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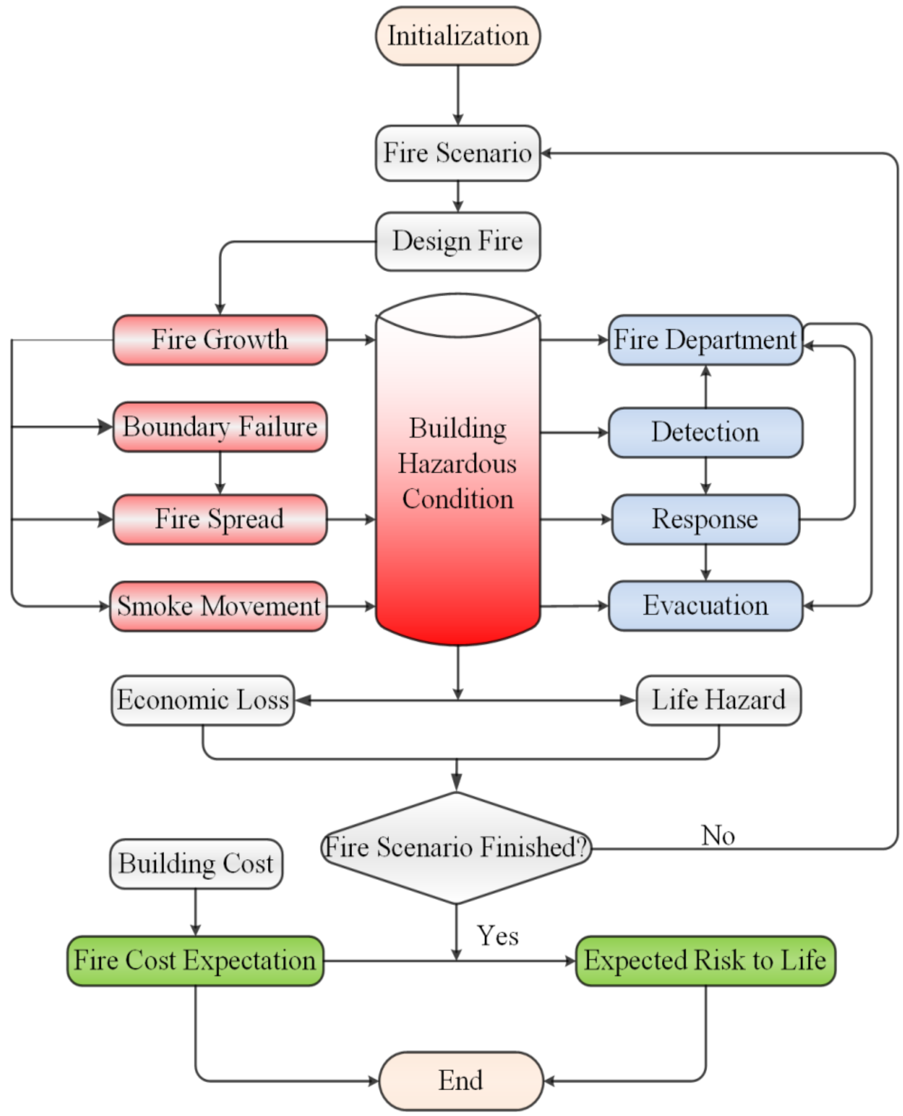
DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

Case Studies of Risk-to-Life due to Fire in Mid- and High-Rise, Combustible and Non-combustible Buildings Using CUrisk



Fire Risk Analysis Model CUrisk

Forestry Innovation Investment
NEWBuildS
FPInnovations FORINTEK
NSERC CRSNG

Case Studies of Risk-to-Life due to Fire in Mid- and High-Rise, Combustible and Non-combustible Buildings Using CUrisk

Final Report

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March 27, 2015

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Executive Summary

Both the BCBC and the NBCC are objective-based codes whose provisions are deemed to be acceptable solutions. Alternative solutions are permitted; however, they must be demonstrated to provide a level of performance equivalent to that of the acceptable solution they are replacing.

There is interest in Canada in constructing tall wood buildings. To aid in the design and approval of such buildings, FPInnovations oversaw the development of a Technical Guide for the Design and Construction of Tall Wood Buildings in Canada. Chapter 5 of the Guide addresses Fire Safety and Protection in tall buildings. Rather than developing site-specific regulations for tall wood buildings, a more robust approach, recommended in Chapter 5 of the Tall Wood Guide, would be to demonstrate quantitatively that the fire safety provisions proposed for the building yield fire risks that are not greater than the fire risks associated with the acceptable solutions of the code.

Unfortunately BCBC and NBCC do not provide a quantitative method for assessing the level of fire safety (or risk-to-life) inherent in the design of a building. However, CUrisk, the most comprehensive model available for assessing the fire risk in buildings, can assess how fire protection measures work together to ensure life safety by computing the risk-to-life due to fire in the building.

In this project, CUrisk was employed to assess and compare the risk-to-life due to fire in mid-rise and high-rise residential and office buildings of wood construction and of non-combustible construction and to demonstrate how fire protection measures can be tuned to ensure a mid-rise or high-rise building of wood construction is as safe as a similar building of non-combustible construction.

The computation results show that:

- For all the compartmented buildings including small-area and large-area 6-storey office and residential buildings and 12-storey residential and compartmented office buildings, life risks of the buildings with different type of construction, areas and heights are very low. In these buildings, life risk is limited to occupants in the fire origin rooms. All deaths and injuries in these buildings are attributable to heat and toxic gases in the fire origin rooms rather than fire spread.
- For the 12-storey open floor concept office buildings, due to uncontrolled smoke movement and very long evacuation time, high concentration toxic gases in the staircases may injure occupants not in the fire origin regions. For this design, the effect of the construction type on the expected risk of injury is insignificant. While the expected risks are similar to those for the compartmented buildings, high occupant load may be an issue. Wider exits can reduce the expected risk of injury significantly.
- Comparisons between the numbers of deaths and injuries of scenarios with and without suitable fire protection systems show the importance of fire protection systems in reducing life risk from fire in all buildings. Sustaining the reliability of fire protection systems through proper design, installation, inspection, and maintenance is important to achieve the life safety objectives.

Based on the CUrisk predictions, the following conclusions are made:

- Life safety performance of buildings depends more on the design solutions as a whole rather than the selection of construction type. Properly designed and protected combustible buildings do not impose higher life risk to occupants than non-combustible buildings.
- In compartmented buildings, casualties are seen in the fire origin room. However, in open floor concept buildings, casualties were also observed in rooms beyond the fire origin region especially for buildings with high occupant load.
- Active protection systems including smoke detectors, smoke alarms, sprinkler systems, and central alarm systems should be designed, installed, inspected, and maintained properly to ensure that they will perform as expected when needed.

Acknowledgements

This project was conducted with financial support from BC Forestry Innovation Investment (FII) through its Wood First program. The development of CUrisk has been supported by FPInnovations, NEWBuildS and NSERC.

1. Introduction

Both the BCBC (BSSB 2012) and the NBCC 2015 (Canadian Codes Centre 2015) are objective-based codes whose provisions are deemed to be acceptable solutions. Objectives and functional statements have been attributed to each acceptable solution. Alternative solutions are permitted; however, they must be demonstrated to provide a level of performance equivalent to that of the acceptable solution they are replacing. The objectives and functional statements attributed to each acceptable solution identify where this equivalency must be demonstrated.

Not all proposed mid-rise wood projects can be supported through the codified alternative solution route. For example, the Wood Innovation Design Centre (WIDC) constructed on the campus of the University of Northern British Columbia in Prince George, BC is a 6-storey multi-use building utilizing innovative wood products such as cross-laminated timber (CLT). A simple alternative solution to the 6-storey combustible construction provisions for residential buildings in the BCBC was out of the question. Instead the Building Safety Standards Branch in BC exempted the project from complying with certain BCBC provisions and substituted site specific regulations in place of those BCBC provisions. There is also interest in Canada in constructing tall wood buildings. In May of 2013, the Canadian Wood Council (CWC) announced the Tall Wood Structure Demonstration Project initiative and issued a request for Expressions of Interest for Canadian design teams to design and build high-rise wood demonstration projects of at least 10-storeys in height with funding support from Natural Resources Canada. To aid in the design and approval of such buildings, FPInnovations oversaw the development of a Technical Guide for the Design and Construction of Tall Wood Buildings in Canada (Karacabeyli and Lum 2014). Chapter 5 of the Guide addresses Fire Safety and Protection in tall buildings. The 1st Edition of the Guide was released early in 2014. The Guide provides design teams with scientifically-supported strategies to address questions that will inevitably arise when designing beyond the height and area limits prescribed by the BCBC or the NBCC.

Rather than developing site-specific regulations for tall wood buildings, a more robust approach, recommended in Chapter 5 of the Tall Wood Guide, would be to demonstrate quantitatively that the fire safety provisions proposed for the building yield fire risks that are not greater than the fire risks associated with the acceptable solutions of the code. That is, the fire risks present in a tall wood building must be demonstrated to be not greater than in a code compliant non-combustible building of similar design. Currently the most comprehensive model available for assessing the fire risk in buildings is CUrisk which has been developed at Carleton University and improved under the NEWBuildS initiative (Li et al. 2015a).

The acceptable solutions spelled out in the BCBC and the NBCC for mid-rise and high-rise buildings entail a suite of fire protection measures addressing the combustibility and fire resistance of structural elements, compartmentalization, fire-stopping, flammability of room linings, fire detection and alarm systems, sprinkler systems, spatial separations, smoke management, and so on. This complete suite of fire protection features is deemed to provide an acceptable level of fire safety. An alternative solution is permitted if it can be shown to provide an equivalent level of fire safety to the acceptable solution.

Unfortunately these codes do not provide a quantitative method for assessing the level of fire safety (or risk-to-life) inherent in the design of a building. However CUrisk can assess how this entire suite of fire protection measures works together to ensure life safety by computing the risk-to-life due to fire in the building. In this project, CUrisk was employed to assess and compare the risk-to-life due to fire in mid-rise and high-rise buildings of wood construction and of non-combustible construction and to demonstrate how the suite of fire protection measures can be tuned to ensure a mid-rise or high-rise building of wood construction is as safe as a similar building of combustible construction.

The Tall Wood Building Guide developed by FPInnovations (Karacabeyli and Lum 2014) recommends, in very general terms, the use of fire risk assessment methods in the development of alternative solutions that would permit the construction of tall wood buildings. However, the Guide does not provide any examples of how this has or can be done, simply because no quantitative examples exist. The application of CUrisk to develop alternative solutions permitting the construction of 12-storey residential and office buildings of combustible construction would provide the needed examples and could be added to Chapter 5 as an appendix.

Furthermore, this project highlights the value of using CUrisk to demonstrate that a proposed alternative solution provides the needed level of fire safety and will thereby encourage the use of the tool by designers wishing to develop alternative solutions permitting combustible construction.

1.1 Project Objectives and Scope

The main objective of this project is to employ CUrisk to compute the risk-to-life from fires in mid-rise (six-storey) and high-rise (twelve-storey) wood and non-combustible residential and office buildings.

Fire safety of six-storey residential occupancies: The BC Building Code currently permits and it is anticipated that the 2015 Edition of the NBCC will also permit construction of six-storey residential buildings of combustible construction. Typically 6-storey residential buildings of combustible construction are being built in BC of light-frame construction. It is, however, possible to build these buildings of mass timber elements such as glulam beams and columns, and CLT floors and walls. CUrisk was employed to assess the risk-to-life due to fire for a code-compliant layout of the following code-compliant 6-storey residential building construction.

1. A BCBC compliant building of light-frame wood construction,
2. A similar layout to 1 but with a structure of mass timber elements, and
3. A larger area, but BCBC compliant building of non-combustible construction

Fire safety of twelve-storey residential occupancies: The BCBC and the NBCC require that a twelve-storey residential building be of non-combustible construction. If built, a twelve-storey residential building of combustible construction would be built of mass timber elements such as glulam beams and columns, and CLT floors and walls. All structural members would have to exhibit a fire resistance rating of 2 hours. CUrisk was employed to assess the risk-to-life due to fire for a typical layout of the following 12-storey residential buildings:

A. As a reference building, a BCBC and NBCC compliant 12-storey building of reinforced concrete with a 2-hour fire resistant structure, 1-hour rated non-loadbearing steel-frame fire separation walls (with 20 minute apartment entrance doors), light hazard sprinkler protection, and no balconies above windows was used.
B. Building with alternative solutions
    a. The same building layout and features as the reference building, but of 2-hour fire rated wood construction with 45 minute apartment entrance doors. (Apartment entrance doors are the weak link for fire and smoke spread).
    b. The same building layout and features as the reference building, but of 2-hour fire rated wood construction with an improved reliability sprinkler system. (Increased sprinkler reliability has been shown to improve life safety).
    c. The same building layout and features as the reference building, but of 2-hour fire rated wood construction with balconies or horizontal projections above all windows. (Balconies or projections are known to reduce upward fire spread from window to window).

Fire safety of six-storey office occupancies: While the BCBC does not permit construction of six-storey office buildings of combustible construction, it is anticipated that the 2015 Edition of the NBCC will. Six-storey office buildings of combustible construction could be built of light-frame wood construction or mass timber elements. CUrisk was employed to assess the risk-to-life due to fire for a typical layout of the following six-storey office buildings:

1. An NBCC 2015 compliant 6-storey building of light-frame wood construction,
2. A similar layout to 1 but with a structure of mass timber elements, and
3. A larger area, but BCBC and NBCC 2015 compliant building of non-combustible construction.

Fire safety of twelve-storey office occupancies: Neither the BCBC nor the NBCC permit construction of twelve-storey office buildings of combustible construction. If built, a twelve-storey office building of combustible construction would be built of mass timber elements such as glulam beams and columns, and CLT floors and walls. All structural members would have to exhibit a fire resistance rating of 2 hours. CUrisk was employed to assess the risk-to-life due to fire for a typical layout of the following 12-storey office buildings:

A. As a reference building a BCBC and NBCC compliant 12-storey building of reinforced concrete, with a 2-hour fire resistant structure, open floor concept, light hazard sprinkler protection, and no window protection.
B. Building with proposed alternative solutions
    a. The same building layout and features as the reference building but with a 2-hour rated mass wood structure and with compartmentation provided by 1-hour rated non-load

bearing wood-frame fire separation walls, (increased compartmentation is known to reduce the spread of fire and smoke),

b. The same building layout and features as the reference building but with a 2-hour rated mass wood structure and additional exit stairs, (additional stairs reduce evacuation times),
c. The same building layout and features as the reference building but with a 2-hour rated mass wood structure and a more reliable sprinkler system, (Increased sprinkler reliability has been shown to improve life safety).
d. The same building layout and features as the reference building but with a 2-hour rated mass wood structure and horizontal projections above all windows, (Horizontal projections are known to reduce upward fire spread from window to window).

1.2 Description of CUrisk

CUrisk is a comprehensive fire risk analysis computer model that consists of a number of sub-models: system, scenario generation, fire spread, fire growth and smoke movement, occupant response, evacuation and life risk analysis. The predictions of the model include two performance parameters which can be used in decision making: the expected risk-to-life; and the fire cost expectation. The expected risk-to-life of any alternative design can be compared to the expected risk-to-life of a code complying design to determine whether the alternative solution is acceptable, while the fire cost expectation is used to determine cost effective designs.

The system sub-model controls the operation of the model, analyses and outputs the final results. The scenario generation sub-model transforms the user defined scenarios to the format that other sub-models can handle. In such a way, multiple scenarios can be performed automatically. The scenarios can be combinations of fire and building descriptions, and active and passive fire protection systems. The fire spread sub-model produces probability of fire spread from the fire origin room to other rooms. The fire growth and smoke movement sub-model predicts the growth of fire and induced smoke movement (Zhang et al. 2012). The results produced by the fire spread, and fire growth and smoke movement sub-models become inputs to the occupant response, evacuation and life safety sub-models. The occupant response sub-model produces the probability of occupants commencing evacuation as a result of response to perception of fire signals and warnings from fire protection systems and other occupants (Zhang et al. 2014).

The probabilities produced by the response sub-model together with the fire and smoke conditions along the evacuation path of each occupant in the form of fire spread probability, radiant heat intensity, temperature of hot gases and concentrations of toxic gases, are then read into the evacuation and life risk analysis sub-models to predict the evacuation process and occupants' life safety. Due to highly random characteristics of human behaviour, the evacuation (Zhang et al. 2013) and life risk analysis sub-models use Monte Carlo methods. In each Monte Carlo run, a number of parameters that cannot be given exactly in a deterministic way vary randomly according to given rules. Random parameters include travel speed, the age and gender of occupants, initial locations of occupants in their room, whether to start evacuation, and door selection in evacuation. Following a large number of Monte Carlo runs, statistical results are produced for parameters like evacuation time, the number of deaths and injuries.

Many of the sub-models have been validated using data available in the literature. The fire growth and smoke movement sub-models have been validated using full-scale fire tests (Zhang et al. 2012). The evacuation sub-model has been compared with data from evacuation tests and from evacuations in real fire emergencies and it was found that it produces results that are in good agreement with the data. The overall risk results of CUrisk for both single family houses (Li et al. 2015b) and mid-rise residential buildings (Li et al. 2013) have been compared to the fire risks in Ontario and the results are in good agreement.

2 Description of Buildings and Alternative Solutions

2.1 Six-Storey Residential Buildings

To comply with the 2012 Edition of the British Columbia Building Code (BCBC) (BSSB 2012), a 6-storey residential building must be sprinklered in conformance with NFPA 13 (NFPA 2013). Table 2.1 provides a summary of the pertinent fire protection requirements governing the construction of a six-storey residential building whose structure exhibits a one-hour fire-resistance rating, whether the building is of combustible, hybrid or non-combustible construction.

Table 2.1 BCBC Fire Safety Requirements for Six-Storey Residential Buildings

Requirement	Combustible or Hybrid Construction	Noncombustible Construction
Maximum Building Area **(maximum single storey area)**	**1,200 m^2** Article 3.2.2.50	**6,000 m^2** Article 3.2.2.48
Structural Fire Resistance Rating **(floors and elements supporting floors)**	**1 hour** Article 3.2.2.50	**1 hour** Article 3.2.2.48
Sprinklers[1] **(Throughout the building)**	**NFPA 13** Article 3.2.2.50	**NFPA 13** Article 3.2.2.48
Fire Resistance Rating of Fire Separations **(Separate apartments from all other spaces)**	**1 hour** Article 3.3.4.2	**1 hour** Article 3.3.4.2
Doors (fire-protection rating)[2] **(between apartment & public corridor)**	**20 minutes** Article 3.1.8.10	**20 minutes** Article 3.1.8.10
Means of Egress **(minimum width of public corridor)**	**1,100 mm** Article 3.3.1.9	**1,100 mm** Article 3.3.1.9
Maximum Travel Distance (Apt Door to Exit) **(Interior stairway considered to be an exit)**	**45 m** Clause 3.4.2.5.(1)(c)	**45 m** Clause 3.4.2.5.(1)(c)
Doors (fire-protection rating)[2] **(between public corridor & exit))**	**45 minutes** Article 3.1.8.8	**45 minutes** Article 3.1.8.8
Flame Spread Ratings **(walls and ceiling within an apartment)**	**150** Sentence 3.1.13.2.(1)	**150** Sentence 3.1.13.2.1(1)
Flame Spread Ratings **(walls and ceiling within a public corridor)**	**150** Sentence 3.1.13.6.(3)	**150** Sentence 3.1.13.6.(3)
Flame Spread Ratings **(walls and ceiling within an exit)**	**25** Table 3.1.13.2	**25** Table 3.1.13.2

1. The sprinkler standard NFPA 13 has additional provisions for buildings of combustible construction compared to provisions for buildings of non-combustible construction, especially for concealed spaces.
2. Doors must be equipped with **a self-closing device** designed to return the door to the closed position after each use (Article 3.1.8.11). Doors must exhibit a *fire-protection rating*, not a *fire-resistance rating*.

From a fire safety perspective, the most significant difference between the BCBC requirements for a six-storey residential building of combustible (or hybrid) construction and one of non-combustible construction is the building area (maximum single storey area). The maximum permitted building area of a six-storey residential building of combustible construction is 1,200 m^2 while the maximum permitted area of a six-storey residential building of non-combustible construction is 6,000 m^2 or five times larger.

In addition to fire safety requirements, there are also acoustic separation requirements in apartment buildings. Whether an apartment building is of combustible, hybrid or non-combustible construction, each apartment must be separated from other apartments and from the public corridor by an assembly that exhibits a sound-transmission coefficient (SDC) of 50 or better (BCBC Article 5.9.1.2).

2.1.1 Small-Area Six-Story Residential Building

Figure 2.1 depicts one storey of a small-area 6-storey residential building that houses 16 apartments each with nominal floor dimensions of 8 m x 8 m. The area of each storey (and hence the building area) is 1,152 m^2. Each apartment is assumed to have 2 bedrooms and hence 4 occupants. Consequently it is assumed that there are 16 x 4 = 64 occupants on each storey and 6 x 64 = 384 occupants in the building.

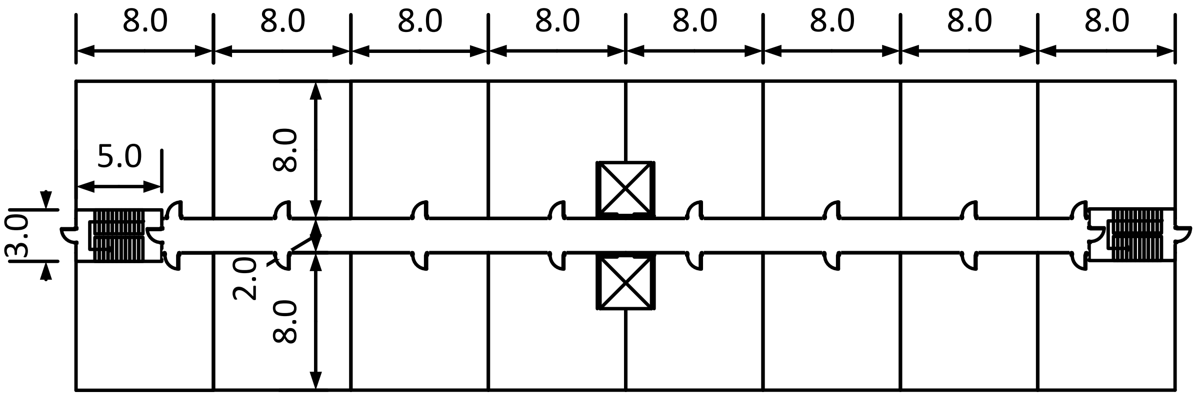

Figure 2.1 Layout of the small-area (1,152 m^2) residential buildings

Walls within each apartment that subdivide the apartment into rooms are not required to be fire or sound rated. Typically they would be wood-stud or steel-stud walls lined with regular gypsum board. Doors in these walls would not be rated and would not be equipped with automatic door closers. Nonetheless these walls would delay fire spread throughout the apartment to some extent. However in this study such walls are ignored; that is, assumed not to be present. This is a conservative assumption as it results in more rapid fire spread throughout the apartment, and hence more rapid development of untenable conditions within the apartment and throughout the building.

There are 3 windows on the exterior wall of each apartment. Each window has a height of 1.5 m x a width of 1.5 m.

All structural elements in the building are assumed to exhibit a one-hour fire resistance rating and all apartments are separated from all other spaces in the building by one-hour rated fire separations. The door between each apartment and the public corridor is assumed to exhibit the required fire-protection rating of 20 min, and the door between the public corridor and the exit staircase is assumed to exhibit the required fire-protection rating of 45 min.

The public corridors on each storey are assumed to be 2,000 mm in width which is significantly wider than the minimum permitted width of 1,100 mm (BCBC Article 3.3.1.9). The maximum travel distance in the public corridor (from a central apartment to the exit staircase) is only about 27 m, well short of the permitted 45 m (BCBC Clause 3.4.2.5.(1)(c). There are exit staircases at either end of the public corridor, within which are scissor stairs with a width of 1,500 mm.

To be consistent with common practice, it is assumed that there are 4 sprinklers in each apartment on a 4 m grid pattern. Each sprinkler has an activation temperature of 57°C and an RTI of 50 $m^{1/2}$ $s^{1/2}$. The reliability of the sprinklers is assumed to be 95% unless otherwise stated (Hall 2012).

Activation of a pull station, smoke detector or water-flow detector in the sprinkler system would sound an alarm in the building and send an alert signal to warn the fire department that an emergency exists.

Clearly this residential building could be of combustible, hybrid or non-combustible construction in compliance with the BCBC 2012.

2.1.1.1 Small-Area Six-Storey Residential Building of Light Wood-frame Construction (RS-LWF)

The building (designated RS-LWF) was designed to be compliant with the BCBC requirements for a six-storey apartment building of combustible construction.

2.1.1.1.1 Floor/Ceiling Assemblies

The pertinent BCBC requirements for the floor/ceiling assemblies are

- 1 hour load-bearing fire resistance rating (FRR), and
- Airborne sound transmission class (STC) ≥ 50.

There are no requirements governing impact sound transmission (ICC) in the BCBC 2012.

In this study, the floor/ceiling assemblies are assumed to be assembly F10f in BCBC Table A-9.10.3.1.B:

- Structural elements: 270 mm deep wooden I-joists spaced 400 mm o.c.,
- Top side: 1 layer of 11 mm sanded OSB and 1 layer of 15.5 mm OSB,
- Resilient channels beneath the I-joists spaced 400 mm o.c.,
- 1 layer of 15.9 mm fire-rated gypsum board attached to bottom of resilient channels, and
- Cavity contains 3 layers of 90 mm thick mineral wool insulation.

Assembly F10f is deemed to exhibit the following properties: FRR = 1 hour; STC = 52 and ICC = 43.

It should be noted that the floor/ceiling assemblies will have a long span, approximately 8 m. From a structural standpoint it might be necessary to employ deeper I-joists than proposed herein. In practice, this would not degrade the fire-resistance rating or the sound transmission class.

2.1.1.1.2 Interior Load-bearing Wall Assemblies

Given the design of the building depicted in Figure 2.1, it can be expected that the walls between apartments and the public corridor, between the apartments and the exit staircase, and between the apartments and the elevator shaft would be load-bearing. They would also be required to exhibit an FRR of 1 hour and an STC ≥ 50.

In this study, the interior load-bearing wall assemblies are assumed to be based on assembly W6d in BCBC Table A-9.10.3.1.A:

- Structural elements: nominal 2 x 6 wood studs (38 mm x 140 mm) spaced 400 mm o.c. rather than the nominal 2 x 4 wood studs (38 mm x 89 mm) in the Table. This is to support the higher structural loads in a 6-storey building compared to in a Part 9 building 3 storeys in height.
- Resilient channels spaced 600 mm o.c. on one side of studs
- 2 layers of 12.7 mm fire-rated gypsum board on each side of the studs
- Insulation: 140 mm of mineral wool or glass-fibre insulation.
- Assembly W6d is deemed to exhibit the following properties: FRR = 1.5 hours and STC = 55.

Note that using the proposed NBCC 2015 Component Additive Method, this assembly would achieve a FRR of 70-85 minutes depending on insulation type provided resilient channels are spaced 400 mm o.c.

2.1.1.1.3 Exterior Load-bearing Wall Assemblies

Exterior walls were assumed to be load bearing and are required to have a fire resistance rating of one hour. There are no sound isolation requirements for exterior walls; however, to meet structural and thermal insulation standards it is common the use 38 mm x 140 mm studs rather than 38 mm x 89 mm studs.

In this study, exterior load-bearing wall assemblies are based on exterior wall assembly EW1a in BCBC Table A-9.10.3.1.A.

- Structural elements: 2 x 4 wood studs (38 mm x 89 mm) spaced 400 mm or 600 mm o.c. in EW1a are replaced by nominal 2 x 6 wood studs (38 mm x 140 mm) spaced 400 mm o.c.
- Interior side of studs: 1 layer of 15.9 mm fire-rated gypsum board
- Insulation: The 89 mm of mineral wool or glass-fibre insulation in EW1a are replaced by 140 mm of mineral wool or glass-fibre insulation
- Exterior side of studs: Exterior sheathing and siding.

The Component Additive Method in NBCC 2010 would assign a value of 75 minutes for the FRR of this exterior wall.

2.1.1.1.4 Fire Separations between Apartments

The walls between two apartments would not be load-bearing. They must however be fire separations with an FRR of 1 hour and an STC ≥ 50. In this study, these walls were assumed to be assembly W6d in BCBC Table A-9.10.3.1.A with nominal 2 x 6 wood studs (38 mm x 140 mm) spaced 400 mm o.c. rather than the nominal 2 x 4 wood studs (38 mm x 89 mm) used for the interior load-bearing wall assemblies described in 3.1.1.1.2.

2.1.1.2 Small-Area Six-Storey Residential Building of Massive Timber Construction (R6S-CLT)

The building was designed to be compliant with the BCBC requirements. The principal building elements were assumed to be cross-laminated timber (CLT). In practise, glulam beams and columns may be used to support the CLT assemblies, but the fire separation requirements would be met by CLT assemblies.

2.1.1.2.1 Floor/Ceiling Assemblies

The pertinent BCBC requirements for the floor/ceiling assemblies are

- 1 hour load-bearing fire resistance rating (FRR), and
- Airborne sound transmission class (STC) ≥ 50.

The floor assembly was assumed to have a single layer of 12.7 mm regular gypsum board attached to the underside of 105 mm thick (3-ply) CLT based on the test result that 105 mm unprotected CLT produced 57-min fire resistance time (NRCC 2013).

In practise, because of the long spans, the structural calculations might suggest a 5-ply CLT would be required. Furthermore to meet the sound transmission requirements, it is necessary to employ 5-ply CLT with two layers of 12.7 mm gypsum suspended below it. (Tall Wood Guide, Section 4.4 page 11). Consequently although the selected assembly meets the fire-resistance requirements, to meet the structural and sound transmission requirements, a more massive assembly would be required which would exhibit a higher fire resistance rating than 1 hour. This means the assumptions herein are quite conservative.

