk to occupants than non-combustible buildings. Life safety performance of buildings depends more on the design solutions as a whole rather than the selection of construction type.

## Acknowledgements

The financial support of BC Forestry Innovation Investment (FII) through its Wood First Program is gratefully appreciated.

## References

[1] Canadian Commission on Building and Fire Codes, National Building Code of Canada 2010, National Research Council Canada, Ottawa, 2010.
[2] Building and Safety Standards Branch, British Columbia Building Code 2012, Building and Safety Standards Branch, Office of Housing and Construction Standards, Victoria, 2012.
[3] E. Karacabeyli, C. Lum, Technical Guide for the Design and Construction of Tall Wood Buildings in Canada, Special Publicaion SP55E, FPInnovations, Pointe-Claire, 2014.
[4] NFPA, NFPA 551: Guide for the Evaluation of Fire Risk Assessments, 2016 edition, National Fire Protection Association, Quincy, 2016.
[5] SFPE, Engineering Guide: Fire Risk Assessment, Society of Fire Protection Engineers, Bethesda, 2006.
[6] X.Zhang, X.Li, J.Mehaffey, G.Hadjisophocleous, A Probability-based Monte Carlo Life-risk Analysis Model For Fire Emergencies, Fire Safety Journal, 2016 (under minor revision).
[7] Z. Fu, G. Hadjisophocleous, A two-zone fire growth and smoke movement model for multi-compartment buildings, Fire Saf. J. 34 (2000) 257–285.
[8] X. Zhang, G. Hadjisophocleous, An improved two-layer zone model applicable to both pre- and post-flashover fires, Fire Saf. J. 53 (2012) 63–71.
[9] X.Zhang, X.Li, G.Hadjisophocleous, A design fire model for the full process of fire, in: Proceedings of the International Fire Safety Symposium, IFireSS 2015, Coimbra, Portugal, 2015.
[10] X. Zhang, X. Li, G. Hadjisophocleous, A probabilistic occupant response model for fire emergencies, Fire Saf. J. 68 (2014) 41–51.
[11] H. Cheng, G. Hadjisophocleous, Dynamic modeling of fire spread in building, Fire Saf. J. 46 (2011) 211–224.
[12] X. Zhang, X. Li, G. Hadjisophocleous, A probabilistic occupant evacuation model

for fire emergencies using Monte Carlo methods, Fire Saf. J. 58 (2013) 15–24.
[13] National Research Council Canada, Full-scale fire resistance tests on cross-laminated timber [Internet], National Research Council Canada, Ottawa, modified 2013 Feb 20, cited March 27 2015. Available from: ⟨http://www.nrc-cnrc.gc.ca/ci-ic/article/v17n4-4⟩.
[14] NFPA, NFPA 13: Standard for the Installation of Sprinkler Systems, 2013 edition, National Fire Protection Association, Quincy, 2013.
[15] X. Zhang, J. Mehaffey, G. Hadjisophocleous, Case Studies of Risk-to-Life due to Fire in Mid- and High-rise, Combustible and Non-combustible Buildings using CUrisk, Final Report, Carleton University, Ottawa, 2015.
[16] M. Ahrens, Smoke Alarms in U.S. Home Fires, National Fire Protection Association, Quincy, 2014.
[17] M. Ahrens, Home Structure Fires, National Fire Protection Association, Quincy, 2012.
[18] U.S. Fire Administration, National Fire Data Center, Structure fire response times, Topical Fire Research Series 5, 2006, pp. 1–5.
[19] J.R. Hall Jr., U.S. Experience with Sprinklers, National Fire Protection Association, Quincy, 2012.
[20] S.Mailvaganam, D.Yung, M.Prencipe, Ontario Fire Loss Statistics for the Risk-Cost Assessment Model, Internal Report No. 622, National Research Council Canada, Ottawa, 1992.
[21] X. Li, X. Zhang, C. McGregor, G. Hadjisophocleous, Experimental study of combustible and non-combustible construction in a natural fire, Fire Technol. 51 (2015) 1447–1474.
[22] B. Karlsson, J.G. Quintiere, Enclosure Fire Dynamics, CRC Press LLC, New York, 1999.
[23] European Committee for Standardization, EN 1991-1-2:2002 (E) Eurocode 1: Actions on Structures – Part 1–2: General Actions – Actions on Structures Exposed to Fire, European Committee for Standardization, Brussels, 2002.
[24] A.C.Bwalya, M.A.Sultan, N.Bénichou, A Pilot Survey of Fire Loads in Canadian Homes, Research Report No. 159, National Research Council Canada, Ottawa, 2004.
[25] Council of Canadian Fire Marshals and Fire Commissioners, Annual Report 2002: Fire Losses in Canada, Council of Canadian Fire Marshals and Fire Commissioners, Ottawa, 2007.
[26] Xia Zhang, Jim Mehaffey, George Hadjisophocleous, Effects of performance of active fire protection systems on life risks due to fire in a mid-rise residential building, in: Proceedings of the 16th International Conference and Exhibition on Fire Science and Engineering, Interflam 2016, Nr Windsor, UK, 2016.