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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

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A B S T R A C T

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).

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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

$$ER = \frac{\sum_{i=1}^{N_S} p_i C_i}{\sum_{i=1}^{N_S} p_i} \tag{1}$$

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 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.

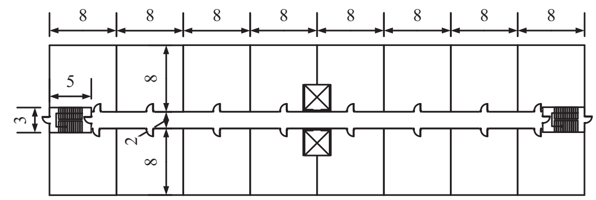

Fig. 1. Layout of the first storey of small-area (1152 m^2) 6-storey building (small building).

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