2.1.1.2.2 Interior Load-bearing Wall Assemblies

Given the design of the building depicted in Figure 2.1, it can be expected that the walls between two apartments, between apartments and the public corridor, between the apartments and the exit staircase, and between the apartments and the elevator shaft would be load-bearing. They would also be required to exhibit an FRR of 1 hour and an STC ≥ 50.

The interior load-bearing wall assemblies are assumed to have a single layer of 12.7 mm regular gypsum board attached to each side of 105 mm thick (3-ply) CLT based on the test result that 105 mm unprotected CLT produced 57-min fire resistance time (NRCC 2013).

In practise, to meet the sound transmission requirements, it is necessary to construct a wall with 38 mm x 64 mm woods and a single layer of 15.9 mm gypsum board on both sides of a 3-ply CLT wall panel (Tall Wood Guide, Section 4.4 page 11). Consequently although the selected assembly meets the fire-resistance requirements, to meet the sound transmission requirements, a more massive assembly would be required which would exhibit a higher fire resistance rating than 1 hour. Furthermore, to meet the structural requirements it might be necessary to employ 5 ply CLT. This means the assumptions herein are quite conservative.

2.1.1.2.3 Exterior Load-bearing Wall Assemblies

Exterior walls were assumed to be load bearing and are required to have a fire resistance rating of one hour. There are no sound isolation requirements for exterior walls.

The exterior load-bearing wall assemblies are assumed to have a single layer of 12.7 mm regular gypsum board attached to the inside 105 mm thick (3-ply) CLT based on the test result that 105 mm unprotected CLT produced 57-min fire resistance time (NRCC 2013).

In practise, to meet structural requirements it may be necessary to employ 5-ply CLT panels, and to meet thermal insulation standards it is likely that a thick layer of insulation would be required between the gypsum board and the CLT panels. This means the assumptions herein are quite conservative.

2.1.1.3 Small-Area Six-Storey Residential Building of Non-combustible Construction (R6S-NC)

The building was designed to be compliant with the BCBC requirements for a six-storey apartment building of non-combustible construction. The structural (load-bearing) elements (floors, columns and beams) are assumed to be constructed of reinforced concrete. The party walls between apartments, the walls separating apartments from the public corridor and the exterior walls are assumed to be nonloadbearing steel-stud walls.

2.1.1.3.1 Floor/Ceiling Assemblies

The pertinent BCBC requirements for the floor/ceiling assemblies are

- 1 hour load-bearing fire resistance rating (FRR), and
- Airborne sound transmission class (STC) ≥ 50.

In this study, the floor/ceiling assemblies are assumed to be assembly F1c in BCBC Table A-9.10.3.1.B:

- A pre-stressed hollow core concrete slab 200 mm deep with 25 mm minimum concrete cover over the reinforcing steel bars.

2.1.1.3.2 Interior Non Load-bearing Wall Assemblies

All interior non load-bearing wall assemblies are assumed to be assembly S14a or S6e in BCBC Table A-9.10.3.1.A. The description of S14a:

- 41 mm x 92 mm steel studs spaced 400 mm or 600 mm with 89 mm thick absorptive material, resilient channels spaced at 600 mm on one side, 2 layers of 15.9 mm regular gypsum board on each side.

2.1.1.3.3 Exterior Non Load-bearing Wall Assemblies

All exterior non load-bearing wall assemblies are assumed to be a blend of assemblies EW1a and S10a in BCBC Table A-9.10.3.1.A:

- Structural elements: 41 mm x 92 mm (or deeper) steel studs spaced 400 mm or 600 mm o.c.
- Interior side of studs: 2 layers of 12.7 mm fire-rated gypsum board
- Insulation: The 89 mm (or deeper) of mineral wool or glass-fibre insulation
- Exterior side of studs: Exterior sheathing and siding.

2.1.2 Large-Area Six-Story Residential Building

Figure 2.2 depicts one storey of a larger-area 6-storey residential building that houses 24 apartments each with nominal floor dimensions of dimensions 8 m x 8 m. The area of each storey (and hence the building area) is 1,728 m^2 and the maximum travel distance in the public corridor (from a central apartment to the exit staircase) is 43 m, just short of the permitted 45 m.

Each apartment is assumed to have 2 bedrooms and hence 4 occupants. Consequently it is assumed that there are 24 x 4 = 96 occupants on each storey and 6 x 96 = 576 occupants in the building. Clearly then there are 24 / 16 = 1.5 times as many occupants on each storey of the large-area six-storey residential building than on each storey of the small-area six-storey residential building.

Clearly this residential building could be of non-combustible construction in compliance with the BCBC 2012, but could not be of combustible or hybrid construction. Nonetheless, in this study, an assessment has been made of the fire performance of buildings of light-weight wood-frame and mass timber construction.

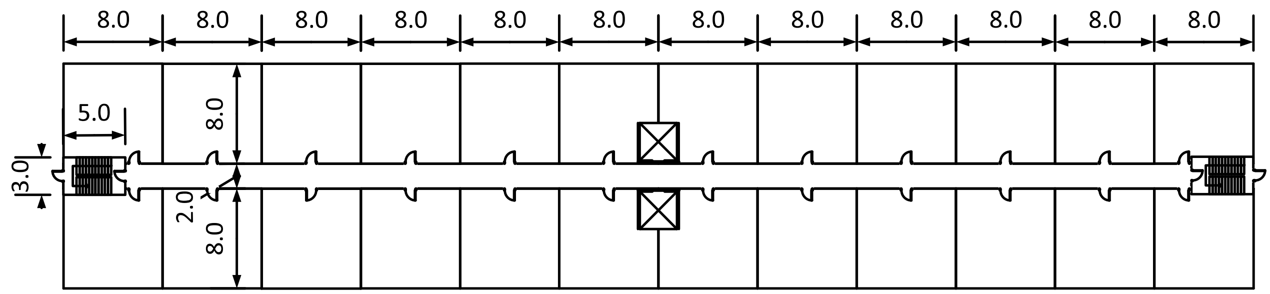

Figure 2.2 Layout of the large-area (1,728 m^2) residential buildings

It has been assumed that the probability of fire occurrence in an apartment is independent of the type of construction of the building. It is therefore assumed that the probability of fire occurring in the large-area six-storey apartment building is 1.5 times the probability of fire occurring in the small-area six-storey apartment building.

The longest travel distance to the nearest exit in the large-area six-storey residential building is 43 m which is less than the permitted 45 m distance. However, in the small-area six-storey residential building the longest travel distance to the nearest exit is considerably less at 27 m.

2.1.2.1 Large-Area Six-Storey Residential Building of Light Wood-frame Construction (R6L-LWF)

With the exception of having more apartments per storey, the types of assemblies and the fire protection features in the large-area six-storey residential building of light wood-frame construction are identical to those for the small-area six-storey residential building of light wood-frame construction described in Section 2.1.1.1 of this report.

2.1.2.2 Large-Area Six-Storey Residential Building of Massive Timber Construction (R6L-CLT)

With the exception of having more apartments per storey, the types of assemblies and the fire protection features in the large-area six-storey residential building of massive timber construction are identical to those for the small-area six-storey residential building of massive timber construction described in Section 2.1.1.2 of this report.

2.1.2.3 Large-Area Six-Storey Residential Building of Non-combustible Construction (R6L-NC)

With the exception of having more apartments per storey, the types of assemblies and the fire protection features in the large-area six-storey residential building of non-combustible construction are identical to those for the small-area six-storey residential building of non-combustible construction described in Section 2.1.1.3 of this report.

2.2 Twelve-Storey Residential Buildings

To comply with the 2012 Edition of the BCBC, a 12-storey residential building must be sprinklered in conformance with NFPA 13, must be of non-combustible construction and must have load-bearing elements exhibiting a fire-resistance rating of 2 hours. Table 2.2 provides a summary of the pertinent fire protection requirements governing the construction of a 12-storey residential building.

Table 2.2 BCBC Fire Safety Requirements for Twelve-Storey Residential Buildings

Requirement	Non-combustible Construction
Maximum Building Area **(maximum single storey area)**	**Unlimited** Article 3.2.2.47
Structural Fire Resistance Rating **(floors and elements supporting floors)**	**2 hours** Article 3.2.2.47
Sprinklers[1] **(Throughout the building)**	**NFPA 13** Article 3.2.2.47
Fire Resistance Rating of Fire Separations **(Separate apartments from all other spaces)**	**1 hour** (if non-loadbearing) Article 3.3.4.2 **2 hours** (if loadbearing) Article 3.2.2.47
Doors (fire-protection rating)[2] **(between apartment & public corridor)**	**20 minutes** (non-loadbearing wall) Article 3.1.8.10 **90 minutes** (non-loadbearing wall) Article 3.1.8.4
Means of Egress **(minimum width of public corridor)**	**1,100 mm** Article 3.3.1.9
Maximum Travel Distance (Apt Door to Exit) **(Interior stairway considered to be an exit)**	**45 m** Clause 3.4.2.5.(1)(c)
Doors (fire-protection rating)[2] **(between public corridor & exit))**	**90 minutes** (non-loadbearing wall) Article 3.1.8.4
Flame Spread Ratings / Smoke Developed **(walls and ceiling within an apartment)** **(floors within an apartment)**	**150 / Unrestricted** Sentence 3.1.13.2.(1) No restrictions
Flame Spread Ratings / Smoke Developed **(walls within a public corridor)** **(ceilings within a public corridor)** **(floors within a public corridor)**	**150 / 100** Sentence 3.1.13.6.(3) / Table 3.1.13.7 **150 / 50** Sentence 3.1.13.6.(3) / Table 3.1.13.7 **300 / 500** Table 3.1.13.7
Flame Spread Ratings / Smoke Developed **(walls, ceilings and floors within an exit)**	**25 / 50** Table 3.1.13.7
Limits to Smoke Movement **(Exit staircases)**	Limited smoke for 2 hours (Sentence 3.2.6.2.(2)

1. The sprinkler standard NFPA 13 has additional provisions for buildings of combustible construction compared to provisions for buildings of non-combustible construction, especially for concealed spaces.
2. Doors must be equipped with **a self-closing device** designed to return the door to the closed position after each use (Article 3.1.8.11). Doors must exhibit a *fire-protection rating*, not a *fire-resistance rating*.

From a fire safety perspective, the most significant differences between the BCBC requirements for a six-storey residential building of non-combustible construction and a twelve storey are

- Relaxation permitted in building areas,
- Increase in structural fire resistance requirements from 1 hour to 2 hours and consequent increase in fire protection ratings of doors,
- More stringent flame-spread ratings in public spaces (public corridors and exit staircases), and
- Measures to limit the danger to occupants and firefighters from exposure to smoke including smoke management in exit staircases.

In addition to fire safety requirements, there are also acoustic separation requirements in apartment buildings. Whether an apartment building is of combustible, hybrid or non-combustible construction, each apartment must be separated from other apartments and from the public corridor by an assembly that exhibits a sound-transmission coefficient (SDC) of 50 or better (BCBC Article 5.9.1.2).

2.2.1 Twelve-Storey Residential Building

Although the building area of a twelve-storey residential building is unrestricted, it was decided to simulate fires in a building with the same building layout as depicted in Figure 2.2 which is the largest floor area that can be served by only two exit staircases.

2.2.1.1 Twelve-Storey Residential Building of Non-combustible Construction (R12-NC)

The building was designed to be compliant with the BCBC requirements for a twelve-storey apartment building of non-combustible construction.

2.2.1.1.1 Floor/Ceiling Assemblies

The pertinent BCBC requirements for the floor/ceiling assemblies are

- 2 hour load-bearing fire resistance rating (FRR), and
- Airborne sound transmission class (STC) ≥ 50.

In this study, the floor/ceiling assemblies are assumed to be assembly F1b in BCBC Table A-9.10.3.1.B:

- A 130 mm reinforced concrete slab with 25 mm minimum concrete cover over the reinforcing steel bars.

It is assumed that the floors are supported by two-hour rated reinforced concrete columns and beams.

2.2.1.1.2 Exit Staircase Wall Assemblies

The exit staircases must be separated from the rest of the floor by 2-hour rated wall assemblies of non-combustible construction (Article 3.4.4.1). They have been assumed to be assembly S6a in BCBC Table A-9.10.3.1.B:

- Structural elements: 31 mm x 92 mm steel studs spaced 600 mm o.c.
- 2 layers of 15.9 mm fire-rated gypsum board on each side of the studs
- Insulation: 89 mm of mineral wool or glass-fibre insulation.
- Assembly S6a is deemed to exhibit the following properties: FRR = 2 hours and STC = 56.

2.2.1.1.3 Non-loadbearing Interior Wall Assemblies

Each apartment must be separated from all other spaces (except the exit staircase) by a fire separation with a fire-resistance rating of 1 hour and a sound transmission classification of 50. Since these walls are also non-loadbearing, they have been assumed to be assembly S6e in BCBC Table A-9.10.3.1.B.

- Structural elements: 31 mm x 92 mm steel studs spaced 600 mm o.c.
- 2 layers of 12.7 mm regular gypsum board on each side of the studs
- Insulation: 89 mm of mineral wool or glass-fibre insulation.
- Assembly S6e is deemed to exhibit the following properties: FRR = 1 hour and STC = 50.

2.2.1.1.4 Non-loadbearing Exterior Wall Assemblies

The exterior walls are nonloadbearing so do not require a fire resistance rating. They also do not require a sound transmission classification. Hence it is assumed that the exterior walls have deep steel studs to create deep cavities that are insulated to achieve an acceptable level of thermal insulation.

- It can be assumed that the interior side of the steel studs is lined with one or two layers of 12.7 mm or 15.9 mm fire-rated gypsum board.
- Insulation: The 65 mm (or deeper) of mineral wool or glass-fibre insulation
- Exterior side of studs: Exterior sheathing and siding.

2.2.1.2 Twelve-Storey Residential Building of CLT Construction (45 Minute Doors) (R12-CLT-D45)

Although not permitted by the BCBC, the building is proposed to be an alternative solution built of CLT panels. In principle, the structure of the building could entail glulam columns and beams that provide most of the load-bearing functions in the building. However, in this study it has been assumed that the CLT panels play significant load-bearing roles.

2.2.1.2.1 Floor/Ceiling Assemblies

Beyond the requirement for non-combustible construction, the pertinent BCBC requirements for the floor/ceiling assemblies are

- 2 hour load-bearing fire resistance rating (FRR), and
- Airborne sound transmission class (STC) ≥ 50.

In this study, based on the test result that 175 mm unprotected CLT produced 113-min fire resistance time (NRCC 2013), the floor/ceiling assemblies are assumed to be:

- Any floor topping
- 175 mm thick (5 ply) CLT panels with
- 1 layer of 12.7 mm regular gypsum board affixed to the underside of the CLT panels.

2.2.1.2.2 Loadbearing Wall Assemblies

Beyond the requirement for non-combustible construction, the BCBC requires that loadbearing wall assemblies and those enclosing the exit staircase must exhibit a 2 hour fire resistance rating (FRR). Staircase walls and walls between suites have been assumed to be loadbearing.

In this study, loadbearing wall assemblies are assumed to be:

- 1 layer of 12.7 mm regular gypsum board attached to each side of 175 mm thick (5 ply) CLT panels, based on the test result that 175 mm unprotected CLT produced 113-min fire resistance time (NRCC 2013).

2.2.1.2.3 Interior Non-loadbearing Wall Assemblies

The walls between suites and the public corridor are assumed to be non-loadbearing. While these walls could be constructed of CLT panels, it is assumed in this study that they are light-frame assemblies. They would be required to exhibit a fire-resistance rating of 1 hour and an STC of 50. In this study, these wall assemblies are assumed to be W6d in BCBC Table A-9.10.3.1.A:

- Structural elements: nominal 2 x 6 wood studs (38 mm x 140 mm).
- Resilient channels spaced 600 mm o.c. on one side of studs.
- 2 layers of 12.7 mm fire-rated gypsum board on each side of the studs.
- Insulation: 140 mm of mineral wool or glass-fibre insulation.
- Assembly W6d is deemed to exhibit the following properties: FRR = 1.5 hours and STC = 55.

2.2.1.2.4 Exterior Non-loadbearing Wall Assemblies

Exterior walls were assumed to be non-loadbearing and as such do not require a fire resistance rating. Furthermore there are no sound isolation requirements for exterior walls. However, to meet thermal insulation standards it is assumed 38 mm x 140 mm studs are employed rather than 38 mm x 89 mm studs.

In this study, exterior load-bearing wall assemblies are based on exterior wall assembly EW1a in BCBC Table A-9.10.3.1.A.

- Structural elements: 2 x 6 wood studs (38 mm x 140 mm) spaced 400 mm o.c.
- Interior side of studs: 1 layer of 15.9 mm fire-rated gypsum board
- Insulation: The 89 mm of mineral wool or glass-fibre insulation in EW1a are replaced by 140 mm of mineral wool or glass-fibre insulation
- Exterior side of studs: Exterior sheathing and siding.

2.2.1.2.5 Doors

Since the exit staircases are enclosed by walls with fire-resistance ratings of 2 hours, the doors between the public corridor and exit staircases are assumed to exhibit a 1.5 hour fire-protection rating in compliance with BCBC 3.1.8.4.

In principle, the doors between suites and the public corridor are permitted to exhibit a fire-protection rating of 20 minutes (BCBC 3.1.8.10). However as this building is not compliant with the BCBC, because it is not of non-combustible construction, it is necessary to propose an alternative solution. As a consequence it has been considered that an alternative solution might be to replace the 20 minute required doors with 45 minute doors. This would serve the purpose of containing smoke and fire in the suite of fire origin longer than the 20 minute door in the code-compliant non-combustible building and make evacuation from other suites safer. Perhaps this could yield an overall equivalent fire performance to the code-compliant non-combustible building.

2.2.1.3 Twelve-Storey Residential Building of CLT Construction (Improved Sprinklers) (R12-CLT-SP)

A second strategy for developing an alternative solution was considered. The building assemblies described in 2.2.1.2 were not altered. The doors between suites and public corridors were assumed to exhibit a code-compliant 20 minute fire-protection rating. The improved performance was to take actions to improve the reliability of the sprinkler system beyond the requirements of the BCBC and NFPA 13. The typical reliability of a sprinkler system is 0.95; that is, the sprinkler system activates and suppresses the fire 95% of the time (Hall 2012).

The alternative solution considered in this section entails taking steps to improve the reliability of the sprinkler system to 0.97.

2.2.1.4 Twelve-Storey Residential Building of CLT Construction (Balconies) (R12-CLT-Balconies)

A third strategy for developing an alternative solution was considered. The building assemblies described in 2.2.1.2 were not altered. The doors between suites and public corridors were assumed to exhibit a code-compliant 20 minute fire-protection rating and the sprinkler system was assumed to exhibit the typical reliability of 0.95.

To prevent fire fatalities in high-rise apartment buildings caused by fire spread from the apartment of fire origin to apartments above through windows, the alternative solution considered in this section entails the construction of balconies 2 m deep beneath each window in the exterior walls of all apartments (except the ground floor).

2.3 Six-Storey Office Buildings

Although the BCBC 2012 does not permit 6-storey office buildings of combustible construction, it is anticipated that the 2015 Edition of the National Building Code of Canada (NBCC) will. Table 2.3 compares the proposed NBCC requirements for 6-storey office buildings of combustible construction and the BCBC 2012 requirements for 6-storey office buildings of non-combustible construction.

From a fire safety perspective, the most significant differences between the BCBC requirements for a six-storey office building of non-combustible combustible and the proposed NBCC requirements for a six-storey office building of combustible (or hybrid) construction are:

- The maximum permitted building area of the six-storey office building of combustible construction is 1,200 m^2 while the maximum permitted area of a six-storey office building of non-combustible construction is 7,200 m^2 or six times larger.
- To facilitate firefighter access a six-storey building of combustible construction must have 25% of its perimeter within 15 m of street. There is no similar requirement for a six-storey office building of non-combustible construction.
- If there are external balconies on a six-storey office building of combustible construction, the balconies must be sprinklered. There is no similar requirement for a six-storey office building of non-combustible construction.

Finally it should be noted that there are no requirements for sound isolation between suites, or between suites and public corridors.

Table 2.3 Proposed NBCC 2015 and BCBC 2012 Requirements for Six-Storey Office Buildings

Requirement	Proposed NBCC 2015 Combustible or Hybrid Construction	BCBC 2012 Noncombustible Construction
Maximum Building Area **(maximum single storey area)**	**3,000 m²**	**7,200 m²** Article 3.2.2.56
Structural Fire Resistance Rating **(floors and elements supporting floors)**	**1 hour**	**1 hour** Article 3.2.2.56
Sprinklers[1] **(Throughout the building)**	**NFPA 13 + exterior balconies**	**NFPA 13** Article 3.2.2.56
Firefighting Access	**25% of perimeter to be within 15 m of street**	No similar requirement
Fire Separations between Suites[2]	**Not Required**	**Not Required** Sentence 3.3.1.1.(4)
Fire Separations between Public Corridors and Suites[2]	**Sometimes Required** (See Footnote 2)	**Sometimes Required** (See Footnote 2)
Maximum Travel Distance (to Exit)	**40 m** Clause 3.4.2.5.(1)(d)	**40 m** Clause 3.4.2.5.(1)(d)
One Egress Door per Suite	**Occupant Load ≤ 60 Area of suite ≤ 300 m2 Max Travel distance to Egress door ≤ 25 m** Assumed	**Occupant Load ≤ 60 Area of suite ≤ 300 m² Max Travel distance to Egress door ≤ 25 m** Sentence 3.3.1.5

1. NFPA 13 has additional provisions for buildings of combustible construction compared to provisions for buildings of non-combustible construction, especially for concealed spaces, but NBCC will require more fire blocking and sprinkler protection of exterior balconies.
2. In the context of office (Group D) buildings, a **suite** is a single room or a series of rooms operated under a single tenancy for business purposes.
    a. In the BCBC 2012, no fire separation is required between suites (Sentence 3.3.1.1.(4))
    b. In the BCBC 2012, no fire separation is required between a public corridor and suites if the travel distance from any part of the floor area to an exit does not exceed 45 m (Clause 3.3.1.4(a)). Otherwise a fire separation is required (Sentence 3.3.1.4.(1)) and must have a fire-resistance rating of 45 minutes (Sentence 3.3.1.4.(2).

2.3.1 Small-Area Six-Storey Office Building

Figure 2.3 depicts one storey of a small-area 6-storey office building that has 16 suites with nominal floor dimensions of 12 m x 14 m and hence area 168 m^2. The area of each storey (and hence the building area) is 2,916 m^2 and hence, in compliance with the proposed NBCC 2015, can be of combustible, hybrid or non-combustible construction.

In compliance with Table 3.1.17.1, the occupant load in each suite is calculated assuming 9.3 m^2 per person. Therefore each suite is assumed to have 18 occupants well below the permitted 60 when there is only one egress door from the suite. Consequently there are 18 x 16 = 288 occupants on each storey and 6 x 288 = 1,728 occupants in the building.

The maximum travel distance within a suite is only 20 m (14 + 6), which is well below the permitted 25 m when there is only one egress door from the suite. The maximum travel distance within a corridor is 37 m which is less than the permitted 40 m.

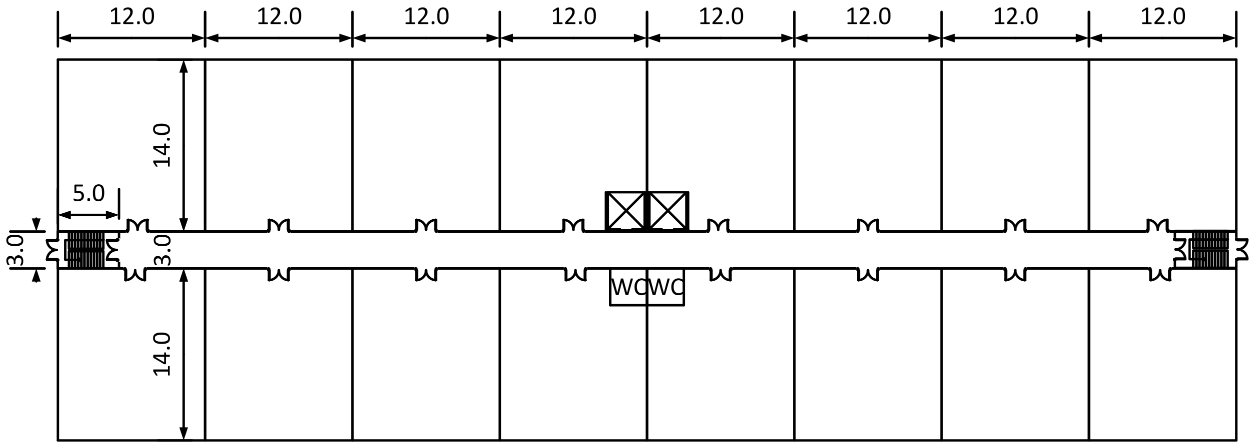

Figure 2.3 Layout of the small-area (2,916 m^2) office buildings

2.3.1.1 Small-Area Six-Storey Office Building of Light Wood-frame Construction (O6S-LWF)

The building was designed to be compliant with the NBCC requirements for a six-storey office building of combustible construction.

2.3.1.1.1 Floor/Ceiling Assemblies

As they are load-bearing, the NBCC requires that the floor/ceiling assemblies exhibit a 1-hour fire resistance rating. In this study, the floor/ceiling assemblies are assumed to be assembly F10f in BCBC Table A-9.10.3.1.B. These have been defined in Section 2.1.1.1.1 of this report.

2.3.1.1.2 Interior Loadbearing Wall Assemblies

Given the design of the building depicted in Figure 2.3, it can be expected that the walls between suites and the public corridor, between suites and the exit staircase, and between suites and the elevator shaft would be load-bearing and hence would be required to exhibit an FRR of 1 hour.

In this study, the interior load-bearing wall assemblies are based on assembly W6d in BCBC Table A-9.10.3.1.A. These have been defined in Section 2.1.1.1.2 of this report.

2.3.1.1.3 Exterior Load-bearing Wall Assemblies

Exterior walls were assumed to be load bearing so are required to have a fire resistance rating of 1 hour. To meet structural and thermal insulation standards it is common to use 38 mm x 140 mm studs rather than 38 mm x 89 mm studs. In this study, exterior load-bearing wall assemblies are based on exterior wall assembly EW1a in BCBC Table A-9.10.3.1.A. These have been defined in Section 2.1.1.1.3 of this report.

2.3.1.1.4 Interior Non-loadbearing Wall Assemblies

The walls between suites are assumed to be non-loadbearing and are not required to be fire separations (BCBC 3.3.1.1.(4)). In this study, they are assumed to be wall assembly W1c in BCBC Table A-9.10.3.1.A:

- Structural elements: nominal 2 x 4 wood studs (38 mm x 89 mm) spaced 600 mm o.c.
- 1 layer of 12.7 mm regular gypsum board on each side of the studs
- Insulation: 140 mm of mineral wool or glass-fibre insulation.

Assembly W1c is deemed to exhibit the following properties: FRR = 0.5 hours and STC = 32.

2.3.1.2 Small-Area Six-Storey Office Building of Massive Timber Construction (O6S-CLT)

The building was designed to be compliant with the NBCC requirements. The principal building elements were assumed to be cross-laminated timber (CLT). In practise, glulam beams and columns may be used to support the CLT floor assemblies, but the fire separation requirements would be met by CLT assemblies.

2.3.1.2.1 Floor/Ceiling Assemblies

As they are load-bearing, the NBCC requires that the floor/ceiling assemblies exhibit a 1-hour fire resistance rating.

As in section 2.3.1.2.1, the floor assembly was assumed to have a single layer of 12.7 mm regular gypsum board attached to the underside of 105 mm thick (3-ply) CLT. In practise, because of the long spans, the structural calculations might suggest a 5-ply CLT would be required which would perform better than the assembly employed in this study.

2.3.1.2.2 Interior Loadbearing Wall Assemblies

Given the design of the building depicted in Figure 2.3, it can be expected that the walls between two suites, between suites and the public corridor, between suites and the exit staircase, and between suites and the elevator shaft would be load-bearing. They would also be required to exhibit an FRR of 1 hour and an STC ≥ 50.

As in section 2.1.1.2.2, these interior load-bearing wall assemblies are assumed to have a single layer of 12.7 mm regular gypsum board attached to each side of 105 mm thick (3-ply) CLT, based on the test result that 105 mm unprotected CLT produced 57-min fire resistance time (NRCC 2013).

2.3.1.2.3 Exterior Load-bearing Wall Assemblies

Exterior walls were assumed to be load bearing and are required to have a fire resistance rating of one hour.

As in section 2.1.1.2.2, the exterior load-bearing wall assemblies are assumed to have a single layer of 12.7 mm regular gypsum board attached to the inside 105 mm thick (3-ply) CLT. In practise, to meet structural requirements it may be necessary to employ 5-ply CLT panels, and to meet thermal insulation standards it is likely that a thick layer of insulation would be required between the gypsum board and the CLT panels. This means the assumptions herein are quite conservative.

2.3.1.3 Small-Area Six-Storey Office Building of Non-combustible Construction (OS6-NC)

The building was designed to be compliant with the BCBC and NBCC requirements for a six-storey office building of non-combustible construction. The structural (load-bearing) elements (floors, columns and beams) are assumed to be constructed of reinforced concrete. The party walls between suites, the walls separating suites from the public corridor and the exterior walls are assumed to be nonloadbearing steel-stud walls.

2.3.1.3.1 Floor/Ceiling Assemblies

The pertinent BCBC requirement for the floor/ceiling assemblies is a 1 hour load-bearing fire resistance rating. The floor/ceiling assemblies are assumed to be assembly F1c in BCBC Table A-9.10.3.1.B and have been described in Section 2.1.1.3.1 in this report.

2.3.1.3.2 Interior Load-bearing Wall Assemblies

The walls separating suites from the public corridor are assumed to be loadbearing steel-stud walls and are assumed to be assembly S10a in BCBC Table A-9.10.3.1.A.

2.3.1.3.3 Exterior Non Load-bearing Wall Assemblies

All exterior non load-bearing wall assemblies are assumed to be a blend of assemblies EW1a and S10a in BCBC Table A-9.10.3.1.A. This assembly is described in Section 2.1.1.3.3 in this report.

2.3.2 Large-Area Six-Story Office Building

Figure 2.4 depicts one storey of a large-area 6-storey office building that has 16 suites with nominal floor dimensions of 12 m x 19 m and hence area 228 m^2. The area of each storey (and hence the building area) is 3,936 m^2 and hence, in compliance with the proposed NBCC 2015, can be of non-combustible construction, but cannot be of hybrid or non-combustible construction.

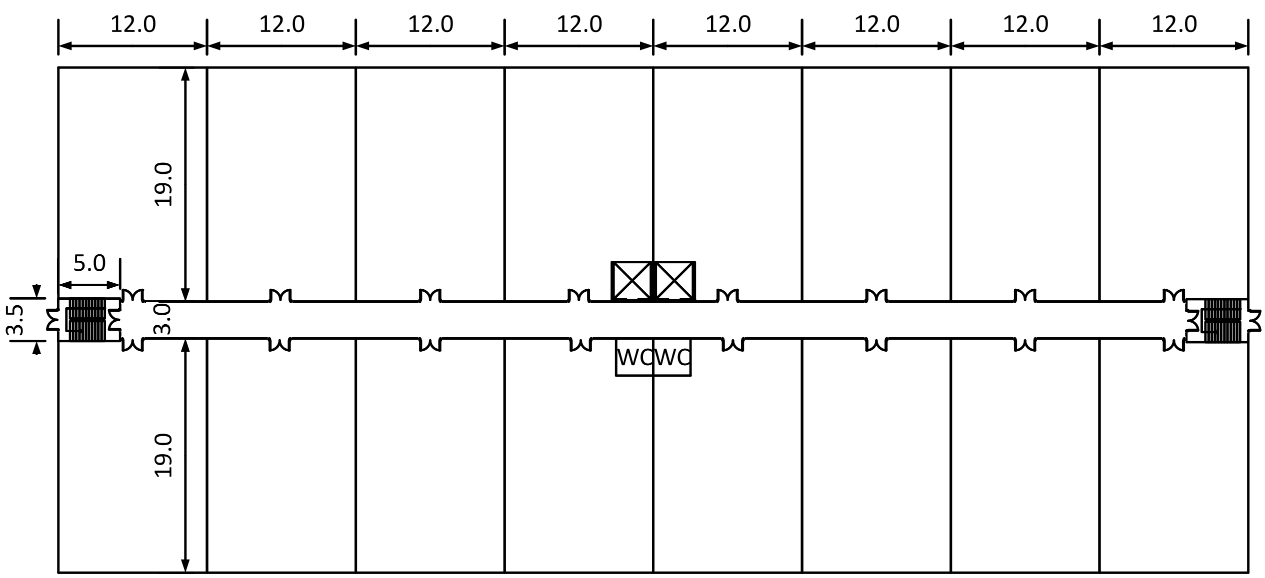

Figure 2.4 Layout of the large-area (3,936 m^2) office buildings

In compliance with Table 3.1.17.1, the occupant load in each suite is calculated assuming 9.3 m^2 per person. Therefore each suite is assumed to have 24 occupants well below the permitted 60 when there is only one egress door from the suite. Consequently there are 24 x 16 = 384 occupants on each storey and 6 x 384 = 2,304 occupants in the building.

The maximum travel distance within a suite is 25 m (19 + 6), which is just the permitted 25 m when there is only one egress door from the suite. The maximum travel distance within a corridor is 37 m which is less than the permitted 40 m.

Consequently the primary differences between the small-area 6-storey office building (which can be of combustible construction) and the large-area office building (which must be of non-combustible construction) are the larger building areas and the distances some occupants must travel to reach an exit staircase.

2.3.2.1 Buildings

Assessments were made for the following 6-storey large-area office buildings

- **O6L-LWF**: Large-Area Six-Storey Office Building of Light Wood-frame Construction
- **O6L-CLT:** Large-Area Six-Storey Office Building of Massive Timber Construction
- **O6L-NC:** Small-Area Six-Storey Office Building of Non-Combustible Construction

2.3.2.2 Assemblies

All assemblies (floor/ceiling assemblies, interior non-loadbearing wall assemblies, and exterior non-loadbearing wall assemblies) for the large-area 6-storey office buildings are assumed to be identical to those described in Section 2.3.1 of this report for the equivalent small-area 6-storey office buildings.

2.4 Twelve-Storey Office Buildings

To comply with BCBC 2012, a 12-storey office building must be sprinklered in conformance with NFPA 13, must be of non-combustible construction and must have load-bearing elements exhibiting a fire-resistance rating of 2 hours. Table 2.4 provides a summary of the fire protection requirements for a 12-storey office building that differ from those listed in Table 2.3 for a 6-storey office building of non-combustible construction in BCBC 2012.

Table 2.4 Differences between 6-Storey and 12-Storey Sprinklered Office Buildings (BCBC 2012)

Requirement	BCBC 2012 6-Storey Office Building	BCBC 2012 12-Storey Office Building
Maximum Building Area **(maximum single storey area)**	**7,200 m^2** Article 3.2.2.56	**Unlimited** Article 3.2.2.54
Structural Fire Resistance Rating **(floors and elements supporting floors)**	**1 hour** Article 3.2.2.56	**2 hours** Article 3.2.2.54

2.4.1 Floor Plans for Twelve-storey Office Buildings

Two floor plans for 12-storey office buildings have been considered: a compartmented floor plan and an open floor plan. The compartmented floor plan is depicted in Figure 2.4.

The ground floor is similar to the higher floors except that it has exits to the outdoors in addition to the 4 stair exits. This design would make a fire on the second floor the worst scenario for these buildings because occupants on the first floor would be able to evacuate with the ground floor exits to the outside without going through the stair exits.

The building area (area of each storey) is 54 m x 54 m = 2,916 m^2.

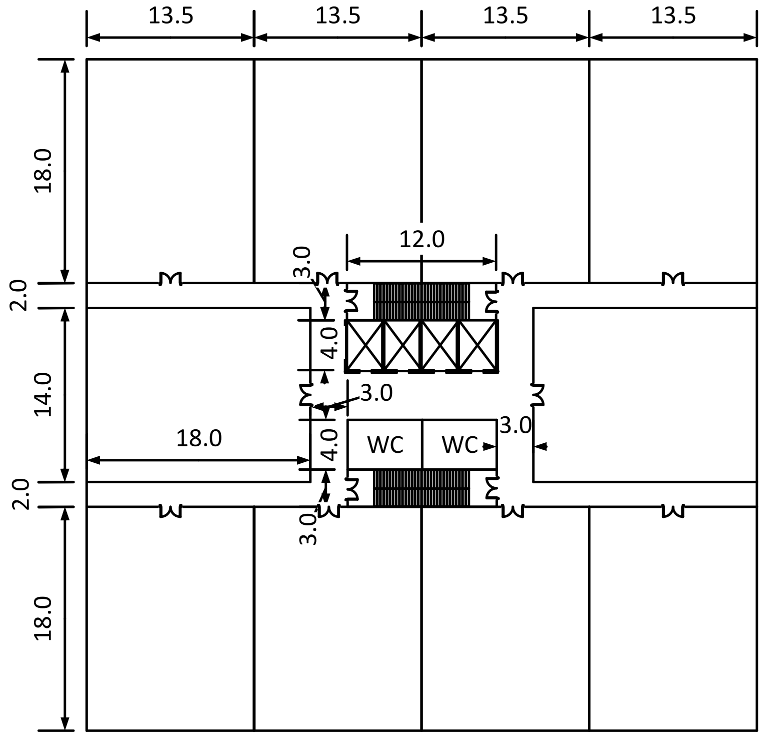

Figure 2.4 12-Storey Compartmented Office Building – High Floors

On each storey there are 8 office suites with a floor area of 18.0 m x 13.5 m = 243 m^2. It is assumed that there are (243 m^2 / 9.3 m^2 per occupant) = 26 occupants in each of these suites. On each storey there are also 2 office suites with floor area 18.0 m x 14 m = 252 m^2. It is assumed that there are (252 m^2 / 9.3 m^2 per occupant) = 27 occupants in each of these suites. There are therefore 8 x 26 + 2 x 27 = 262 occupants on each storey.

The open floor plan has the same building area, elevator shafts, staircases and washrooms as the compartmented floor plan. However, in the open floor plan, all of the partitions defining suites in Figure 2.4 are removed.

2.4.1.1 Twelve-Storey Office Building of Non-combustible Construction (Open Floor Plan) (O12-NC)

The twelve-storey office building of non-combustible construction is assumed to have an open floor plan and to be fully compliant with the BCBC 2012.

2.4.1.1.1 Floor/Ceiling Assemblies

The pertinent BCBC requirement for the floor/ceiling assemblies is a 2-hour loadbearing fire resistance rating (FRR). In this study, the floor/ceiling assemblies are assumed to be assembly F1b in BCBC Table A-9.10.3.1.B which has been described in Section 2.2.1.1.1 of this report.

It is assumed that the floors are supported by two-hour rated reinforced concrete columns and beams.

2.4.1.1.2 Exit and Elevator Staircase Wall Assemblies

The exit and elevator staircases must be separated from the rest of the floor by 2-hour rated wall assemblies of non-combustible construction. These walls are not required to be load-bearing. They have been assumed to be assembly S6a in BCBC Table A-9.10.3.1.B.

2.4.1.1.3 Non-loadbearing Exterior Wall Assemblies

The exterior walls are nonloadbearing so do not require a fire resistance rating. They also do not require a sound transmission classification. Hence it is assumed that the exterior walls have deep steel studs to create deep cavities that are insulated to achieve an acceptable level of thermal insulation.

- It can be assumed that the interior side of the steel studs is lined with one or two layers of 12.7 mm or 15.9 mm fire-rated gypsum board.
- Insulation: The 65 mm (or deeper) of mineral wool or glass-fibre insulation
- Exterior side of studs: Exterior sheathing and siding.

2.4.1.2 Twelve-Storey Office Building of Combustible Construction (Compartmented) (O12-CLT-CPT)

Although not permitted by the BCBC, an alternative solution is proposed whereby the building is of combustible construction and compartmented as shown in Figure 2.4. The structure of the building is constructed of glulam columns and beams that support CLT floor panels. Fire separations enclosing office suites are not required to be fire-rated; however, in this study, as part of the alternative solution, they are assumed to be 1-hour rated wood-frame walls.

2.4.1.2.1 Floor/Ceiling Assemblies

Beyond the requirement for non-combustible construction, the BCBC requires the CLT floor/ceiling assemblies to exhibit a 2 hour load-bearing fire resistance rating (FRR). In this study, the floor/ceiling assemblies are assumed to be identical to that described in Section 2.2.1.2.1 for a 12-storey residential building of combustible construction.

2.4.1.2.2 Exit and Elevator Staircase Wall Assemblies

Beyond the requirement for non-combustible construction, the BCBC requires that loadbearing wall assemblies and those enclosing the exit staircase must exhibit a 2 hour fire resistance rating (FRR). Staircase walls and walls between suites have been assumed to be loadbearing.

In this study, these wall assemblies are assumed to be the same as in Section 2.2.1.2.2 of this report; namely 1 layer of 12.7 mm regular gypsum board attached to each side of 175 mm thick (5 ply) CLT panel.

2.4.1.2.3 Loadbearing Wall Assemblies

In this study, the walls between suites have been assumed to be load-bearing and hence must exhibit a 2-hour fire resistance rating. These walls are therefore also assumed to be of the same construction of as those described in 2.4.1.2.2.

2.4.1.2.4 Non-loadbearing Wall Assemblies

The walls between suites and the public corridor are assumed to be non-loadbearing. While these walls could be constructed of CLT panels, it is assumed in this study that they are light-frame assemblies. As this is an office building these walls are not required to be fire-rated. As part of the alternative solution proposed herein, it is assumed that they are wall assemblies W1a in BCBC Table A-9.10.3.1.A:

- Structural elements: nominal 2 x 4 wood studs (38 mm x 89 mm).
- Resilient channels spaced 600 mm o.c. on one side of studs.
- 1 layer of 15.9 mm type X gypsum board on each side of the studs.
- Insulation: 89 mm of mineral wool or glass-fibre insulation.
- Since it is non-loadbearing, assembly W1a is deemed to exhibit a FRR of 1 hour.

2.4.1.2.5 Exterior Non-loadbearing Wall Assemblies

Exterior walls were assumed to be non-loadbearing and as such do not require a fire resistance rating. Furthermore there are no sound isolation requirements for exterior walls. However, to meet thermal insulation standards it is assumed 38 mm x 140 mm studs are employed rather than 38 mm x 89 mm studs.

In this study, exterior load-bearing wall assemblies are based on exterior wall assembly EW1a in BCBC Table A-9.10.3.1.A.

- Structural elements: 2 x 6 wood studs (38 mm x 140 mm) spaced 400 mm o.c.
- Interior side of studs: 1 layer of 15.9 mm fire-rated gypsum board

- Insulation: The 89 mm of mineral wool or glass-fibre insulation in EW1a are replaced by 140 mm of mineral wool or glass-fibre insulation
- Exterior side of studs: Exterior sheathing and siding.

2.4.1.2.6 Doors

Since the exit staircases are enclosed by walls with fire-resistance ratings of 2 hours, the doors between the public corridor and exit staircases are assumed to exhibit a 1.5 hour fire-protection rating in compliance with BCBC 3.1.8.4.

Since the walls between the suites and public corridors do not need to be fire-rated, the doors in these walls also need not be fire rated. However, as part of the alternative solution, we have assumed these walls exhibit a 1 hour rating and therefore have chosen to select doors to the suites that exhibit a 20-minute fire-protection rating.

2.4.1.3 Twelve-Storey Open Concept Office Building of Combustible Construction with Extra Exit Staircase (O12-CLT-Exit)

A second strategy for developing an alternative solution permitting combustible construction was considered. Each storey was assumed to be open concept office space. The floor/ceiling assemblies, the wall assemblies enclosing the exits and the exterior wall assemblies were assumed to be those described in the first alternative solution (Section 2.4.1.2). However wider exit staircases were used to provide for easier evacuation of a storey. The walls enclosing this stair case were assumed to be identical to those enclosing the exit staircases as described in Section 2.4.1.2.

2.4.1.4 Twelve-Storey Open Concept Office Building of Combustible Construction with More Reliable Sprinklers (O12-CLT-SP)

A third strategy for developing an alternative solution was considered. Each storey was assumed to be open concept office space. The floor/ceiling assemblies, the wall assemblies enclosing the exits and the exterior wall assemblies were assumed to be those described in the first alternative solution (Section 2.4.1.2). However the reliability of the sprinkler system was improved beyond the requirements of the BCBC and NFPA 13. In this study it has been assumed that the typical reliability of a sprinkler system is 0.89; that is, the sprinkler system activates and suppresses the fire 89% of the time. The alternative solution considered in this section entails taking steps to improve the reliability of the sprinkler system to 0.97.

2.4.1.5 Twelve-Storey Open Concept Office Building of Combustible Construction with Balconies (O12-CLT-Balconies)

A fourth strategy for developing an alternative solution was considered. The building assemblies described in 2.2.1.2 were not altered. The alternative solution considered in this section entails the construction of balconies 2 m deep beneath each window in the exterior walls of all apartments (except the ground floor).

3 Case Study Descriptions

Based on the building designs and solutions proposed in Chapter 2, characteristics of simulated cases are summarized together with applicable codes references in Tables 2.1 – 2.3.

The number of occupants in each building is the maximum permitted by codes.

The annual fire frequencies are derived from statistical data. For residential buildings, the frequencies are calculated based on 22,186 residential fires reported by an estimated population of 31,485,263 in Canada, 2002 (CCFMFC 2007). The results are similar to 2.61 x 10^{-3} /unit, given by Mailvaganam et al. (1992). For office buildings, the frequencies are calculated based on 7.68 x 10^{-6} /m^2 given by Mailvaganam et al. (1992).

The scenarios for each office building include combinations of 2 response times of the fire department and whether sprinklers are activated. For residential buildings, ignition time, daytime or night, is also considered. Thus, there are 4 scenarios for each office building and 8 scenarios for each residential building. Event trees for the office buildings and the residential buildings are shown in Figures 3.1 and 3.2. The reliability of smoke detectors and smoke alarms is not explicitly considered in the event tree. Instead, their effects are considered in the response model. The probabilities of the scenarios are calculated based on the occupancy specific reliabilities of sprinklers given by Hall (2012), response times of fire department given by U.S. Fire Administration (2006) and ignition times given by Ahrens (2012).

Event trees for the calculation of risk for buildings with higher reliable sprinklers are shown in Figure 3.3 and 3.4.

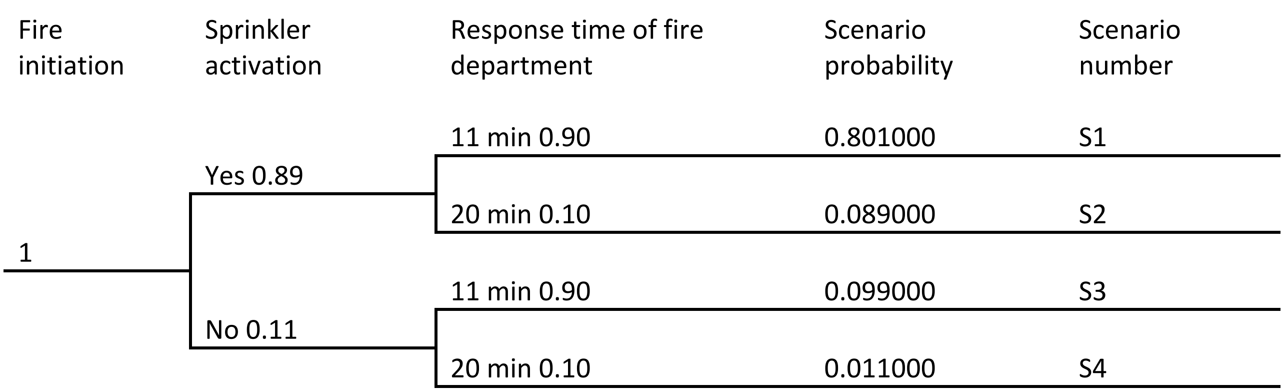

Figure 3.1 Event tree for office buildings (4 scenarios)

For all cases, the notification time of fire department is taken as the earliest of the activation time of smoke detectors or sprinklers and 150 s, at which heat release rate of a medium fire has reached 250 kW. The setup time of the fire department is taken as 240 s according to Mailvaganam et al. (1992).

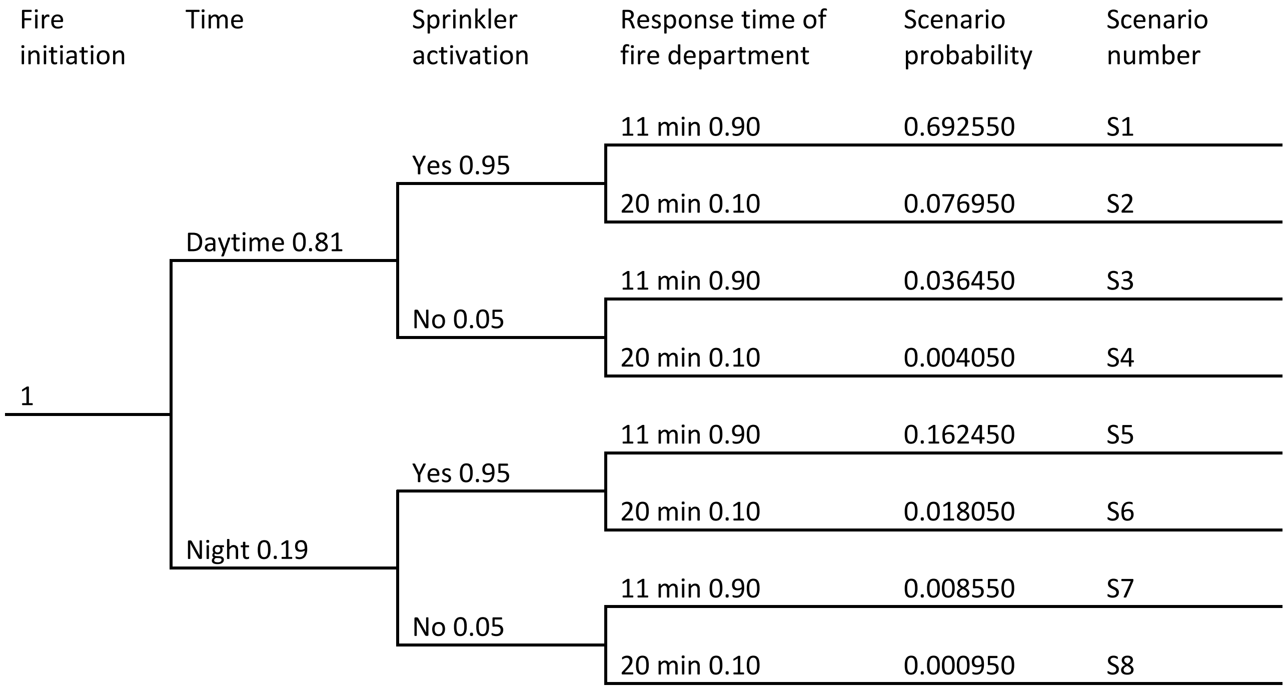

Figure 3.2 Event tree for residential buildings (8 scenarios)

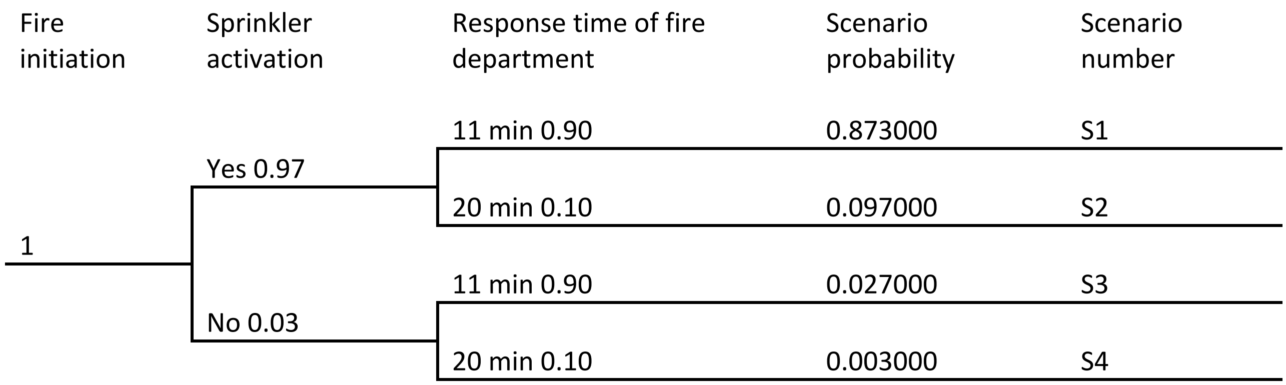

Figure 3.3 Event tree for office buildings with higher reliable sprinklers (4 scenarios)

For sprinkler systems, temperature rating, response time index, maximum distance between adjacent sprinklers are taken as 57 °C, 50 $m^{1/2}s^{1/2}$ and 4 m according to NFPA 13. The placement of sprinklers indicates 4 sprinklers in an 8 m x 8 m residential suite which place a sprinkler in each room if we include internal partitions. For office buildings, it means 12 sprinklers in a 12 m x 14 m suite and 16 sprinklers in a 12 m x 19 m suite.

Fuel loads in residential buildings and office buildings are taken as 854 MJ/m^2 and 1182 MJ/m^2 respectively. The value for residential buildings is the 90% percentile of the statistical data of Bwalya et al. (2004) for all home types since the number of the apartment suites surveyed was only 6. The value is slightly lower than 80% percentile, 948 MJ/m^2 for dwellings, proposed in Eurocode (EC1 2002). For office, the value used in the study is the 90% percentile of the statistical results of Zalok (2011). The 80% percentile proposed by Eurocode, 511 MJ/m2, may be not conservative.

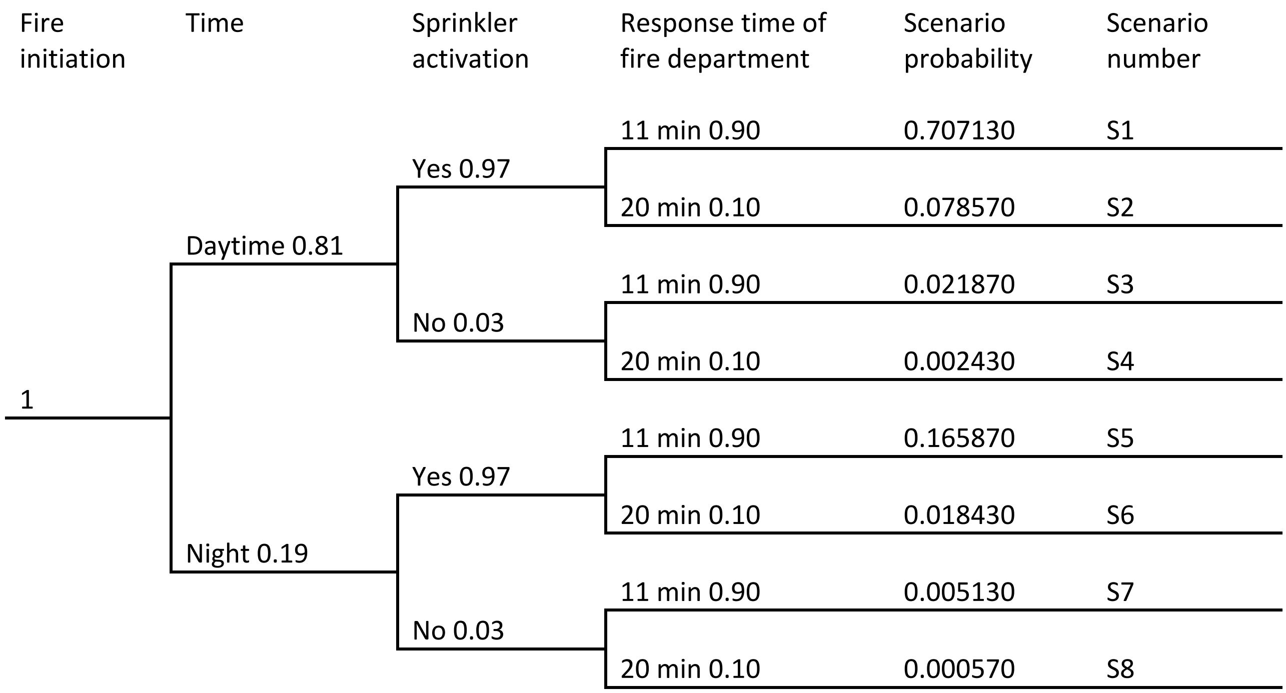

Figure 3.4 Event tree for residential buildings with higher reliable sprinklers (8 scenarios)

The design fires used in the case study are the medium t-squared fire for residential buildings based on the observations of the full-size bedroom fire tests performed at Carleton University (Li at al. 2015) and the recommendation of Karlsson and Quintiere (1999) and Eurocode 1 (CEN 2002). For office buildings, Karlsson and Quintiere (1999) proposed the fast t-squared fire, but Eurocode 1 (CEN 2002) recommends the medium t-squared fire. In the case study, the medium t-squared fire has been used for comparisons among residential and office buildings.

The maximum heat release rate of a fuel-controlled fire is taken as 275 kW/m^2 for both dwellings and office buildings. The value is based on the observations of the full-scale bedroom fire tests performed by Carleton University and is 10% higher than values recommended by Eurocode 1 (CEN 2002).

In the study, fire is set to happen in a suite on the first floor close to an exit for all the buildings except for the 12-storey office buildings, and in a suite on the second floor close to an exit for the 12-storey office buildings.

The code compliant fire protection system designs used in the study are shown in Table 3.4. The reliabilities of smoke alarms and smoke detectors are taken as 0.93 for residential buildings and 0.94 for office buildings, according to the statistical data given by Ahrens (2007, 2014).

Each suite of residential buildings has 3 windows of 1.5 m x 1.5 m. This produces a total window area equivalent to 10% of the living area. For office buildings, the number and height of windows for each suite are the same as those for the residential buildings. The width is determined so that a total window area equivalent to 10% of the floor area. However, the total width of 3 windows cannot be more than the width of the exterior wall of the suite. Therefore, the widths of the windows of the suite in 6-storey office buildings with 12 m x 14 m and 12 m x 19 m plan are 3.7 m and 4.0 m, respectively. For 12-storey office buildings, total width of the 3 windows is equal to the full width of the exterior wall of a compartmented suite.

Table 3.4 Fire protection system designs

Item	**Residential building**	**Office building**
Sprinklers	In suites and public corridors	In suites and public corridors
Heat detector	No	No
Smoke alarms	In suites	No
Smoke detectors	In public corridors and exit stair shafts	In exit stair shafts
Central alarm	Yes	Yes
Central alarm connected to fire department	Yes	Yes

The door of each room and corridor of the residential buildings has a width of 0.8 m and a height of 2.03 m. For office buildings, the door has a width of 1.6 m and a height of 2.03 m.

The initial leakage fraction of windows and doors is taken to be 0.15. This value means the ratio of the leaking area on a window or door to its area. The window will break and the leakage fraction will be changed to 1 when

$$(T - 20)/(300 - 20) + \mathrm{Abs}(\Delta p)/1500 \geq 1 \quad (3.1)$$

where T is the temperature in °C of the upper layer of the room and Δp is the pressure difference in Pa between the two sides of the window.

The leakage fraction of a door will be increased linearly after the accumulative energy of the door in fire is equal to the accumulative energy of the door exposed in the standard fire for a time period equivalent to its fire protection rating. When the accumulative energy in fire is 1.5 times that in the standard fire for a time period equivalent to its fire resistance rating, the fraction is increased to 1. The calculation of equivalent energy is based on Kodur et al. (2010).

In the case studies, all parameters used are applicable to typical occupants and buildings conforming to building codes. For example, 5 s is used as the time needed to awaken sleeping occupants. Occupants are assumed to be healthy occupants consisting of half adult people and half seniors.

All life risk results are given in the form of deaths and / or injuries in persons / fire and further analysis is based on these results.

The calculation process is time-consuming. To save time, each case is simulated for a time period which is just sufficient for all occupants to evacuate from the building.

The numbers of Monte Carlo runs of the evacuation and risk analysis models for all office buildings are set to from 200 to 1600, for 6-storey residential buildings from 800 to 6400, and for 12-storey residential buildings from 1600 to 3200. These numbers of runs can produce results with comparable precision, since the numbers of occupants in each room of office buildings are much greater than in residential buildings. The lower maximum number of Monte Carlo runs for 12-storey residential building is to avoid a very long running time. When Monte Carlo runs reach the maximum values or the change of the number of deaths is lower than 0.1%, the calculation for a scenario stops and that for next scenario starts.

Table 3.1 Characteristics of Simulated Cases

No.	R6S	R6L	R12	O6S	O6L	O12
Occupancy	Residential	Residential	Residential	Office	Office	Office
Storeys	6	6	12	6	6	12
Building area (m^2)	1152 BCBC 3.2.2.50	1728 BCBC 3.2.2.48	1728 BCBC 3.2.2.48	2976 NBCC 2015	3936 BCBC 3.2.2.56.(1)(c)	2916 NBCC 2015
Plan size (m x m)	18 x 64	18 x 96	18 x 96	31 x 96	41 x 96	54 x 54
Maximum travel distance in corridor (m)	27 BCBC 3.4.2.5.(1)(c)	43 BCBC 3.4.2.5.(1)(c)	43 BCBC 3.4.2.5.(1)(c)	37 BCBC 3.4.2.5.(1)(d)	37 BCBC 3.4.2.5.(1)(d)	40.5 BCBC 3.4.2.5.(1)(d)
Width of means of egress (m)	1.50 BCBC 3.3.1.9	1.50 BCBC 3.3.1.9	1.50 BCBC 3.3.1.9	1.50 BCBC 3.4.3.2.(1)	1.75 BCBC 3.4.3.2.(1)	1.10 / 1.70 BCBC3.4.3.2.(1)
Number of suites per storey	16	24	24	16	16	Open floor / 10
Total number of suites	96	144	288	96	96	12 / 120
Number of occupants per storey	64	96	96	288	384	290 / 262
Total number of occupants	384	576	1152	1728	2304	3480 / 3144
Annual fire frequency ($year^{-1}$)	0.2706	0.4058	0.8116	0.1371	0.1814	0.2687
Scenarios	8	8	8	4	4	4
Simulated time (s)	3000	3300	4200	3300	3300	4500

3.2 Specific settings for residential buildings

Case No.	R6S-NC / R6L-NC	R6S-LWF / R6L-LWF	R6S-CLT / R6L-CLT	R12-NC	R12-CLT	R12-CLT-D45	R12-CLT-BCN
Storeys	6	6	6	12	12	12	12
Building area (m^2)	1152 / 1728	1152 / 1728	1152 / 1728	1728	1728	1728	1728
Construction	Non-combustible	Light wood frame	CLT	Non-combustible	CLT	CLT with suite doors of 45 min FRR	CLT with balconies
Floor and ceiling assemblies: fire resistance rating	1 h BCBC 3.2.2.50 / BCBC 3.2.2.48	1 h BCBC 3.2.2.50 / BCBC 3.2.2.48	1 h BCBC 3.2.2.50 / BCBC 3.2.2.48	2 h NBCC 3.2.2.47	2 h NBCC 3.2.2.47	2 h NBCC 3.2.2.47	2 h NBCC 3.2.2.47
Floor and ceiling assemblies: configuration	F1c	F10f	1 layer of 12.7 mm regular gypsum board attached to bottom of 105 mm CLT	F1b	1 layer of 12.7 mm regular gypsum board attached to bottom of 175 mm CLT	1 layer of 12.7 mm regular gypsum board attached to bottom of 175 mm CLT	1 layer of 12.7 mm regular gypsum board attached to bottom of 175 mm CLT
Staircase walls: fire resistance rating	Non-loadbearing 1 h NBCC 3.4.4.1	Loadbearing 1 h NBCC 3.4.4.1	Loadbearing 1 h NBCC 3.4.4.1	Non-Loadbearing 2 h NBCC 3.4.4.1	Loadbearing 2 h NBCC 3.4.4.1	Loadbearing 2 h NBCC 3.4.4.1	Loadbearing 2 h NBCC 3.4.4.1
Staircase walls: configuration	S14a	W6d	1 layer of 12.7 mm regular gypsum board attached to each side of 105 mm CLT	S6a	1 layer of 12.7 mm regular gypsum board attached to each side of 175 mm CLT	1 layer of 12.7 mm regular gypsum board attached to each side of 175 mm CLT	1 layer of 12.7 mm regular gypsum board attached to each side of 175 mm CLT
Exterior walls: fire resistance rating	Non-loadbearing 1 h BCBC 3.2.2.50	Loadbearing 1 h BCBC 3.2.2.50 / BCBC 3.2.2.48	Loadbearing 1 h BCBC 3.2.2.50 / BCBC 3.2.2.48	Non-loadbearing 1 h NBCC 3.2.3.7	Non-Loadbearing 1 h NBCC 3.2.3.7	Non-Loadbearing 1 h NBCC 3.2.3.7	Non-Loadbearing 1 h NBCC 3.2.3.7

	/ BCBC 3.2.2.48						
Exterior wall: configuration	S10a	EW1a with 38 mm x 89 mm studs replaced by 38 mm x 140 mm studs	1 layer of 12.7 mm regular gypsum board attached to interior side of 105 mm CLT	S2d	EW1a with 38 mm x 89 mm studs replaced by 38 mm x 140 mm studs	EW1a with 38 mm x 89 mm studs replaced by 38 mm x 140 mm studs	EW1a with 38 mm x 89 mm studs replaced by 38 mm x 140 mm studs
Public corridor walls: fire resistance rating	Non-loadbearing 1 h BCBC 3.2.2.50 / BCBC 3.2.2.48	Loadbearing 1 h BCBC 3.2.2.50 / BCBC 3.2.2.48	Loadbearing 1 h BCBC 3.2.2.50 / BCBC 3.2.2.48	Non-loadbearing 1 h BCBC 3.3.4.2	Non-Loadbearing 1 h BCBC 3.3.4.2	Non-Loadbearing 1 h BCBC 3.3.4.2	Non-Loadbearing 1 h BCBC 3.3.4.2
Public corridor walls: configuration	S14a	W6d	1 layer of 12.7 mm regular gypsum board attached to each side of 105 mm CLT	S6e	W6d with 38 mm x 89 mm studs replaced by 38 mm x 140 mm studs	W6d with 38 mm x 89 mm studs replaced by 38 mm x 140 mm studs	W6d with 38 mm x 89 mm studs replaced by 38 mm x 140 mm studs
Walls between suites: fire resistance rating	Non-loadbearing 1 h BCBC 3.3.4.2	Non-loadbearing 1 h BCBC 3.3.4.2	Non-loadbearing 1 h BCBC 3.3.4.2	Non-Loadbearing 1 h BCBC 3.3.4.2	Loadbearing 2 h NBCC 3.2.2.47	Loadbearing 2 h NBCC 3.2.2.47	Loadbearing 2 h NBCC 3.2.2.47
Walls between suites: configuration	S6e	W6d with 38 mm x 89 mm studs replaced by 38 mm x 140 mm studs	W6d with 38 mm x 89 mm studs replaced by 38 mm x 140 mm studs	S6e	1 layer of 12.7 mm regular gypsum board attached to each side of 175 mm CLT	1 layer of 12.7 mm regular gypsum board attached to each side of 175 mm CLT	1 layer of 12.7 mm regular gypsum board attached to each side of 175 mm CLT
Public doors: fire resistance rating	45 min BCBC 3.1.8.4	45 min BCBC 3.1.8.4	45 min BCBC 3.1.8.4	1.5 h BCBC 3.1.8.4	1.5 h BCBC 3.1.8.4	1.5 h BCBC 3.1.8.4	1.5 h BCBC 3.1.8.4
Suite doors: fire	20 min	20 min	20 min	20 min	20 min	45 min	20 min

protection rating	BCBC 3.1.8.10	BCBC 3.1.8.10	BCBC 3.1.8.10	BCBC 3.1.8.10	BCBC 3.1.8.10	Alternative solution	BCBC 3.1.8.10
Balconies	No	No	No	No	No	No	Yes

Table 3.3 Specific settings for office buildings

Case No.	O6S-NC/O6L-NC	O6S-LWF/O6L-LWF	O6S-CLT/O6L-CLT	O12-NC	O12-CLT	O12-CLT-CPT	O12-CLT-Exit	O12-CLT-BCN
Storeys	6	6	6	12	12	12	12	12
Building area (m^2)	2976 / 3936	2976 / 3936	2976 / 3936	2916	2916	2916	2916	2916
Construction	Non-combustible	Light wood frame	CLT	Non-combustible with open floor	CLT with open floor	CLT with 1 h rated non-loadbearing wood frame separation	CLT with open floor and wider exit stairs	CLT with open floor and balconies
Floors and ceiling assemblies: loadbearing fire resistance rating	1 h BCBC3.2.2.56.(2)	1 h BCBC3.2.2.56.(2)	1 h BCBC3.2.2.56.(2)	2 h NBCC 3.2.2.54	2 h NBCC 3.2.2.54	2 h NBCC 3.2.2.54	2 h NBCC 3.2.2.54	2 h NBCC 3.2.2.54
Floors and ceiling assemblies: configurations	F1c	F10f	1 layer of 12.7 mm regular gypsum board attached to bottom of 105 mm CLT	F1b	1 layer of 12.7 mm regular gypsum board attached to bottom of 175 mm CLT	1 layer of 12.7 mm regular gypsum board attached to bottom of 175 mm CLT	1 layer of 12.7 mm regular gypsum board attached to bottom of 175 mm CLT	1 layer of 12.7 mm regular gypsum board attached to bottom of 175 mm CLT
Staircase walls: fire resistance rating	Loadbearing 1 h NBCC 3.4.4.1	Loadbearing 1 h NBCC 3.4.4.1	Loadbearing 1 h NBCC 3.4.4.1	Non-Loadbearing 2 h NBCC 3.4.4.1	Loadbearing 2 h NBCC 3.4.4.1	Loadbearing 2 h NBCC 3.4.4.1	Loadbearing 2 h NBCC 3.4.4.1	Loadbearing 2 h NBCC 3.4.4.1
Staircase walls:	S10a	W6d with 38 mm x 89 mm	1 layer of 12.7 mm regular	S6a	1 layer of 12.7 mm	1 layer of 12.7 mm	1 layer of 12.7 mm	1 layer of 12.7 mm

configuration		studs replaced by 38 mm x 140 mm studs	gypsum board attached to each side of 105 mm CLT		regular gypsum board attached to each side of 175 mm CLT	regular gypsum board attached to each side of 175 mm CLT	regular gypsum board attached to each side of 175 mm CLT	regular gypsum board attached to each side of 175 mm CLT
Exterior wall: fire resistance rating	Loadbearing 1 h BCBC 3.2.2.56(2)	Loadbearing 1 h BCBC 3.2.2.56(2)	Loadbearing 1 h BCBC 3.2.2.56(2)	Non-loadbearing 1 h NBCC 3.2.3.7	Loadbearin g 2 h NBCC 3.2.2.54	Non-Loadbearin g 1 h NBCC 3.2.3.7	Loadbearin g 2 h NBCC 3.2.2.54	Loadbearin g 2 h NBCC 3.2.2.54
Exterior wall: configuration	S10a	EW1a with 38 mm x 89 mm studs replaced by 38 mm x 140 mm studs	1 layer of 12.7 mm regular gypsum board attached to interior side of 105 mm CLT	S2d	1 layer of 12.7 mm regular gypsum board attached to interior side of 175 mm CLT	EW1a with 38 mm x 89 mm studs replaced by 38 mm x 140 mm studs	1 layer of 12.7 mm regular gypsum board attached to interior side of 175 mm CLT	1 layer of 12.7 mm regular gypsum board attached to interior side of 175 mm CLT
Public corridor walls: fire resistance rating	Loadbearing 1 h BCBC 3.2.2.56(2)	Loadbearing 1 h BCBC 3.2.2.56(2)	Loadbearing 1 h BCBC 3.2.2.56(2)	N/A	N/A	Non-Loadbearin g 1 h Alternative solution	N/A	N/A
Public corridor walls: configuration	S10a	W6d with 38 mm x 89 mm studs replaced by 38 mm x 140 mm studs	1 layer of 12.7 mm regular gypsum board attached to each side of 105 mm CLT	N/A	N/A	W1a	N/A	N/A
Walls between	Not required	Not required	Not required	N/A	N/A	Loadbearin g 2 h	N/A	N/A

suits: fire resistance rating						Alternative solution		
Walls between suits: configuration	S1a	W1c	W1c	N/A	N/A	1 layer of 12.7 mm regular gypsum board attached to interior side of 175 mm CLT	N/A	N/A
Public doors: fire protection rating	45 min BCBC 3.1.8.4	45 min BCBC 3.1.8.4	45 min BCBC 3.1.8.4	1.5 h BCBC 3.1.8.4	1.5 h BCBC 3.1.8.4	1.5 h BCBC 3.1.8.4	1.5 h BCBC 3.1.8.4	1.5 h BCBC 3.1.8.4
Suite doors: fire protection rating	20 min BCBC 3.1.8.10	20 min BCBC 3.1.8.10	20 min BCBC 3.1.8.10	N/A	N/A	20 min BCBC 3.1.8.10	N/A	N/A
Balconies	No	No	No	No	No	No	No	Yes

4 Results and Discussion

In this chapter, the modeling results are compared with statistical data and case studies for the residential and office buildings proposed in Chapters 2 and 3 are presented.

4.1 Comparison of Simulation Results with Statistical Data

Fires in non-combustible apartment buildings with the layouts shown in Figures 2.1 and 2.2 (R6S-NC, R6L-NC and R12-NC) are simulated to represent apartment buildings of various areas and storeys found in statistical surveys. These buildings are called small, large, and high buildings in this Section. More details of these buildings are given in Tables 3.1 and 3.2.

Figure 4.1 shows the event tree for the buildings to simulate the scenarios based on which statistical data were produced. Compared with 8 scenarios given in Figure 3.2, 16 scenarios are used in this section, with 8 additional scenarios without smoke alarms. The reason is that the event tree in Figure 3.2 reflects requirements on new buildings but Figure 4.1 shows the installation situation and performance of fire protection systems in existing buildings. According to US statistical data, 4.6% of homes (including apartments) had sprinklers, showing a reliability of 0.95 (Hall 2012), and 87% of apartments had smoke alarms, showing a reliability of 0.90 (Ahrens 2014). The reliability of sprinklers is explicitly considered in the scenario probability calculation but that of smoke alarms is implicitly included in the response model.

Figures 4.2 and 4.3 show the numbers of deaths and injuries for different scenarios in the three buildings. Figures 4.4 – 4.10 show the expected risks of death and injury, calculated by dividing the summation of the product of the probability and consequence by the summation of the probability of each applicable scenario. These figures show that the effects of the construction area and storeys on the numbers of deaths and injuries for scenarios and on the expected risks of death, injury, and casualty for scenario combinations are slight. The reason is that for residential buildings with properly protected exits, casualty is limited to occupants in the fire origin room.

Comparisons between the results of different scenarios show that sprinklers and smoke alarms can make a large difference. For the scenarios with activated sprinklers, Figures 4.2 and 4.3 show that the simulation produces no deaths and no injuries. This is in good agreement with the statistical data for 2006 – 2010 US home (including apartments) fires that the presence of sprinklers cut the fire death rate by 83%, from 0.0073 persons / fire to 0.0013 persons / fire (Hall 2012), considering the difference between the activation and presence of sprinklers.

Figures 4.2 and 4.3 show that smoke alarms reduce night fire deaths significantly, but their effects on fire injuries and daytime fire deaths are slight. As compared in Figure 4.4, the expected risks of death are 0.00575 persons / fire for scenarios with smoke alarms and 0.04452 persons / fire for scenarios without smoke alarms. The ratio of the number without smoke alarms to that with smoke alarms, 7.7, is much larger than the ratio 1.2, derived from the statistical data for 2007 – 2011 US fire deaths of 0.00342 persons / fire for apartments with smoke alarms and 0.00405 persons / fire for apartments without smoke alarms (Ahrens 2014).

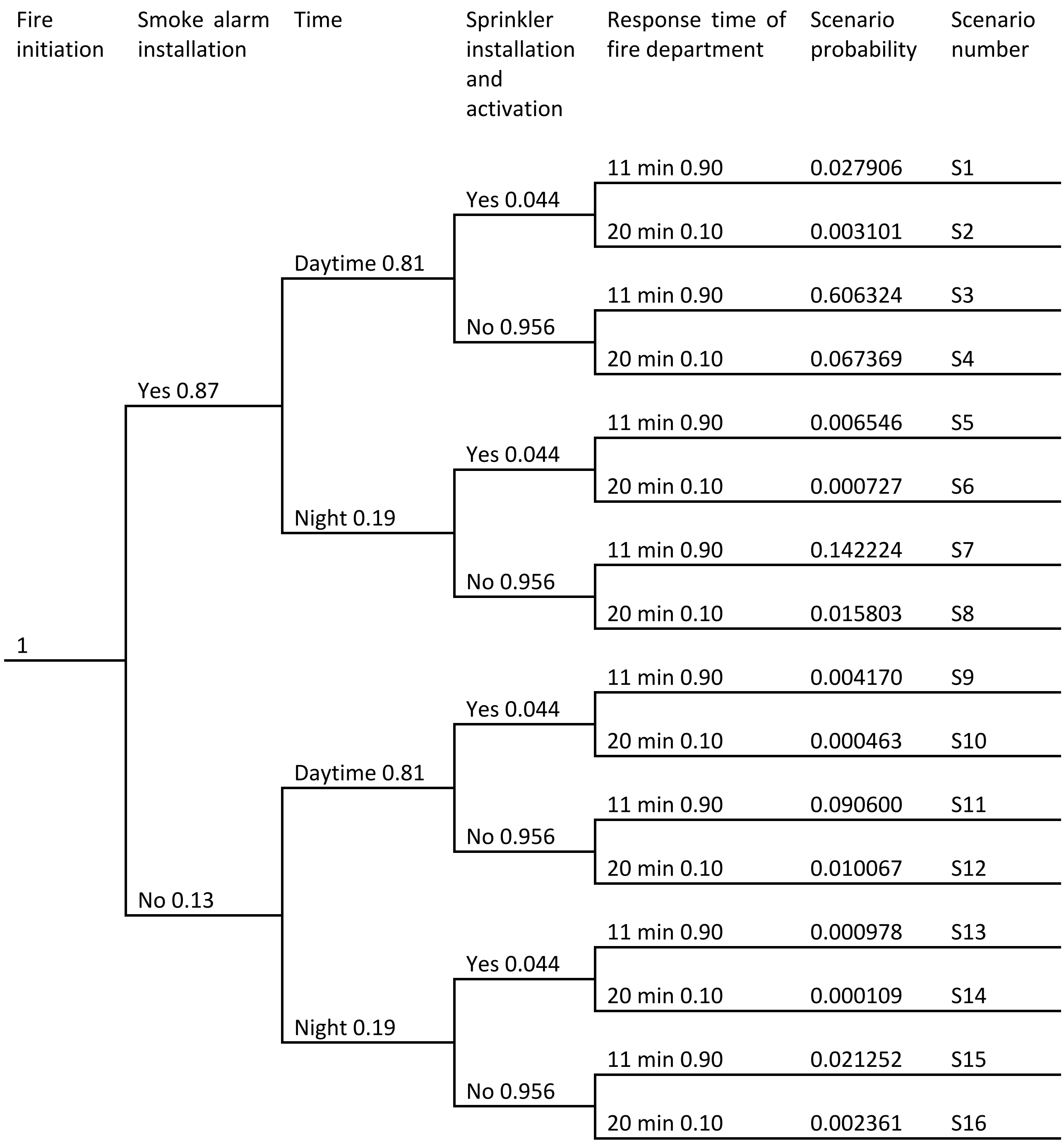

Figure 4.1 Event tree for residential buildings to simulate statistical data (16 scenarios)

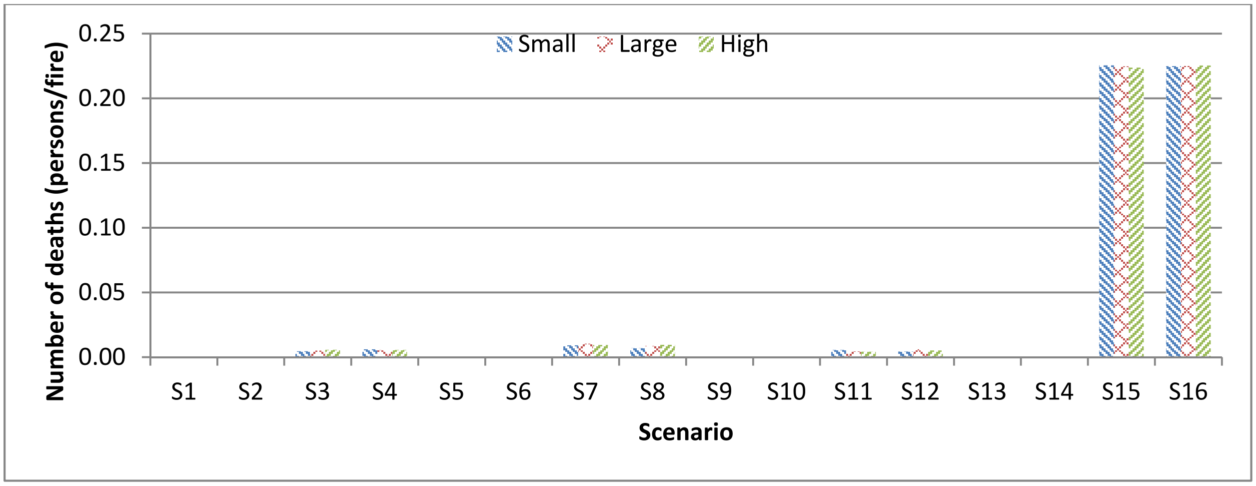

Figure 4.2 Number of deaths for different scenarios of non-combustible residential buildings

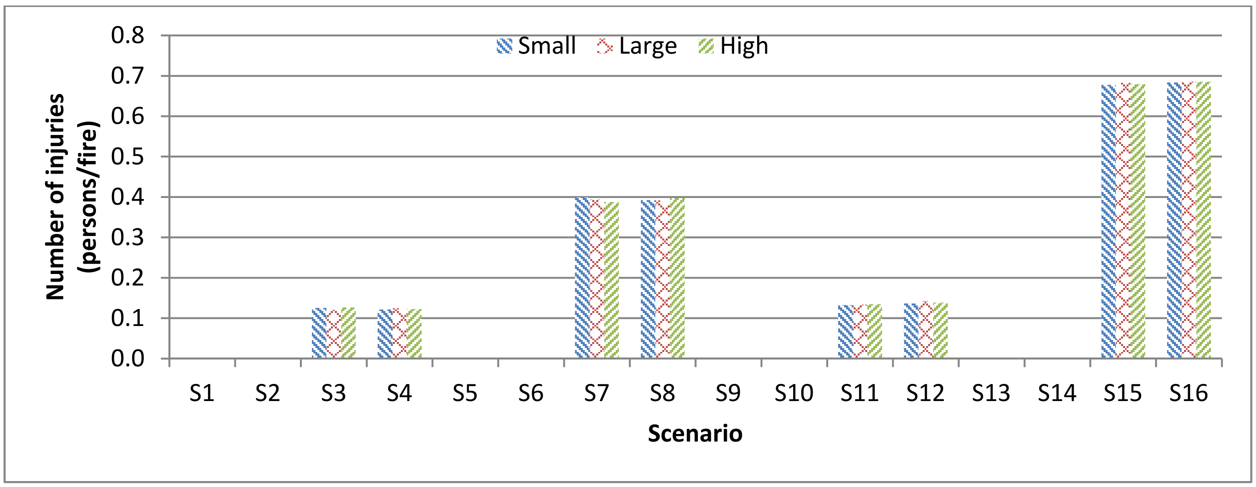

Figure 4.3 Number of injuries for different scenarios of non-combustible residential buildings

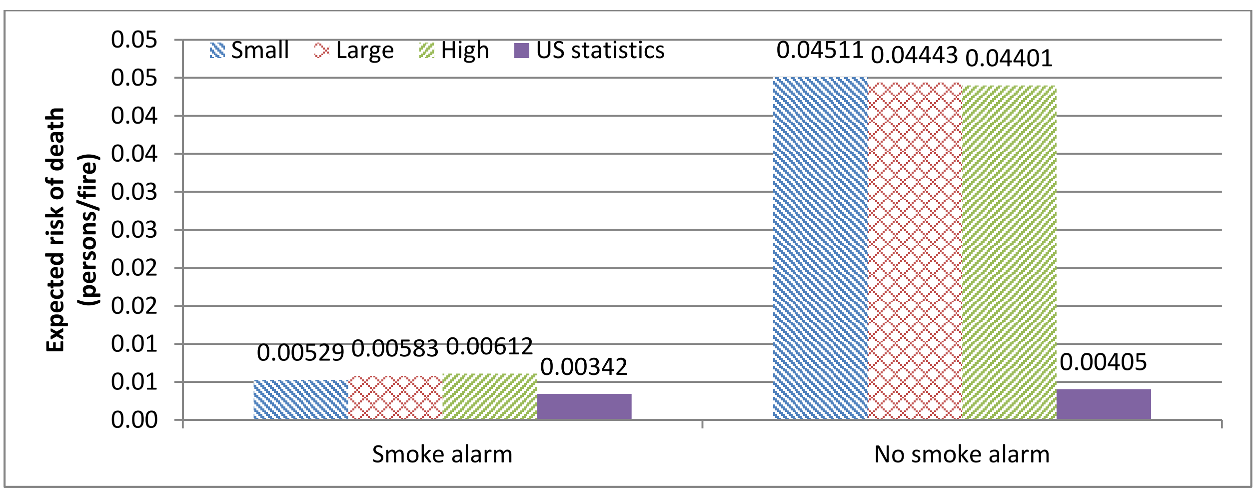

Figure 4.4 Expected risk of death for non-combustible residential buildings with and without smoke alarms

Figure 4.5 shows that the expected risks of injury are 0.1679 persons / fire for scenarios with smoke alarms and 0.2279 persons / fire for scenarios without smoke alarms. The ratio of the number without smoke alarms to that with smoke alarms, 1.4, is in rough agreement with the statistical data for 2007 – 2011 US fire injuries of 0.0575 persons / fire for apartments with smoke alarms and 0.0493 persons / fire for apartments without smoke alarms (Ahrens 2014). The lower number of injuries for apartments without smoke alarms than that with smoke alarms shows the insignificant effects of smoke alarms on injuries.

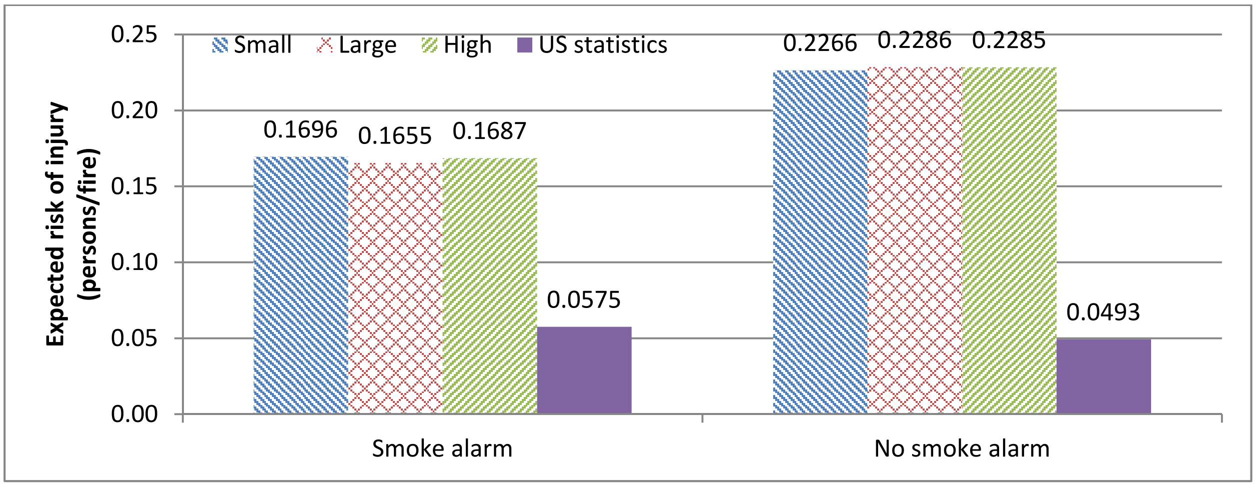

Figure 4.5 Expected risk of injury for non-combustible residential buildings with and without smoke alarms

The time of fire affects the numbers of deaths and injuries remarkably. As shown in Figures 4.2, the night fire death rates are about 45 times the daytime rates for the scenarios without sprinklers and smoke alarms, and about 2 times for the scenarios without sprinklers but with smoke alarms. Figure 4.6 shows that the expected risks of death are 0.00491 persons / fire for daytime scenarios and 0.03583 persons / fire for night scenarios, producing a ratio of the night number to the daytime number of 7.3. The ratio is in approximate agreement with the ratio 3.6 derived from the statistical results for 2006 – 2010 US apartment fires that the daytime and night fire deaths were 0.00261 persons / fire and 0.00927 persons / fire (Ahrens 2012).

Figure 4.7 shows the expected risks of injury are 0.1203 persons / fire for the daytime scenarios and 0.4121 persons / fire for the night scenarios. The ratio between the two numbers is 3.4, in rough agreement with the ratio 1.8, derived from the statistical data for 2006 – 2010 US fire injuries of 0.0328 persons / fire for daytime fires and 0.0605 persons / fire for night fires (Ahrens 2012).

Figures 4.8 – 4.10 show that the expected risks of death, injury, and casualty (death and injury) are about 0.01067 persons / fire, 0.1757 persons / fire, and 0.1864 persons / fire. These values are only 7% lower than, 9% higher than, and 8% higher than 0.01146 persons / fire, 0.1613 persons / fire, and 0.1728 persons / fire, which are the corresponding statistical data for 2002 Canadian apartment fires (CCFMFC 2007). But they are 3.0, 3.1, and 3.1 times 0.00350 persons / fire, 0.0566 persons / fire, and 0.0601 persons / fire, the corresponding statistical values for 2007 – 2011 US apartment fires (Ahrens 2014).

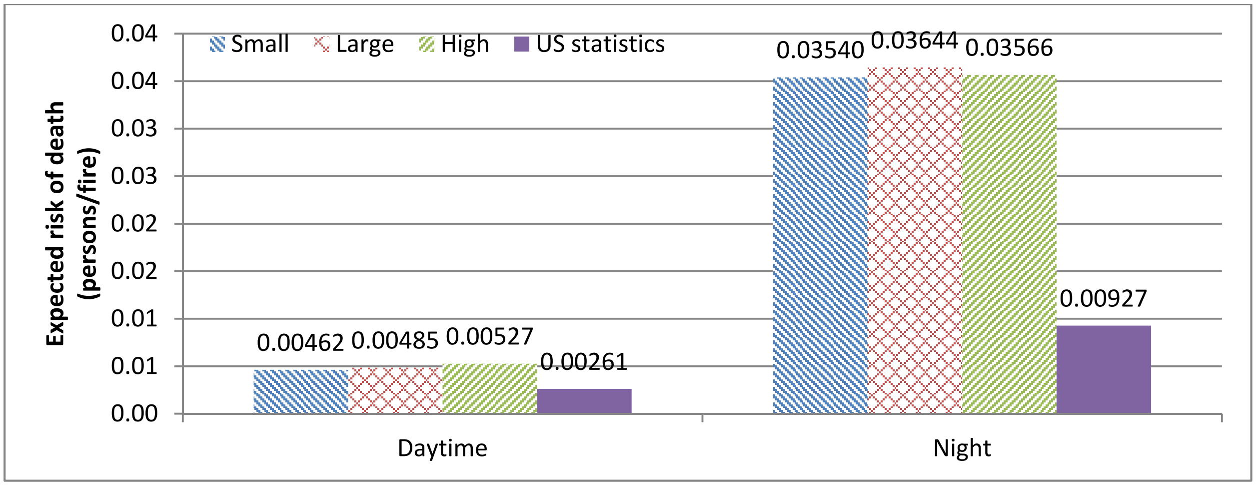

Figure 4.6 Expected risk of death for non-combustible residential buildings in daytime and at night

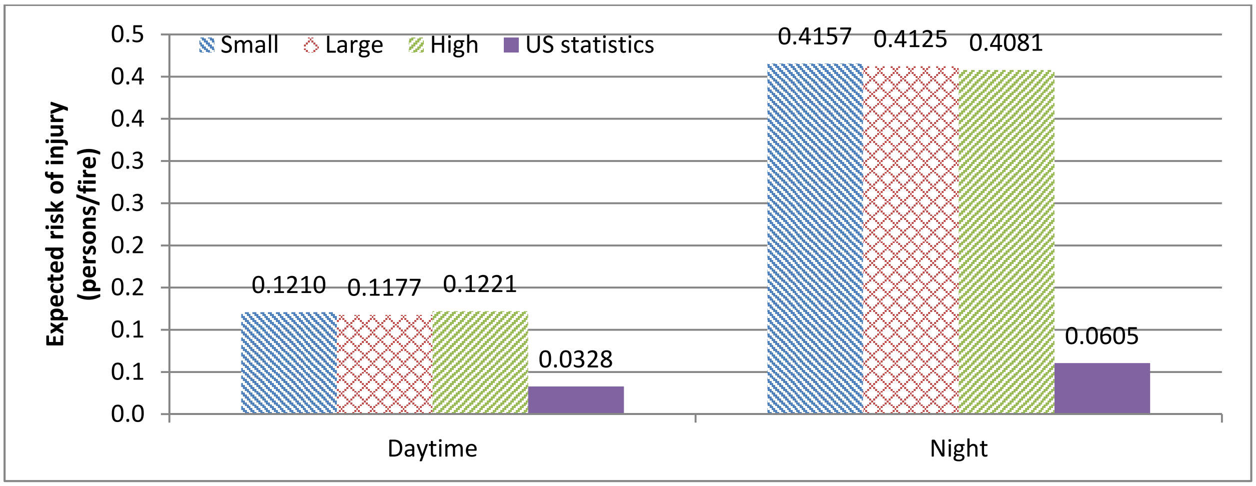

Figure 4.7 Expected risk of injury for non-combustible residential buildings in daytime and at night

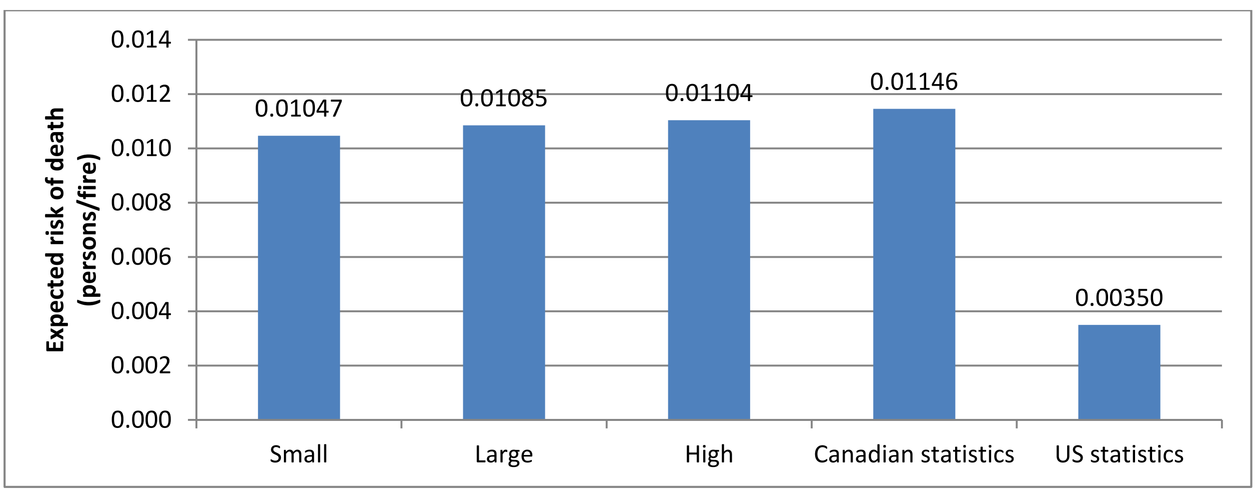

Figure 4.8 Expected risk of death for non-combustible residential buildings

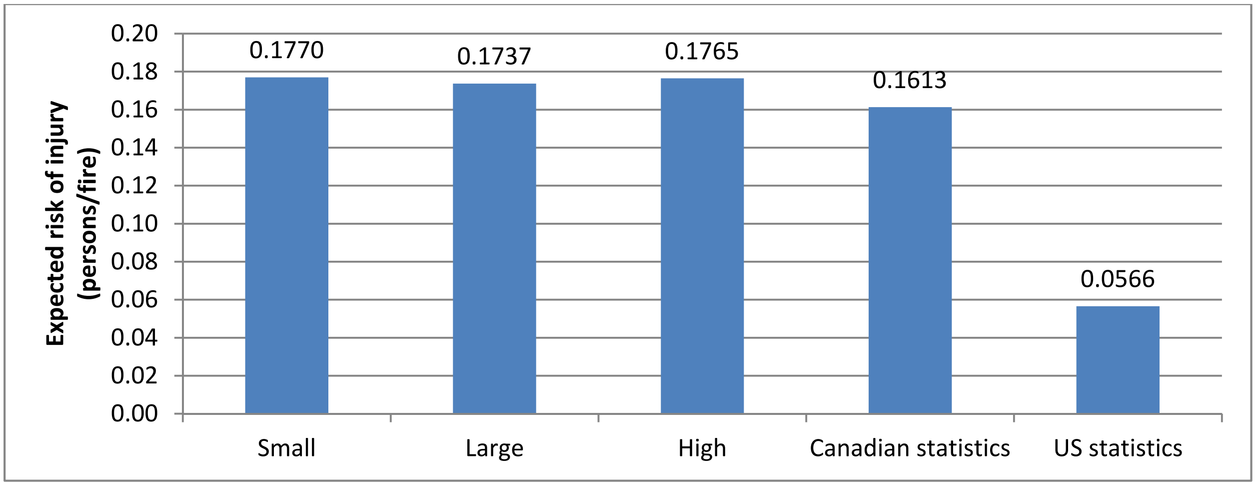

Figure 4.9 Expected risk of injury for non-combustible residential buildings

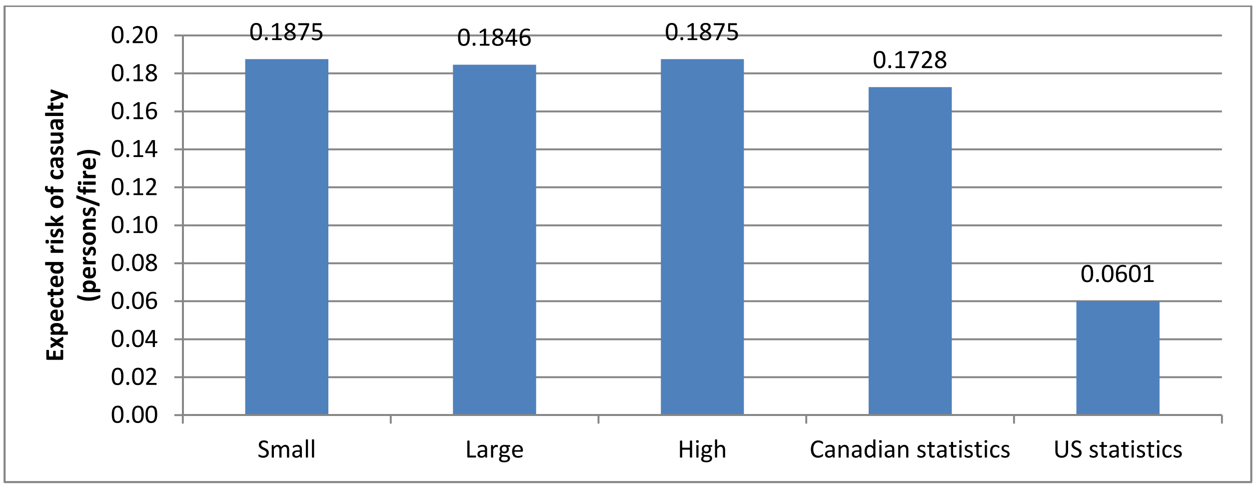

Figure 4.10 Expected risk of casualty (death or injury) for non-combustible residential buildings

The results conform to Canadian statistics much better than to US data. This may be due to the different statistical data, which have been discussed elsewhere (Hall 2005).

The comparison of the predictions and statistical data shows that the results produced by CUrisk are in good agreement with the corresponding Canadian statistical values, but more conservative than the US statistical data. Since the difference between the statistical data of different sources is significant, it is difficult to produce predictions quantitatively conforming to the statistical data from all sources. Therefore, the results given are expected to be explained in relative rather absolute ways. However, absolute values can be valuable supplements. Additionally, the numbers of deaths and injuries are generally larger and more stable than those for deaths and can be a better risk indicator in the event that difference between fire deaths is insignificant.

4.2 Office Buildings

4.2.1 Small-Area Six-Storey Office Buildings

The small-area office buildings with the layout shown in Figure 2.3 (O6S-CLT, O6S-LWF and O6S-NC) are simulated. These buildings are called CLT, LWF, and NC buildings in this section. More details of these buildings are given in Tables 3.1 and 3.3. The event tree is given in Figures 3.1 and 3.3. Simulation results are shown in Figures 4.11 – 4.19.

Figures 4.11 and 4.12 show the temperature development in the fire origin rooms, corridors and staircases close to the fire origin rooms for scenario S4, in which sprinklers fail to activate. Figure 4.13 shows the maximum and minimum occupants still in the building as a percentage of total occupants in all Monte Carlo evacuation processes for scenario S4. The range between the minimum and maximum remaining occupants reflects the randomness of the evacuation process, which is considered in Monte Carlo simulations.

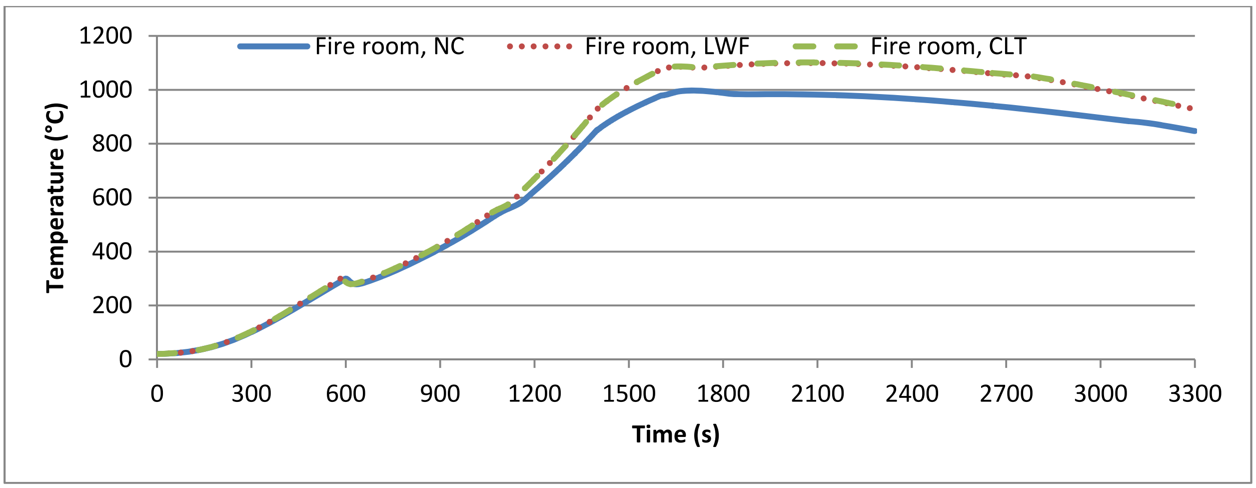

Figure 4.11 Upper layer temperatures in fire origin rooms for scenario S4 of small office buildings

The temperatures in the staircases are always under 120 °C. Temperatures in corridors are lower than 120 °C until 1608 s for the LWF and CLT buildings and until 1698 s for the NC building. Below 120 °C, the Fractional Effective Dose (FED) due to high temperature or heat is not accumulated so hot gases do not injure occupants. By this time, less than 6% of occupants remain in the buildings. They are occupants on floors different from the fire origin floors since the times that the occupants on the fire floors need to evacuate the buildings are 226 s to 1500 s including response times of 198 s to 402 s. These indicate that the fire deaths or injuries happen in the fire origin rooms.

At 328 s, the temperatures in the fire origin rooms have been 120 °C. Further rise can lead to injury or death of occupants, since the times that the occupants in the fire origin rooms start to evacuate are 198 s to 240 s and the times that the occupants have evacuated the buildings are 226 s to 1350 s. Occupants with low travel speed may be killed or injured in the evacuation process as shown in Figure 4.15. The numbers of deaths for different scenarios and the expected risk of death combining all scenarios are not given because the numbers are too small to show stable results.

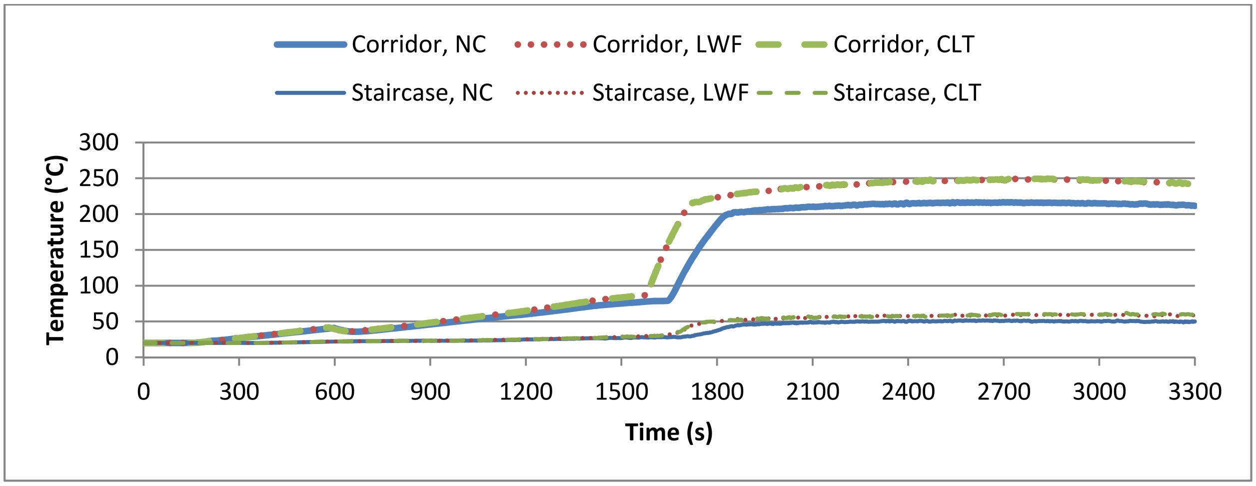

Figure 4.12 Upper layer temperatures in corridors and staircases close to fire origin rooms for scenario S4 of small office buildings

The timelines of temperature development in the fire origin rooms and corridors, and evacuation also indicate that the corridor of the NC building provides slightly longer safe evacuation time than those of the LWF and CLT buildings, but the fire origin rooms of all three buildings are similar in terms of both life risk and safety margin. This is a result of different predominant processes in the different locations.

In the fire origin rooms, the heat released by the fire is very large, the smoke temperatures are very high and the temperature rise is fast. The effect of boundary heat absorption is insignificant before the temperature difference between the gas and boundary becomes very large. The differences between the temperatures in the fire origin rooms of the three buildings are no more than 10 °C within 788 s, which will lead to similar fractional effective dose accumulation and probabilities of death and injury due to heat. After 788 s, while the temperatures of the CLT and LWF buildings start to become higher than that of the NC building, all of them are high enough (more than 345 °C) to lead to fast fractional effective dose accumulation and therefore produce similar probabilities of injury and death.

In the corridors, the smoke temperatures are low and the temperature rise is a slow process. In the long duration of smoke movement, the temperatures become sensitive to the heat transfer to boundaries. This will eventually lead to different temperature levels for the corridors constructed with different materials.

Figure 4.13 shows that the maximum and minimum of remaining occupants as a percentage of total occupants do not change with the construction type because of the similar fire development in the three buildings.

The full evacuation process can be broken into three stages.

In the first stage, the occupants in the fire origin rooms perceive fire cues or receive warning signals, pull the central fire alarm and evacuate. During this period, the number of evacuating occupants is small. As a result, no queuing happens and the travel speeds of occupants determine the evacuation speed. Additionally, the probability of central alarm being pulled is close to 1 due to the large numbers of occupants in the fire origin rooms.

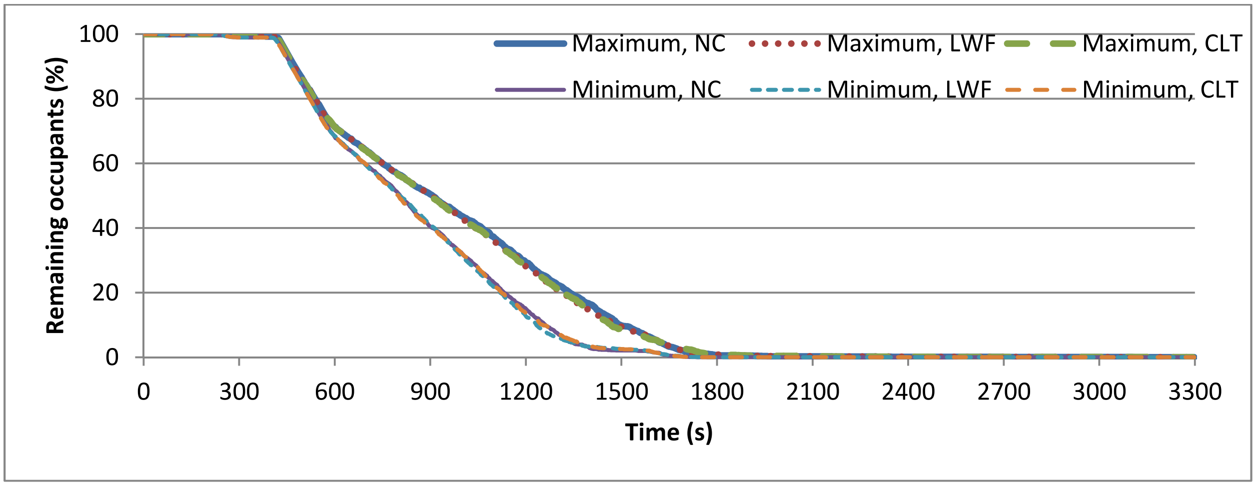

Figure 4.13 Maximum and minimum remaining occupants as a percentage of total occupants for scenario S4 of small office buildings

In the second stage, the occupants in other rooms hear the central alarm and evacuate. At first, the population density of evacuating occupants is not high; queuing is not a serious problem; the evacuation speed is dependent on the travel speeds of occupants. As the number of evacuating occupants increases, the population density becomes increasingly higher and queuing happens. The evacuation speed becomes the minimum of the values determined by the travel speeds based on the population density and by evacuation capacities of doors and staircases.

Since the probability of the central alarm activation is lower than 1, a small percentage of occupants do not evacuate until the third stage starting from the arrival of the fire department. Occupants evacuating out of the buildings in this stage also include those with very low travel speed. The evacuation in this stage is strongly random. The times at which 90%, 99%, and 100% of occupants evacuate the buildings are 1498 s, 1786 s, and 3184 s.

Similar analysis can be made for scenario S3. As shown in Figure 4.15, the numbers of injuries for scenarios S3 and S4 are in agreement with or on the same magnitudes as the statistical data for 2002 Canadian office fires (CCFMFC 2007) and 2000 – 2004 US office fires (Ahrens 2007).

Scenarios S1 and S2 have much milder temperature development due to the activation of sprinklers as shown in Figure 4.14 for scenario S2. As a result, Figure 4.15 shows that for these scenarios, no fire injury is predicted.

Figures 4.16 - 4.19 show that all three buildings have very low life risk in terms of injury and casualty due to the use of sprinklers. Specifically, the expected risk is 7.5% of the Canadian statistical value and 28%

of the US statistical value in terms of injury. If sprinklers with higher reliability, 0.97 (shown as CLT-SP in the Figures), instead of general reliability, 0.89, are used, the risk will be reduced further to 27% of that for sprinklers with general reliability. The reason is that the risk is a result of the failure of fire protection systems. When the reliability of sprinklers increases from 0.89 to 0.97, the probability of failure will decrease from 0.11 to 0.03.

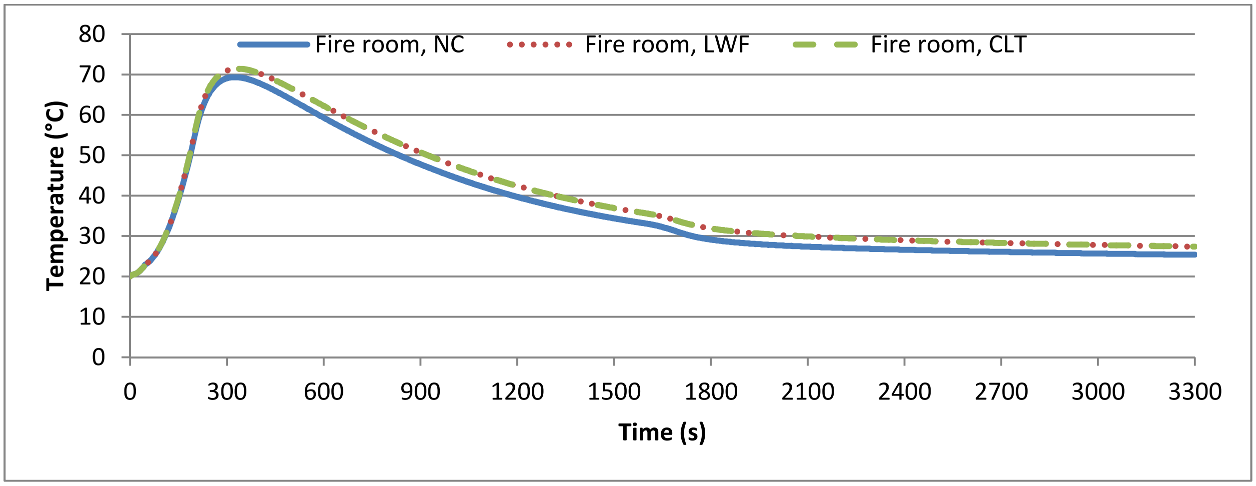

Figure 4.14 Upper layer temperatures in fire origin rooms for scenario S2 of small office buildings

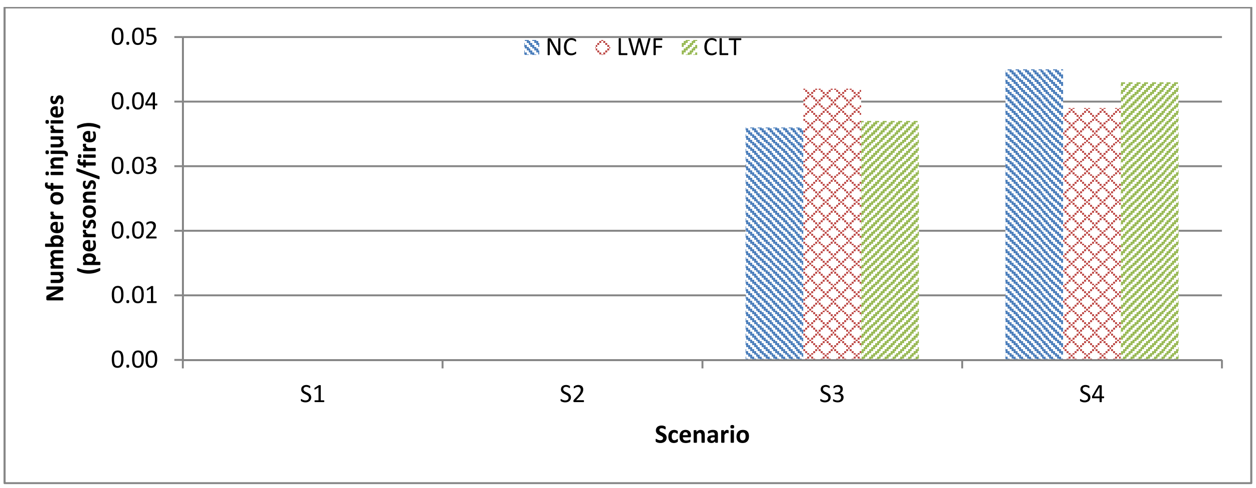

Figure 4.15 Number of injuries for different scenarios of small office buildings

Figures 4.18 and 4.19 show the relative risk, defined as the ratio of the expected risk of casualty (death or injury) of a building to a reference value.

$$R_r = (EROD + EROI)/(EROD_r + EROI_r) \quad (4.1)$$

where EROD and EROI are the expected risks of death and injury, and subscript r denotes the applicable reference values.

The three buildings show relative risk of about 0.08 – 0.09 compared to the Canadian statistical value, indicating that all three buildings have similar risk and all are much lower than the statistical value. The

LWF and CLT buildings show relative risk of 1.11 and 1.03 compared to the expected risk of casualty of the NC building. Additionally, the expected risks of death for the three buildings are quite similar. Therefore, the risks of the three buildings are very close. It is clear that the difference between the life risks of different constructions is insignificant.

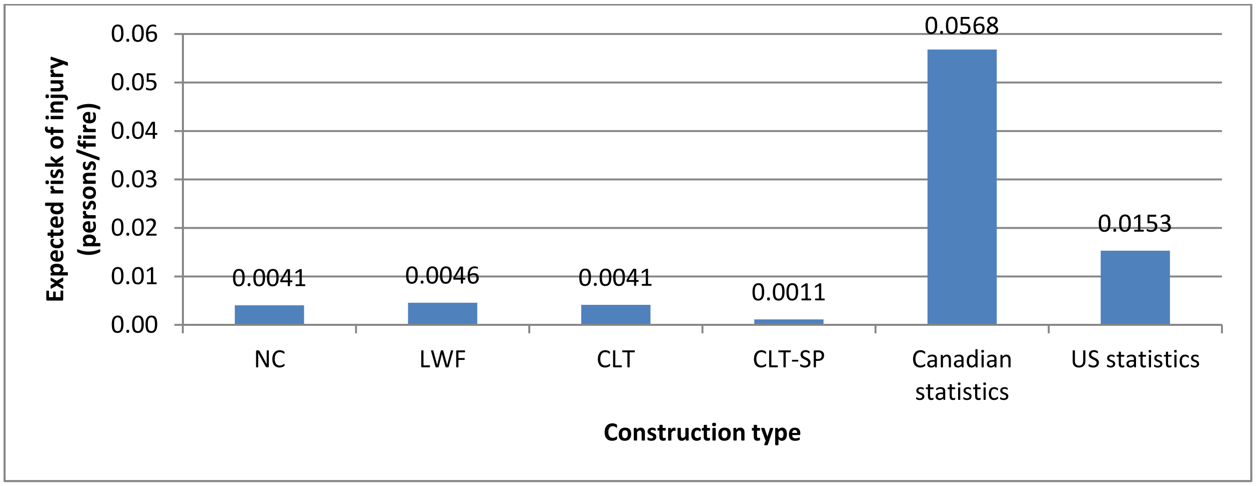

Figure 4.16 Expected risk of injury for small office buildings

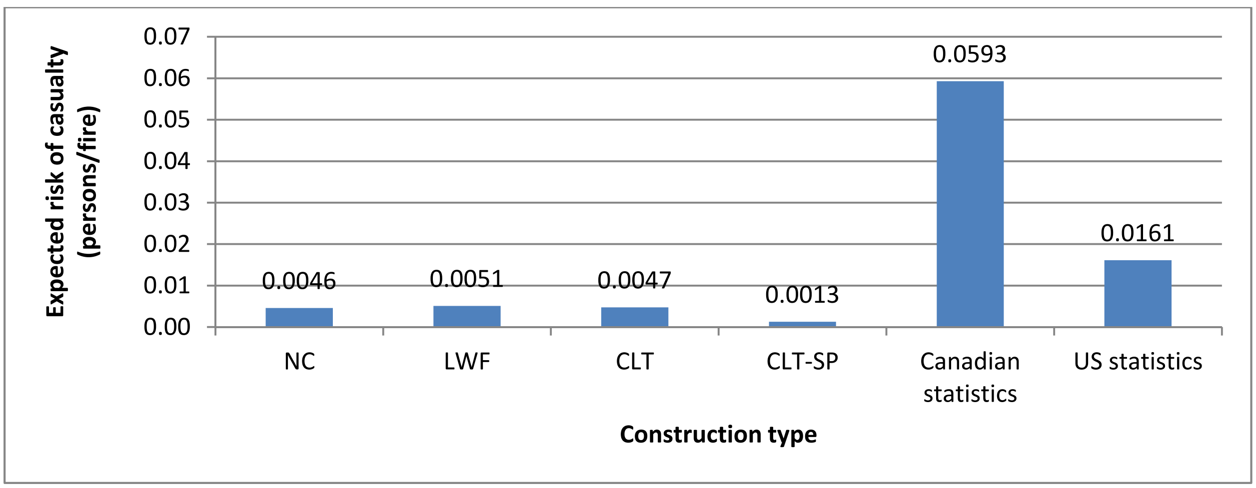

Figure 4.17 Expected risk of casualty (death or injury) for small office buildings

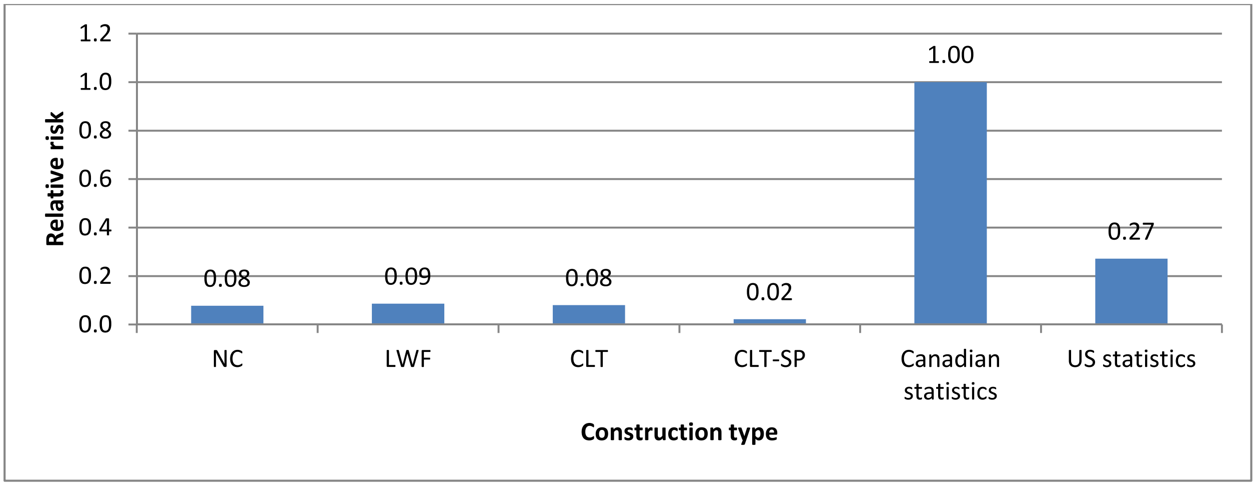

Figure 4.18 Relative risk of casualty for small office buildings compared to Canadian statistics

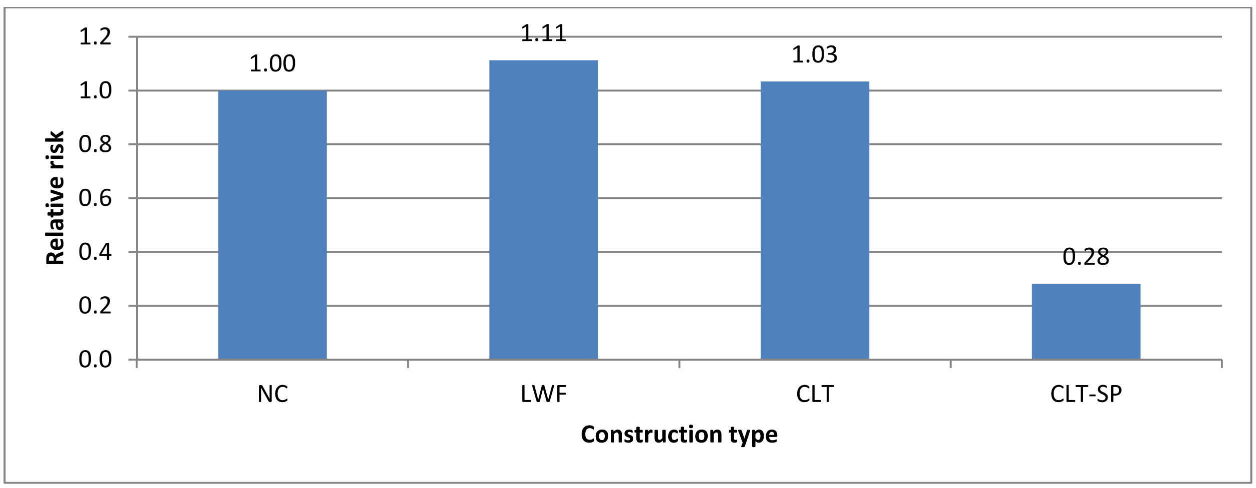

Figure 4.19 Relative risk of casualty for small office buildings compared to non-combustible construction

4.2.2 Large-Area Six-Storey Office buildings

Fires in the large office buildings with the layout shown in Figure 2.4 (O6L-CLT, O6L-LWF and O6L-NC) have also been simulated. These buildings are called CLT, LWF, and NC buildings in this section. More details of these buildings are given in Tables 3.1 and 3.3. The event tree is given in Figures 3.1 and 3.3. Simulation results are shown in Figures 4.20 – 4.28. Similar to the results for the small office buildings, the difference in the expected risks of injury and casualty of different constructions is insignificant.

Figures 4.20 and 4.21 show the temperature development in the fire origin rooms, corridors and staircases close to the fire origin rooms for scenario S4. Sprinklers in the scenario fail to activate. Figure

4.22 shows the maximum and minimum remaining occupants as a percentage of total occupants in all Monte Carlo evacuation processes for scenario S4.

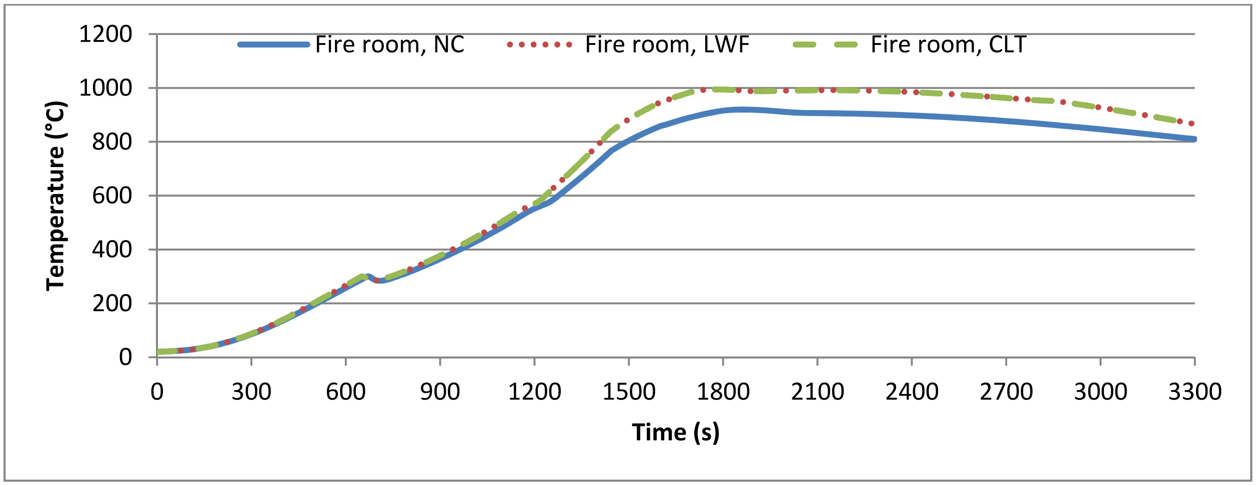

Figure 4.20 Upper layer temperatures in fire origin rooms for scenario S4 of large office buildings

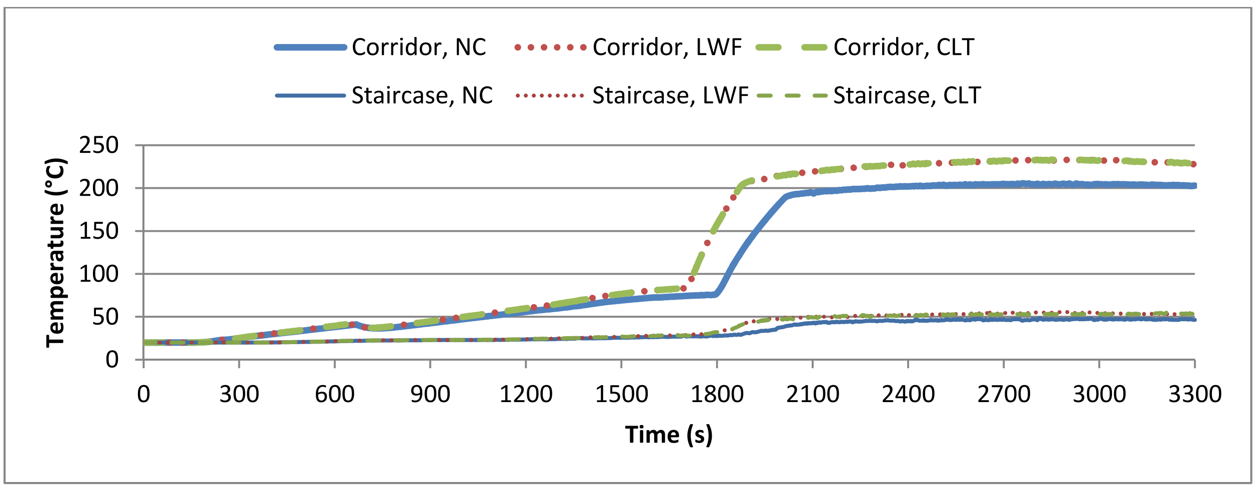

Figure 4.21 Upper layer temperatures in corridors and staircases close to fire origin rooms for scenario S4 of large office buildings

The temperatures in the staircases are always under 120 °C and are slightly lower than those in the small office buildings due to the large area of the corridors. The temperatures in the corridors are lower than 120 °C within 1748 s for the LWF and CLT buildings and within 1866 s for the NC building. The two times are 140 s and 168 s later than those in the small office buildings, which provides longer safe evacuation time. Additionally, the smoke temperatures in the corridors of the large office buildings are slightly lower than those in the small office buildings. This can be a benefit in case occupants have to go through the corridor at a late time.

By the times the corridor temperatures have risen to 120 °C, less than 6% of occupants remain in the buildings. The ratio is similar to that for the small office buildings as both occupant loads and the times corresponding to 120 °C increase. They are mainly occupants on the floors different from the fire origin floors since the times the occupants on the fire origin floors need to evacuate the buildings are 234 s to

1578 s including the response times of 204 s to 402 s for scenario S4. These numbers are slightly larger than those for the small office buildings. These indicate that the fire deaths or injuries happen in the fire origin rooms.

The times at which the temperatures of the fire origin rooms have reached 120 °C is 366 s, 38 s later than in the small office buildings as a result of the larger office area. Due to the same reason, the smoke temperatures in the fire origin rooms in the large office buildings are lower than in the small office buildings. The increasingly rising temperatures can lead to the injury or death of occupants, since the time the occupants in the fire origin rooms start to evacuate is 204 s to 246 s and the times the occupants have evacuated the building are 234 s and 1352 s. Occupants with low travel speed may be injured in the evacuation process as shown in Figure 4.24. The numbers of deaths for different scenarios and the expected risk of death combining all scenarios are not given because the numbers are too small to show stable results. Lower temperatures in the fire origin rooms lead to the lower number of deaths and injuries compared to the results for the small office buildings.

Figure 4.22 shows that the maximum and minimum remaining occupants as a percentage of total occupants for scenario S4 do not change with the construction type due to similar fire development in the three buildings. The evacuation process for the large office building is similar to that for the small office buildings. The times at which 90%, 99%, and 100% of occupants have evacuated the buildings are 1662 s, 1898 s and 3080 s. The times for the 90% of occupants for the large office buildings are 164 s longer than that for the small office buildings. The slight increase of the time is a result of the occupant load increase from 1728 persons for the small office buildings to 2304 persons for the large office buildings, and the width increase of the stairs from 1.5 m to 1.75 m. Since the smoke conditions in the corridors and staircases are better than hazardous conditions when occupants are evacuating, longer evacuation times do not affect the number of deaths and injuries.

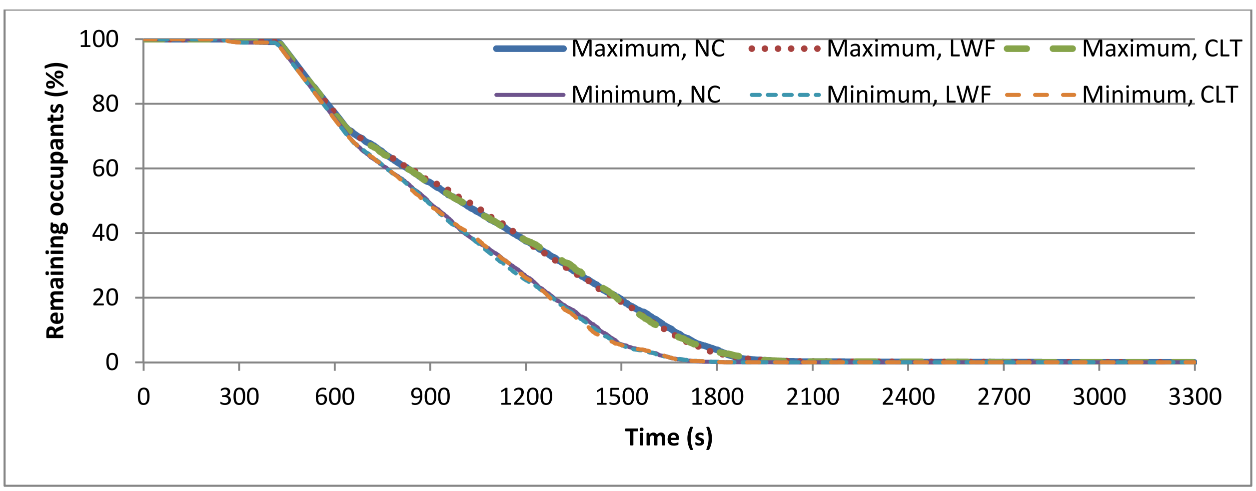

Figure 4.22 Maximum and minimum remaining occupants as a percentage of total occupants for scenario S4 of large office buildings

Similar analysis can be made for Scenario S3. As shown in Figure 4.24, the numbers of injuries for scenarios S3 and S4 are in agreement with or on the same magnitudes as the statistical data for 2002 Canadian office fires (CCFMFC 2007) and 2000 – 2004 US office fires (Ahrens 2007).

Scenarios S1 and S2 have much milder temperature development due to the activation of sprinklers, as shown in Figure 4.23. As a result, Figure 4.24 shows that for scenarios S1 and S2, no fire injury is predicted.

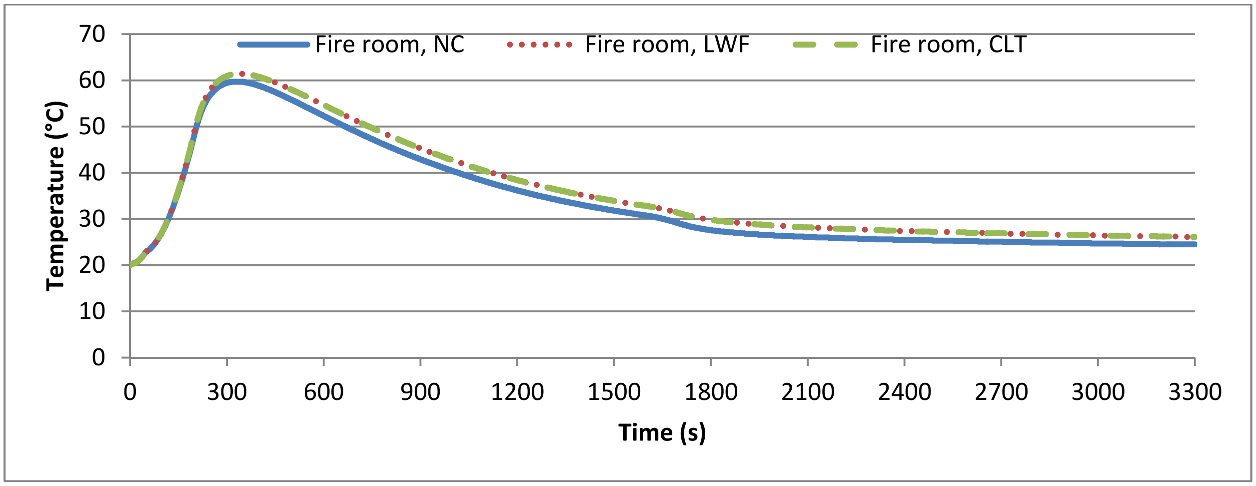

Figure 4.23 Upper layer temperatures in fire origin rooms for scenario S2 of large office buildings

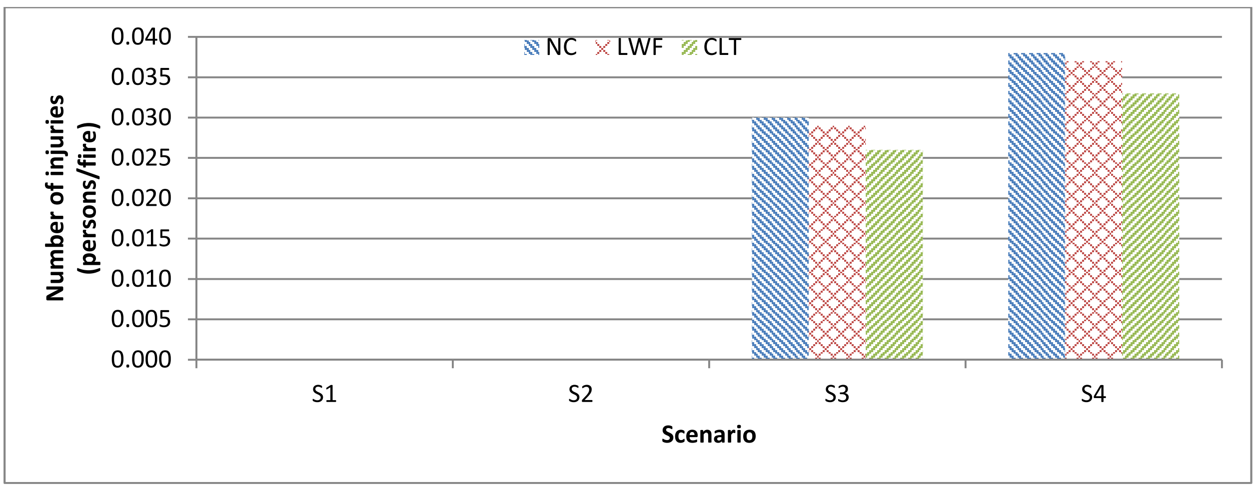

Figure 4.24 Number of injuries for different scenarios of large office buildings

Figures 4.25 - 4.28 show that all the three buildings have very low life risk in terms of injury and casualty due to the use of sprinklers. Specifically, the expected risk is 6% of the Canadian statistical value and 23% of the US statistical value in terms of injury, smaller than those of the small office buildings. If sprinklers with higher reliability, 0.97 (shown as CLT-SP in the Figures), instead of general reliability, 0.89, are used, the risk will be reduced further to 27% of that for sprinklers with general reliability.

The three buildings show relative risk of about 0.06 – 0.07 compared to the Canadian statistical value, indicating that all three buildings have similar risk and all are much lower than the statistical value. The

LWF and CLT buildings show relative risk of 1.00 and 0.87 compared to the expected risk of casualty of the NC building. Additionally, the expected risks of death for the three buildings are quite similar. Therefore, the risks of the three buildings are very close. It is clear that the difference between the life risks of different constructions is insignificant.

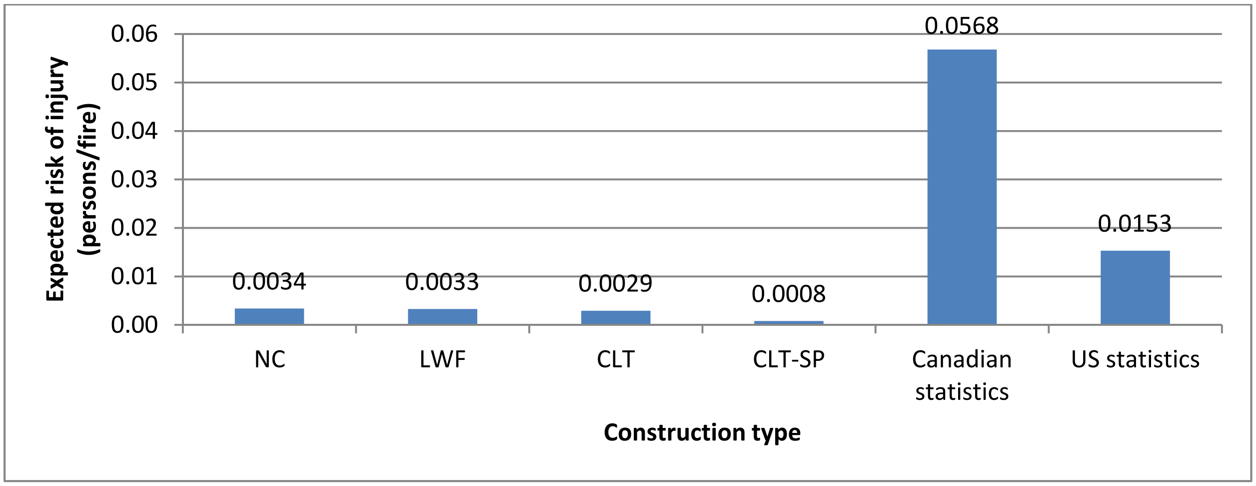

Figure 4.25 Expected risk of injury for large office buildings

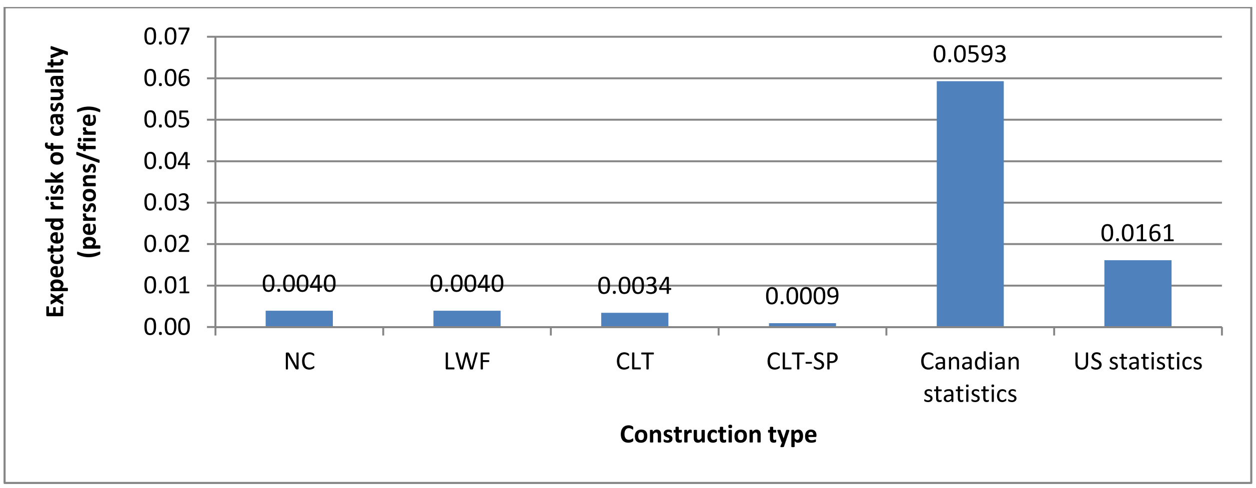

Figure 4.26 Expected risk of casualty (death or injury) for large office buildings

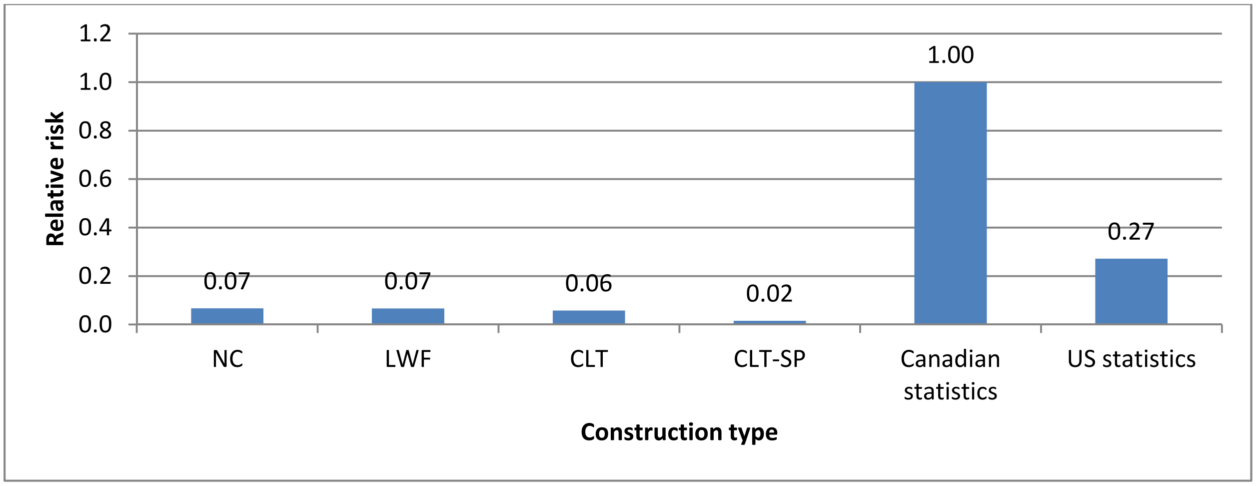

Figure 4.27 Relative risk of casualty for large office buildings compared to Canadian statistics

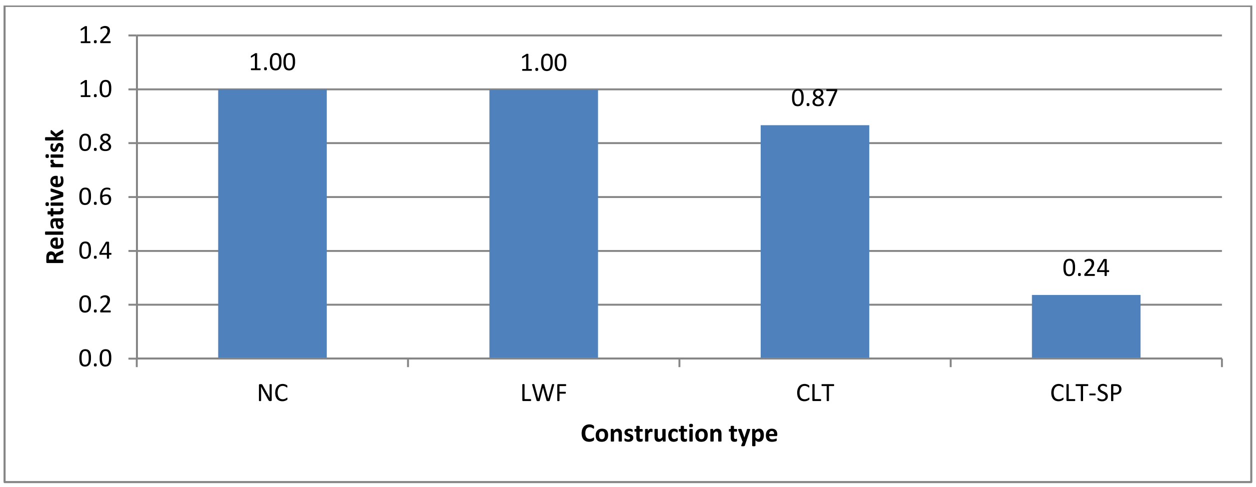

Figure 4.28 Relative risk of casualty for large office buildings compared to non-combustible construction

4.2.3 Twelve-Storey Office Buildings

Fires in the high office buildings with the layout shown in Figure 2.5 (O12-NC, O12-CLT, O12-CLT-CPT, O12-CLT-Exit, and O12-CLT-BCN) have been simulated. These buildings are called NC, CLT, CLT-CPT, CLT-Exit, and CLT-BCN buildings in this section. More details of these buildings are given in Tables 3.1 and 3.3. The event tree is given in Figures 3.1 and 3.3. Simulation results are shown in Figures 4.29 – 4.37.

In these buildings, the CLT-CPT building is a compartmented building, while others are open floor concept buildings. The CLT-Exit building has wider exits. The CLT-BCN building has balconies. The difference among the expected risks injury and casualty of different constructions is insignificant, similar to the results for the small-area and large-area 6-storey office buildings.

As indicated in Chapter 2 and 3, fire is set to happen in the suite on the second floor and close to the staircase for the CLT-CPT building. For the open floor concept buildings, fire happens at the similar locations as in the CLT-CPT building. In the following discussion, the fire origin regions mean similar regions to the fire origin room of the CLT-CPT building, and the corridors mean the corridor in the CLT-CPT building or similar regions to the corridor in the CLT-CPT building even though there is no real corridor.

Figures 4.29 – 4.31 show the temperature development in the fire origin rooms or regions, corridors and staircases close to the fire origin rooms or regions for scenario S4. Sprinklers in the scenario fail to activate. The effect of balcony on fire development inside the building is not considered and therefore the temperature development of the CLT-BCN building is the same as that of the CLT building.

Figures 4.32 and 4.33 show the maximum and minimum remaining occupants as a percentage of total occupants in all Monte Carlo evacuation processes for scenario S4.

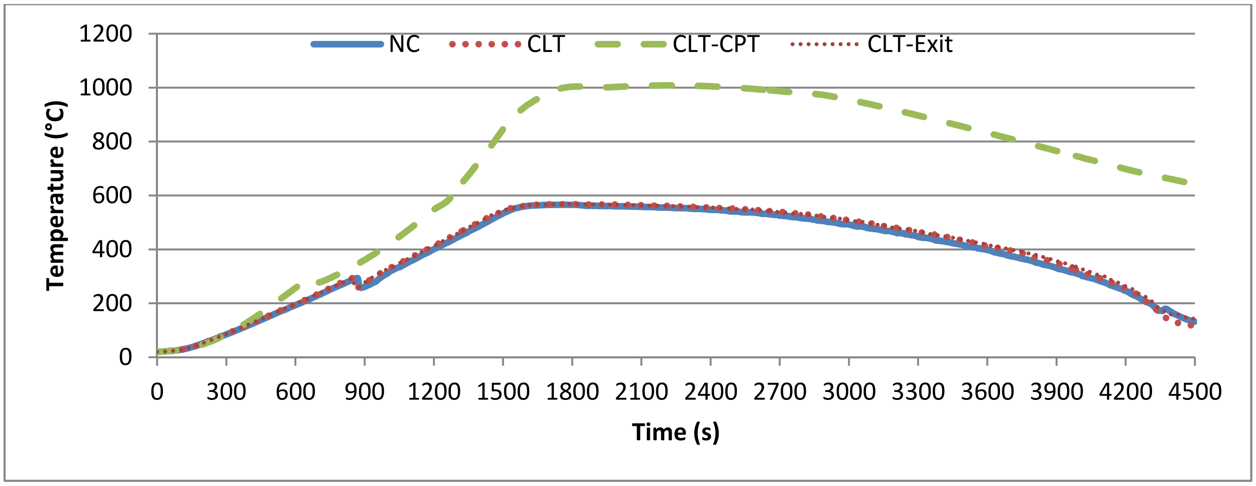

Figure 4.29 Upper layer temperatures in fire origin rooms or regions for scenario S4 of high office buildings (2nd floor fire)

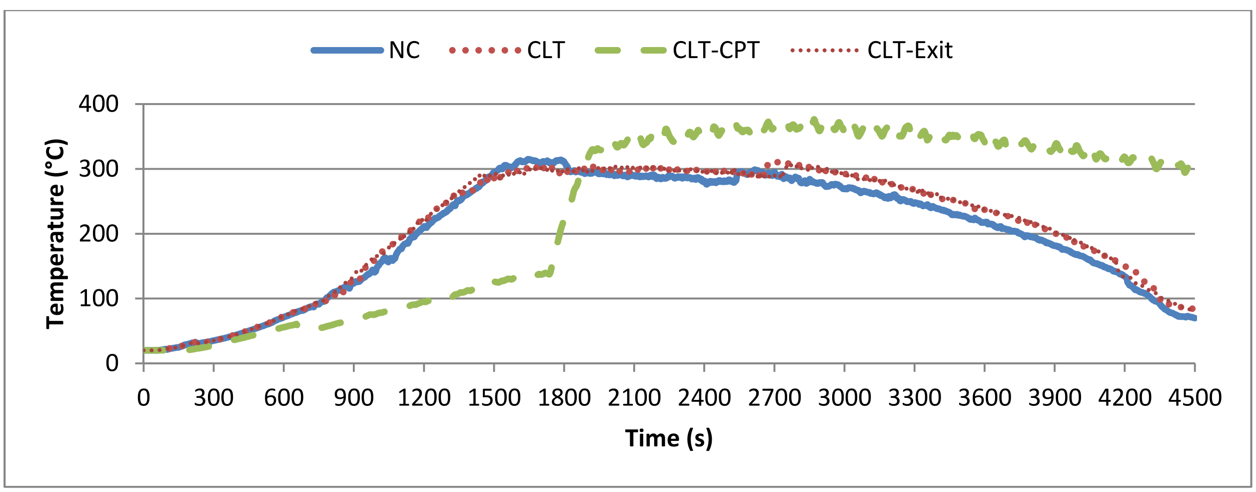

Figure 4.30 Upper layer temperatures in corridors close to fire origin rooms for scenario S4 of high office buildings (2nd floor fire)

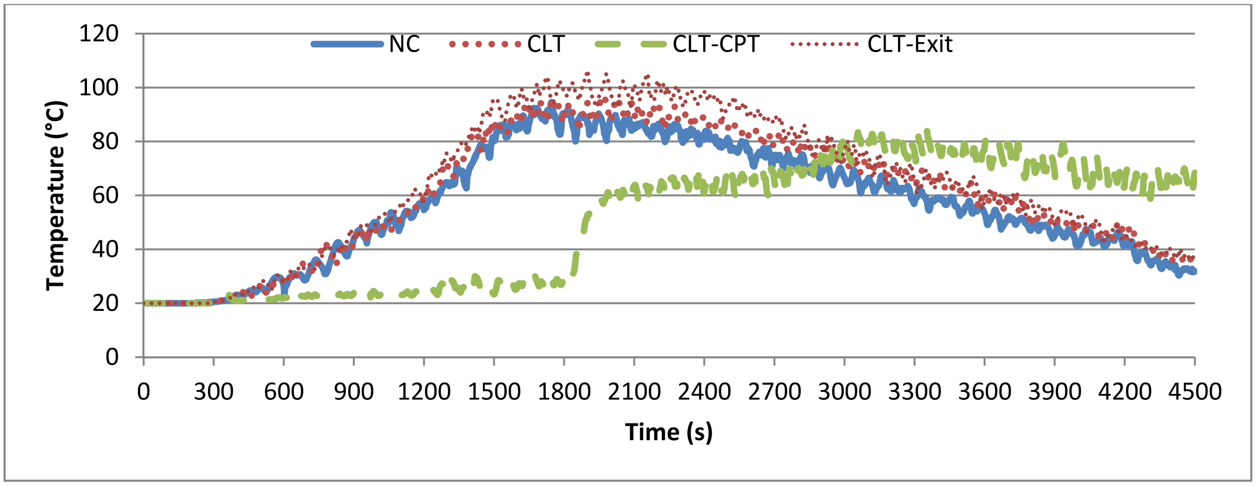

Figure 4.31 Upper layer temperatures in staircases close to fire origin rooms or regions for scenario S4 of high office buildings (2nd floor fire)

Similar to the results for the small-area and large-area 6-storey office buildings, the temperatures in the staircases in the high office buildings are always under 120 °C but higher than those in the small-area and large-area 6-storey office buildings due to the unrestricted smoke movement for the open floor concept buildings or the shorter corridor for the CLT-CPT building. In the CLT-CPT building, the temperature in the staircase is lower than in other buildings as a result of compartment, providing a better margin of safety for evacuation.

The temperatures in the corridors of the NC, CLT, CLT-CPT, and CLT-Exit buildings reach 120 °C at 872 s, 878 s, 1450 s, and 854 s. The times are much earlier than those of the small-area and large-area 6-storey office buildings since the corridors of NC, CLT, and CLT-Exit buildings are not compartmented from the fire origin regions and the corridor of the CLT-CPT building is much shorter though compartmented. By these times, up to 68%, 68%, 38%, and 68% of occupants remain in the NC, CLT, CLT-CPT, and CLT-Exit buildings. The percentages are much higher than those for the small-area and large-area 6-storey office buildings due to the much earlier time and higher occupant load. These occupants are mainly on the floors different from the fire origin floors since the times the occupants on the fire origin floors need to evacuate the buildings are 254 s to 2076 s including response times of 204 s to 400 s. Additionally, the smoke temperatures in the corridors of the high office buildings are much higher than those in the small-area and large-area 6-storey office buildings.

The times at which the temperatures of the fire origin rooms or regions reach 120 °C are 402 s, 394 s, 374 s, and 394 s for the NC, CLT, CLT-CPT and CLT-Exit buildings. The time for the CLT-CPT building is slightly later than those for the large-area 6-storey office buildings due to a slightly larger compartmented area. The smoke temperature in the fire origin rooms in the CLT-CPT building is similar to those in the large-area 6-storey office CLT building. This will in turn lead to the similar numbers of deaths and injuries for the occupants in the fire origin rooms to those in the large-area 6-storey office buildings. However, the times for NC, CLT and CLT-Exit buildings are about 30 s later than those for the large-area 6-storey office buildings due to the absence of compartments. The smoke temperatures in the fire origin regions in the NC, CLT and CLT-Exit buildings are significantly lower than those in the large-area 6-storey office buildings. This will cause the much lower number of deaths and injuries for the occupants in the fire origin regions than in the large-area 6-storey office buildings.

The temperature in the fire origin room in the CLT-CPT building always increases faster than in the buildings with the open floor concept (NC, CLT and CLT-Exit). This will cause the relatively higher expected risk of death and injury for the occupants in the fire origin rooms in the compartmented building than in the open-concept floor buildings. On the other hand, compartmentation can prevent smoke spread and delay temperature rise in other areas such as the corridors and staircases close to the fire origin room before the compartment fails. As long as the door of the fire origin room fail, however, temperatures in corridors and staircases close to the fire origin rooms will rise quickly up to a value higher than the temperatures in the same region of the open floor concept buildings since hot smoke cannot spread to other areas in the event of compartment.

Figures 4.32 and 4.33 show that the evacuation process changes remarkably with the building. The evacuation processes of the NC, CLT, and CLT-BCN buildings are similar. The evacuation of the occupants in the CLT-CPT and CLT-Exit buildings is faster. For the NC, CLT, and CLT-BCN buildings, the times at which 90%, 99%, and 100% of occupants evacuate the buildings are 2060 s, 2678 s and 3946 s. The times for 90% of occupants for the high office buildings are 398 s longer than that for the large-area 6-storey office buildings. The increase of the time is because the occupant load increases from 2304 persons for the large 6-storey office buildings to 3144 persons for the high office buildings, and the increase of the aggregate stair width from 3.5 m to 4.4 m. For the CLT-CPT buildings, the times at which 90%, 99%, and 100% of occupants evacuate the buildings are 1822 s, 2372 s and 4088 s. The slightly shorter time for 90% of occupants is a result of slightly lower occupant load in the compartmented building. For the CLT-Exit building, the times at which 90%, 99%, and 100% of occupants evacuate the buildings are 1482 s, 2064 s and 3968 s. The significantly shorter time for 90% of occupants is due to the increase of aggregate stair width from 4.4 m to 6.8 m.

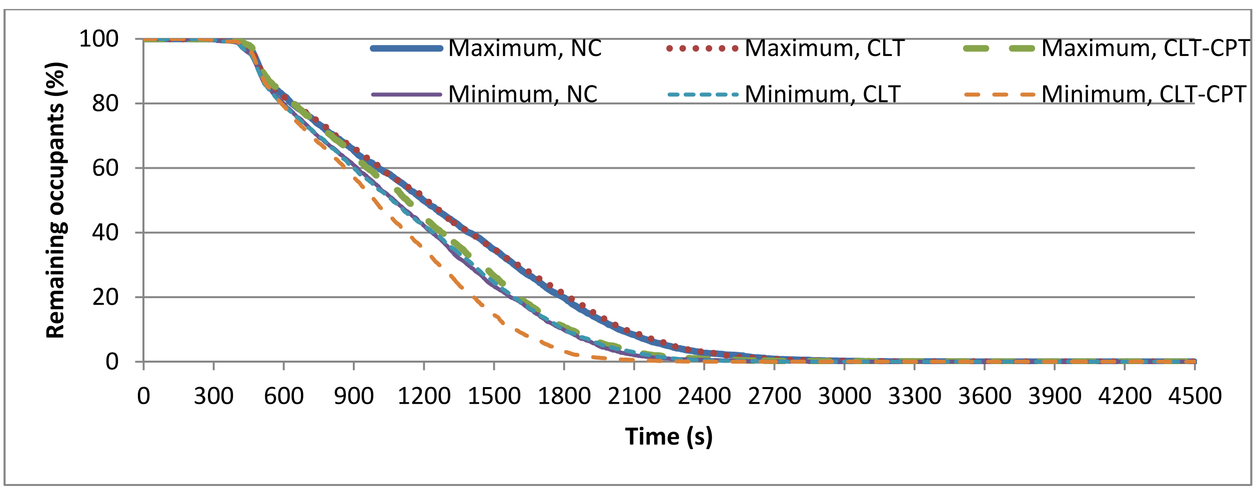

Figure 4.32 Maximum and minimum remaining occupants as a percentage of total occupants for scenario S4 of high office buildings (2nd floor fire)

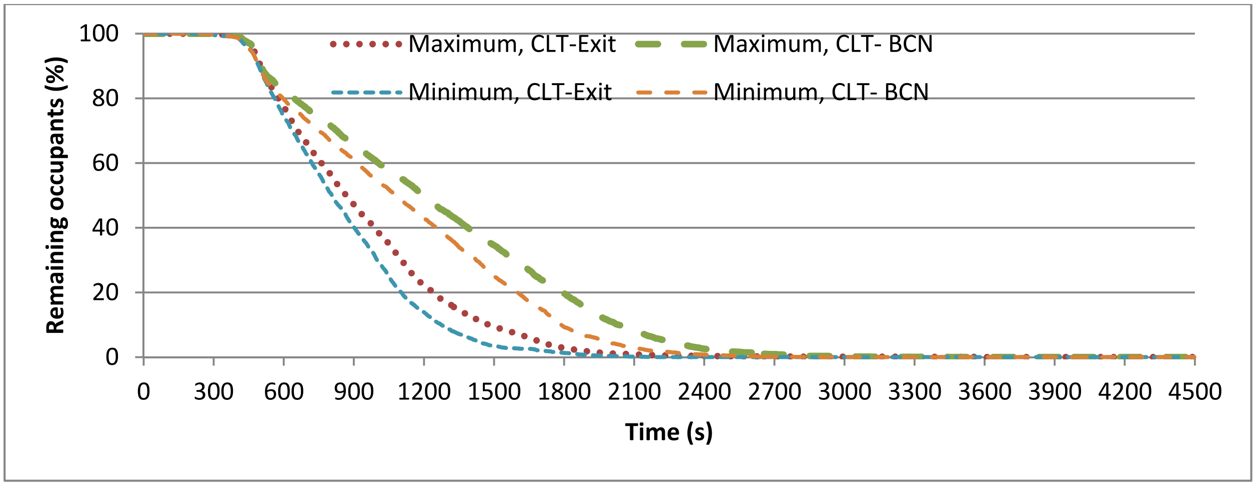

Figure 4.33 Maximum and minimum remaining occupants as a percentage of total occupants for scenario S4 of high office buildings (2nd floor fire)

In the CLT-CPT building, compartment makes the deaths and injuries similar to those of the small-area and large-area 6-storey office buildings.

But for the open floor concept buildings, while temperatures in the staircases do not reach the degree to injure occupants, the smoke does, especially if evacuation process is very long. As a result, injury happens both in the fire origin regions and in the staircases. In the staircases, the injury is due to toxic gases rather than heat or high temperature. This spreads the life risks to occupants not in the fire origin regions. For this design, the effect of the construction type on the expected risk of injury is insignificant. While the expected risks are similar to those for the compartmented buildings, high occupant load can make this an issue. Wider exits can reduce the expected risk of injury significantly by allowing a shorter evacuation time.

For Scenario S3, the fire department arrives within 10 min. This will lead to early control of fire and decrease the numbers of injuries significantly. As shown in Figure 4.34, the numbers of injuries for scenarios S3 and S4 are in agreement with or on the same magnitudes as the statistical data for 2002 Canadian office fires (CCFMFC 2007) and 2000 – 2004 US office fires (Ahrens 2007).

Scenarios S1 and S2 have much milder temperature development due to the activation of sprinklers. As a result, for scenarios S1 and S2, no fire injuries are predicted.

Figures 4.35 - 4.37 show that all the five buildings have very low life risk in terms of injury and casualty due to the use of sprinklers. Specifically, the expected risk for the NC, CLT, CLT-BCN, and CLT-CPT buildings, is 7% of the Canadian statistical value and 28% of the US statistical value in terms of injury, slightly larger than those of the large-area 6-storey office buildings but similar to those of the small-area 6-storey office buildings. The expected risk for the CLT-Exit building is much lower due to faster evacuation. If sprinklers with higher reliability, 0.97 (shown as CLT-SP in the Figures), instead of general reliability, 0.89, are used, the risk will be reduced further to 27% of that for sprinklers with general reliability.

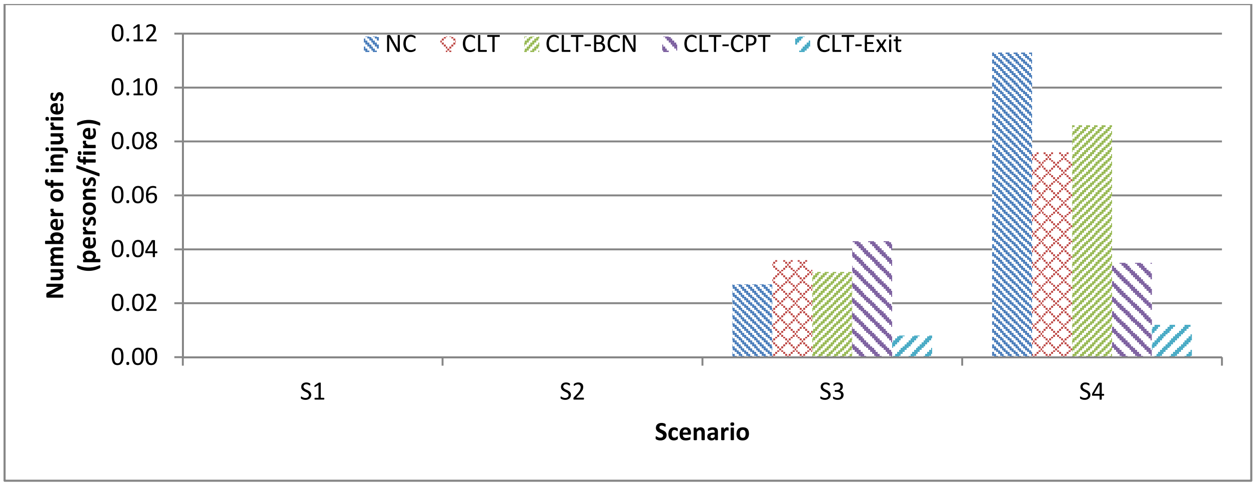

Figure 4.34 Number of injuries for different scenarios in high office buildings (2nd floor fire)

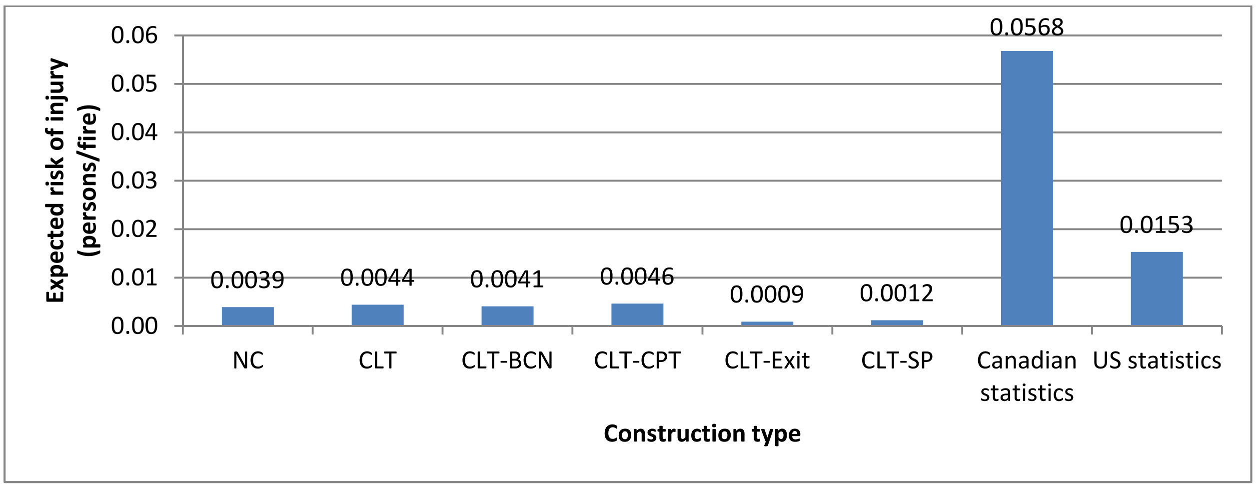

Figure 4.35 Expected risk of injury for high office buildings (2nd floor fire)

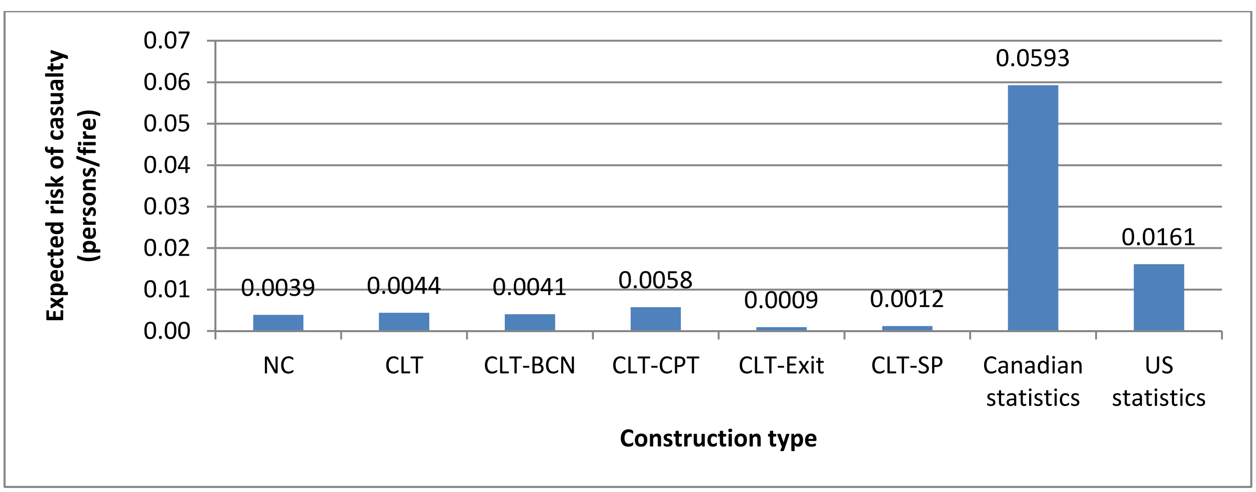

Figure 4.36 Expected risk of casualty (death or injury) for high office buildings (2nd floor fire)

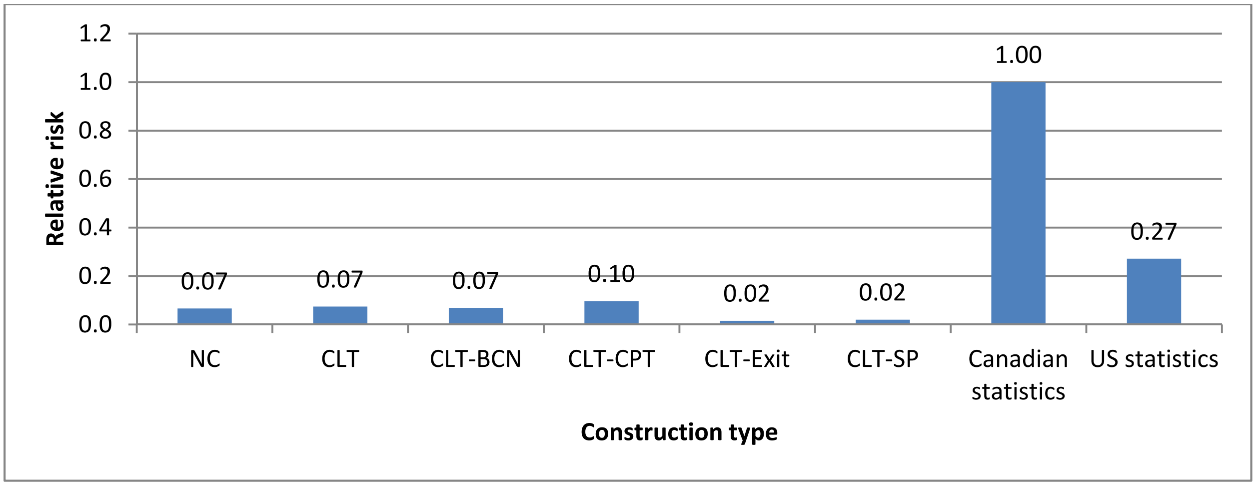

Figure 4.37 Relative risk for high office buildings compared to Canadian statistics (2nd floor fire)

In the studies, no death or injury due to fire spread is predicted. As a result, the numbers of deaths and injuries for different scenarios and the expected risks of injury and casualty for all scenarios of the CLT-BCN building are quite similar to those of the CLT building. Balconies do not show an effect on reducing fire risk for these buildings.

The NC, CLT, CLT-BCN and CLT-CPT buildings show relative risks of about 0.07 – 0.10 compared to the Canadian statistical value, indicating that all the four buildings have similar risk and all are much lower than the statistical value. The relative risks are on the same magnitude as 0.08 – 0.09 for the small-area 6-storey office buildings and 0.06 – 0.07 for the large-area 6-storey office buildings. The CLT-Exit building shows much lower relative risk of 0.02. This means the risk of this building is even lower.

Considering these numbers are very small and they are sensitive to Monte Carlo simulations, maybe it is reasonable to say the small-area 6-storey, large-area 6-storey and 12-storey office buildings have similar risk. This also indicates that area and height of a building in the simulated range do not affect risk significantly.

As shown in Figures 4.35 and 4.36, the expected risks of injury and casualty are very low compared to the statistical value. Relative comparison between these small numbers is very sensitive and can lead to misunderstandings. Therefore, only relative risks compared to the statistical value are given in Figure 4.37. Relative risks compared to the value of a specific building are not given and not recommended to be used. In this case, if relative risks compared to the Canadian statistical data are of the same magnitude, the risks should be taken to be similar. Based on this, the risks of the non-combustible building (NC), CLT building (CLT), CLT building with balconies (CLT-BCN), and compartmented CLT building (CLT-CPT) are similar, but the CLT building with wider exits (CLT-Exit) and CLT building with more reliable sprinklers (CLT-SP) have lower risk when fire happens on the second floor.

4.3 Residential Buildings

An obvious difference between the life risks of residential and office buildings is that both daytime and night fires have to be considered for residential buildings and only daytime fires are necessary for office buildings.

4.3.1 Small-Area Six-Storey Residential Buildings

Fires in the small residential buildings with layouts shown in Figure 2.1 (R6S-NC, R6S-LWF and R6S-CLT) are simulated. These buildings are called CLT, LWF, and NC buildings in this section. More details of these buildings are given in Tables 3.1 and 3.2. The event tree is given in Figures 3.2 and 3.4. Simulation results are shown in Figures 4.38 – 4.49.

Figures 4.38 and 4.39 show the temperature development in the fire origin rooms, corridors and staircases close to the fire origin rooms for scenarios S4 and S8. Sprinklers in both scenarios fail to activate. The difference between the two scenarios is that S4 happens during the daytime and S8 at night. There is no difference in terms of fire development but evacuation can be different. Figures 4.40 and 4.41 show the maximum and minimum remaining occupants as a percentage of total occupants in all Monte Carlo evacuation processes for scenarios S8 and S4.

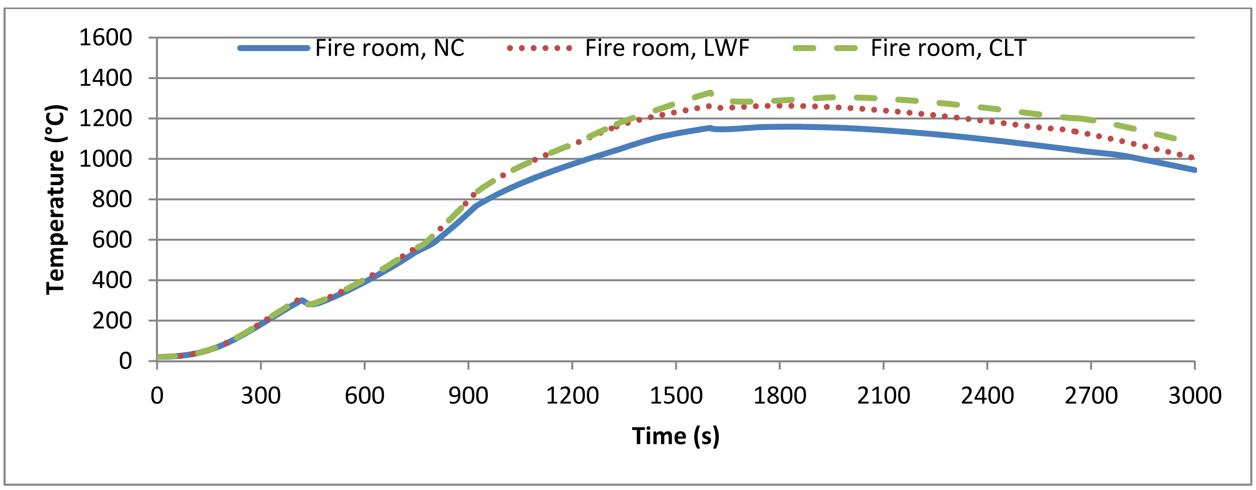

Figure 4.38 Upper layer temperatures in fire origin rooms for scenarios S4 and S8 of small residential buildings

The temperatures in the staircases are always under 120 °C. Temperatures in corridors are lower than 120 °C until 1242 s for the LWF and CLT buildings and until 1328 s for the NC building. Below 120 °C, hot gases do not injure occupants. By this time, less than 9% of occupants remain in the building. They are occupants on the floors other than the fire origin floors since the times the occupants on the fire origin floors need to evacuate the buildings are 220 s to 1216 s including response time for scenario S8 and 206 s to 1162 s for scenario S4. These indicate that fire deaths or injuries happen in the fire origin rooms.

At 236 s, the temperatures of the fire origin rooms have reached 120 °C. Further rise can lead to the injury or death of occupants, since the times the occupants in fire origin rooms start to evacuate are from 200 s to 254 s for scenario S8 and 184 s to 238 s for scenario S4 and the times the occupants have evacuated the building are between 220 s and 1012 s for scenario S8 and between 206 s and 844 s for scenario S4. Longer response and evacuation times for night evacuations lead to the higher numbers of deaths and injuries as shown in Figures 4.43 and 4.44.

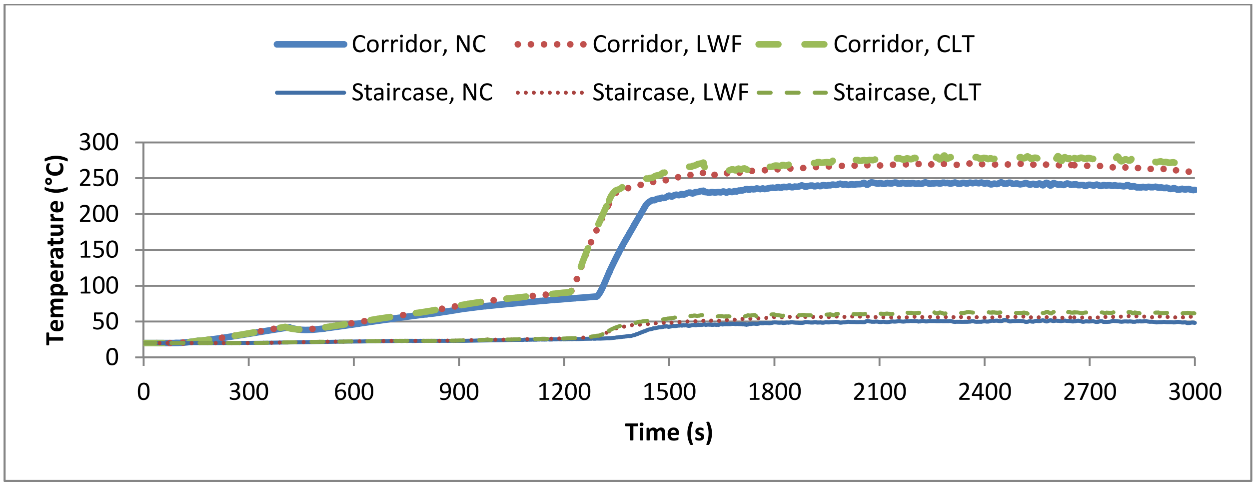

Figure 4.39 Upper layer temperatures in corridors and staircases close to fire origin rooms for scenarios S4 and S8 of small residential buildings

The timelines of temperature development of the fire origin rooms and corridors, and evacuation also indicate that the corridor of the NC building provides a slightly longer safe evacuation time than those of the LWF and CLT buildings, but the fire origin rooms of all three buildings are similar in terms of both life risk and safety margin. This is caused by different predominant processes in different places. The analysis is similar to those given for the small 6-storey office buildings in Section 4.2.1.

Figure 4.40 shows that the maximum and minimum remaining occupants as a percentage of total occupants do not change with the construction type, because the fire development in the three buildings is similar. The time at which 90%, 99%, and 100% of occupants evacuate the buildings are 1010 s, 2084 s, and 2854 s.

Figure 4.41 compares the maximum and minimum remaining occupants for the daytime scenario S4 and night scenario S8. The time at which 90%, 99%, and 100% of occupants evacuate the buildings for scenario S4 are 972 s, 1980 s, and 2844 s. Compared to the daytime evacuation, the night evacuation has time delays of 38 s, 104 s and 10 s for 90%, 99%, and 100% occupants to complete evacuation. The delays are due to lower probability of occupants perceiving fire cues through direct perception and 5 s awakening time following the activation of alarms. In the case studies, the presence and activation of smoke alarms produces short delays. For cases without smoke alarms, delays could be longer, which may lead to increased numbers of deaths and injuries.

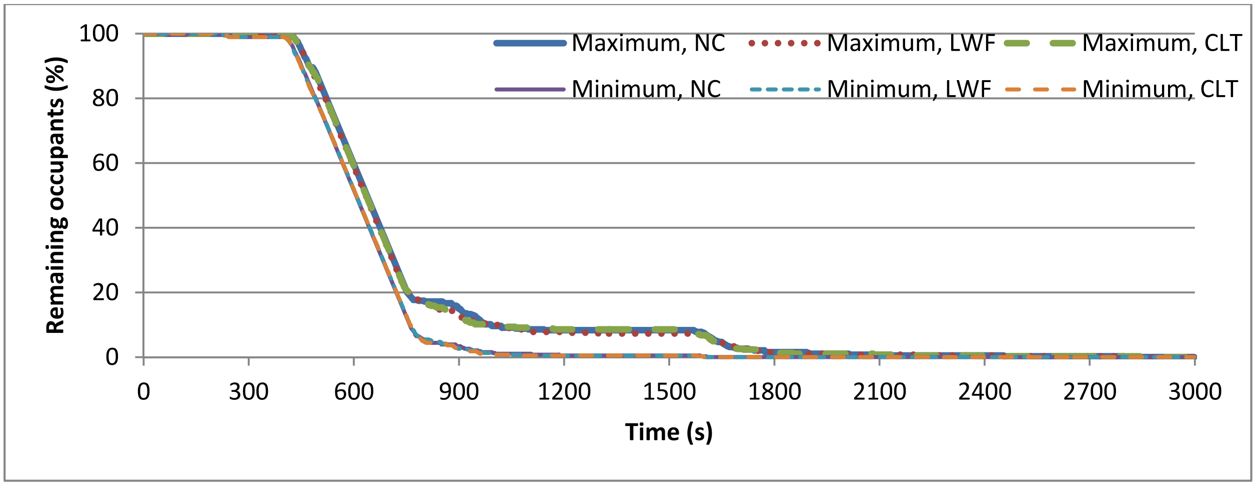

Figure 4.40 Maximum and minimum remaining occupants as a percentage of total occupants for scenario S8 of small residential buildings

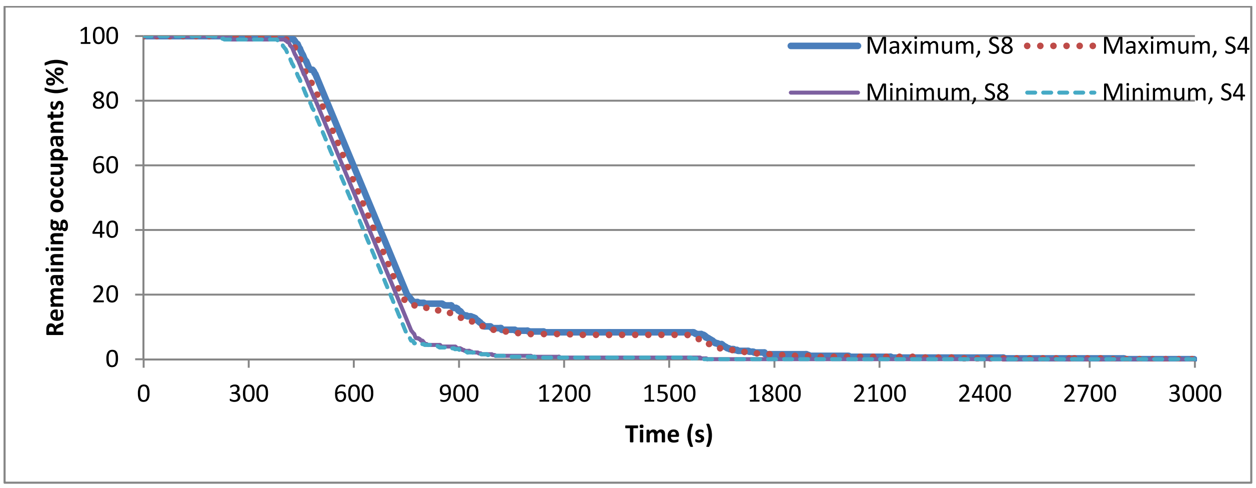

Figure 4.41 Maximum and minimum remaining occupants as a percentage of total occupants for scenarios S4 and S8 for NC building

Similar analysis can be made for Scenarios S3 and S7. The numbers of deaths and injuries for scenarios S3, S4, S7 and S8 are in agreement with or of the same magnitudes as the statistical data for 2002 Canadian apartment fires (CCFMFC 2007) and 2007 – 2011 US apartment fires (Ahrens 2014).

Scenarios S1, S2, S5, and S6 have much milder temperature development due to the activation of sprinklers as shown in Figure 4.42 for scenarios S2 and S6. As a result, Figures 4.43 and 4.44 show that for scenarios S1, S2, S5, and S6, no fire death or injury is predicted.

Figures 4.45 - 4.47 show that all the three buildings have very low fire risk in terms of death and injury due to the use of sprinklers. Specifically, the expected risk is about 3% of the Canadian statistical value and 9% of the US statistical value in terms of death, and 5% of the Canadian statistical value and 15% of the US statistical value in terms of injury. If sprinklers with higher reliability, 0.97 (shown as CLT-SP in the Figures), instead of general reliability, 0.95, are used, the risk will be reduced further to 60% of the risk for the general sprinklers. The reason is that the risk is a result of the failure of fire protection systems.

When reliability of sprinklers increases from 0.95 to 0.97, the probability of failure will decrease from 0.05 to 0.03.

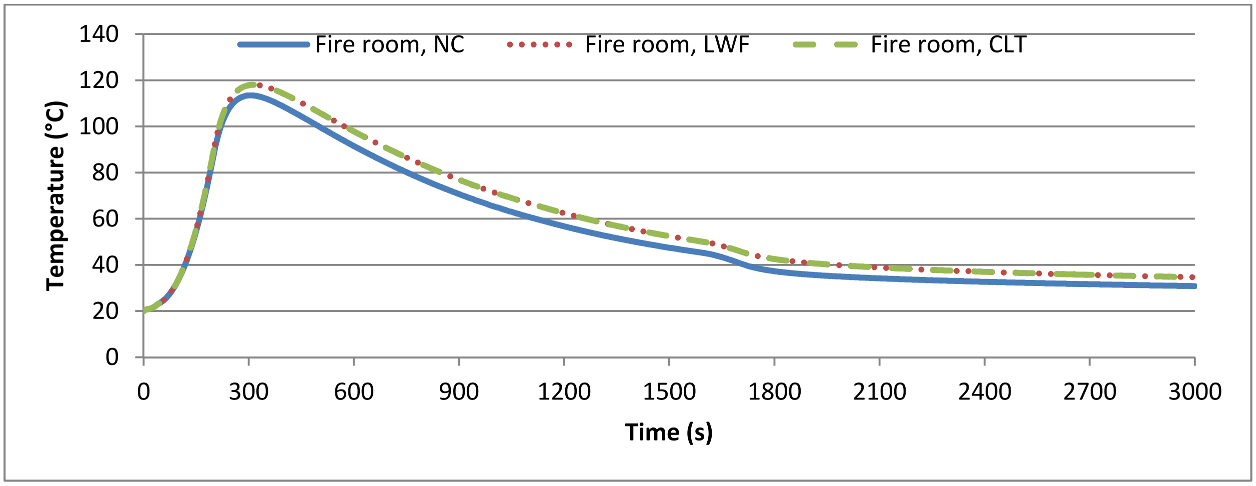

Figure 4.42 Upper layer temperatures in fire origin rooms for scenarios S2 and S6 of small residential buildings

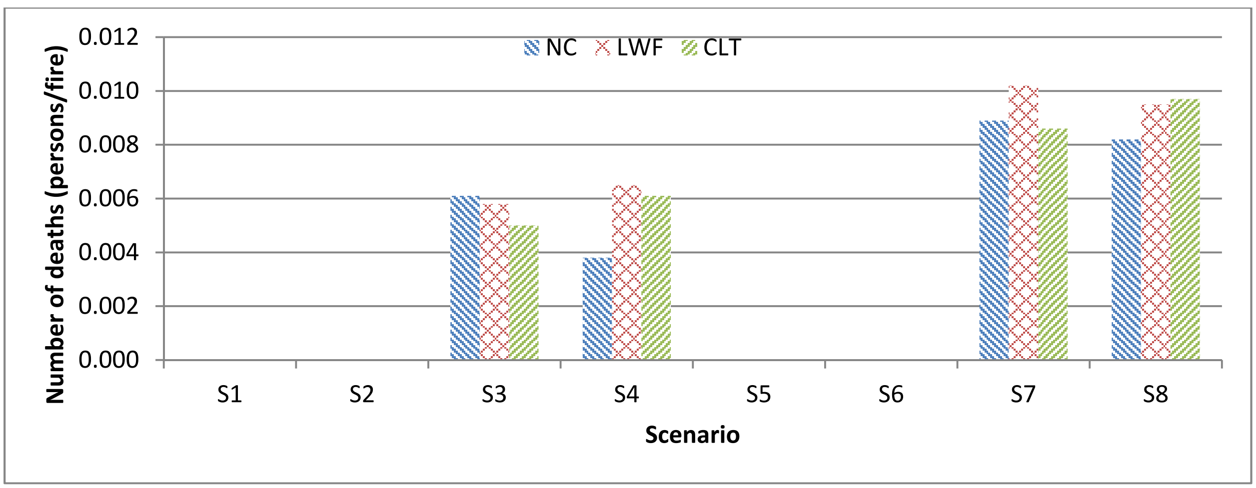

Figure 4.43 Number of deaths for different scenarios in small residential buildings

Figures 4.48 and 4.49 show the relative risk, defined as the ratio of the expected risk of casualty of a building to a reference value. The three buildings show relative risk of 0.05 compared to the Canadian statistical value, indicating that all three buildings have similar risk and all are much lower than the reference value. The LWF and CLT buildings show relative risk of 0.97 and 0.95, compared to the NC building. Additionally, the expected risks of death for the three buildings are quite similar. Therefore, the risks of the three buildings are very close.

Compared with the fire origin rooms in the small and large office buildings in Section 5.2.1 and 5.2.2, the fire origin rooms in the residential buildings have a faster temperature rise process and a higher peak temperature because of the much smaller areas of the residential buildings. This in turn leads to the much higher number of injuries for the daytime scenarios, 0.12 persons / fire, compared to 0.04 persons / fire for the small-area 6-storey office buildings.

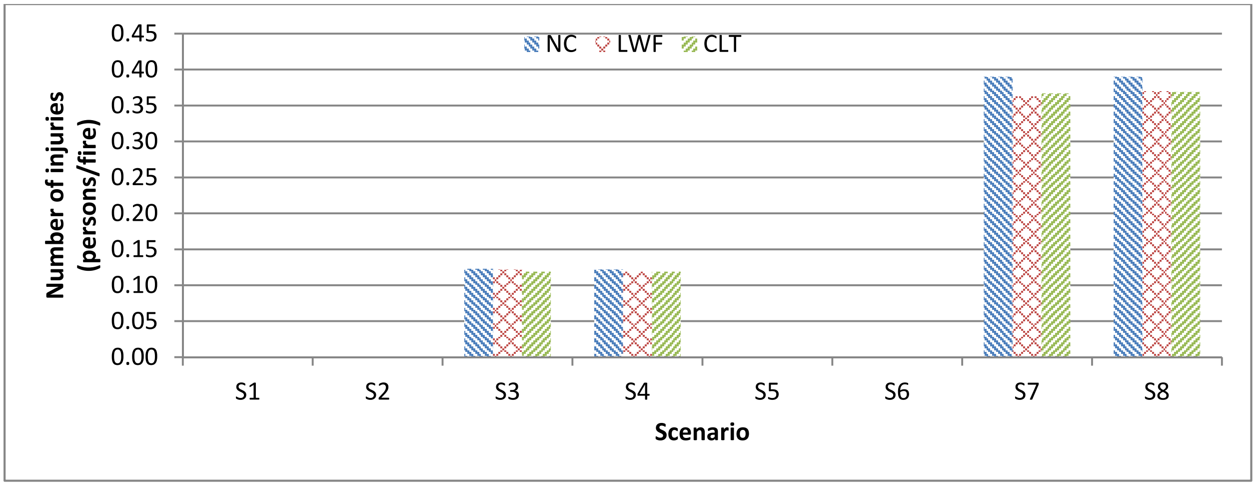

Figure 4.44 Number of injuries for different scenarios in small residential buildings

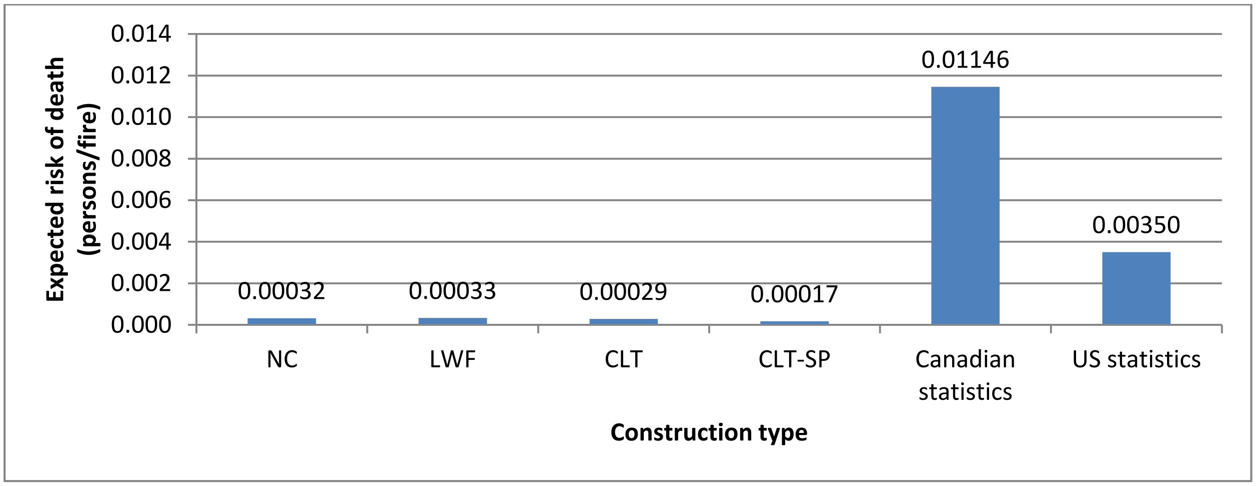

Figure 4.45 Expected risk of death for small residential buildings

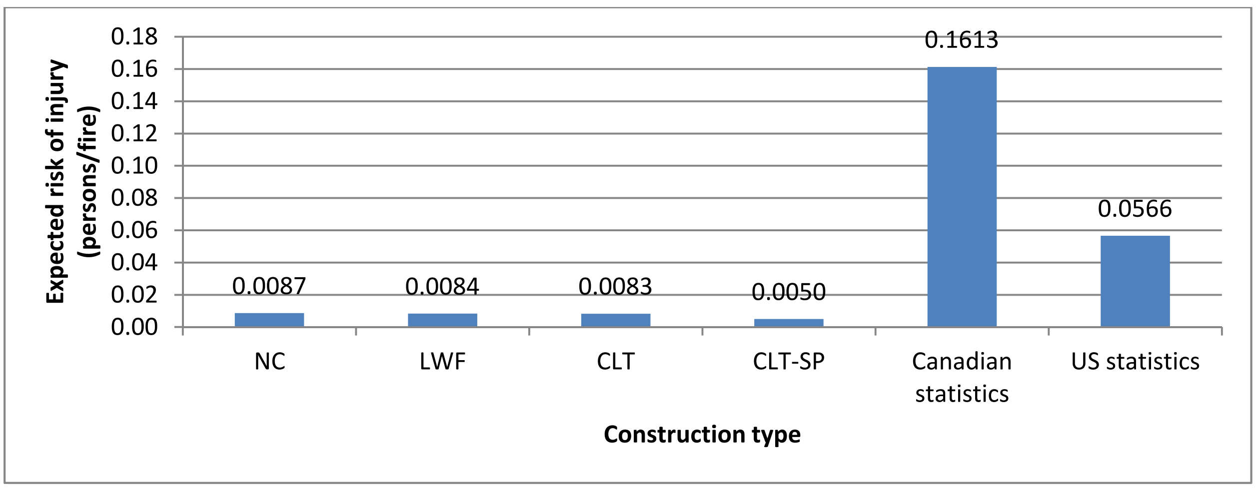

Figure 4.46 Expected risk of injury for small residential buildings

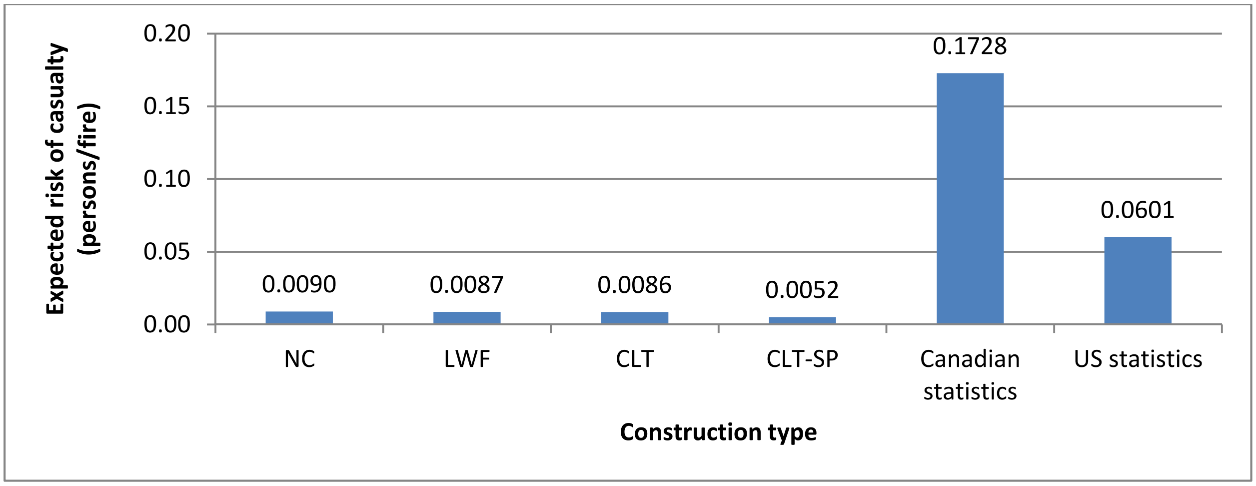

Figure 4.47 Expected risk of casualty (death or injury) for small residential buildings

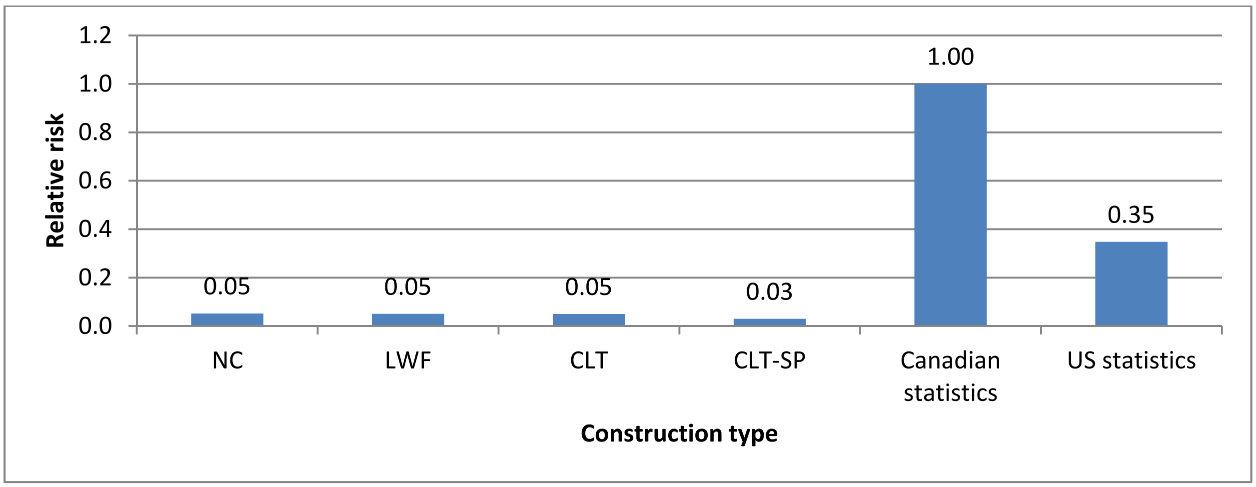

Figure 4.48 Relative risk of casualty for small residential buildings compared to Canadian statistics

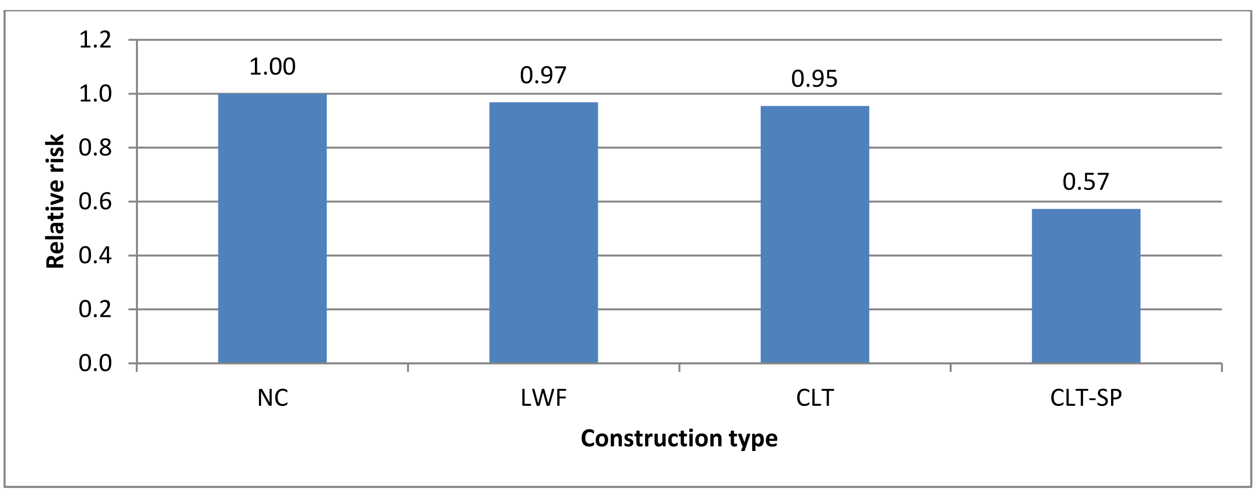

Figure 4.49 Relative risk of casualty for small residential buildings compared to non-combustible construction

Similarly, the temperature development in the corridors and staircases in the residential buildings is also faster than that in the office buildings, and the peak temperatures in the corridors and staircases in the residential buildings are higher than those in the office buildings. This can be explained by both smaller areas and early failure of doors due to higher temperatures in the fire origin rooms. This could be a negative effect. However, shorter corridor can decrease the time occupants go through the corridor.

Due to the smaller occupant load of the residential buildings compared with those of the office buildings, the residential buildings only need a maximum of 972 s during the day and 1010 s at night to evacuate 90% of occupants, while the small office buildings need a maximum of 1498 s to evacuate the same percentage of occupants. This indicates that to sustain the tenable conditions in exits is more important for the office buildings than for the residential buildings.

4.3.2 Large-Area Six-Storey Residential Buildings

The large residential buildings with the layout shown in Figure 2.2 (R6L-NC, R6L-LWF and R6L-CLT) are simulated. These buildings are called CLT, LWF, and NC buildings in this section. More details of these buildings are given in Tables 3.1 and 3.2. The event tree is given in Figures 3.2 and 3.4. Simulation results are shown in Figures 4.50 – 4.59.

Figures 4.50 and 4.51 show the temperature development in the fire origin rooms, corridors and staircases close to the fire origin rooms for scenarios S4 and S8. Sprinklers in both scenarios fail to activate. The difference between the two scenarios is that S4 happens during the day and S8 at night. Figure 4.52 shows the maximum and minimum remaining occupants as a percentage of total occupants in all Monte Carlo evacuation processes for scenarios S8 and S4.

The temperatures in the staircases are always under 120 °C and are lower than that in the small residential buildings. The temperatures in the corridors are lower than 120 °C within 1266 s for the LWF and CLT buildings and within 1358 s for the NC building. The two times are 24 s and 30 s later than those in the small residential buildings, which provides slightly longer safe evacuation time. Additionally, the smoke temperatures in the corridors of the large residential buildings are 200 °C to 225 °C, which are 40 °C to 50 °C lower than those in the small residential buildings. This can be a benefit in case occupants have to go through the corridor at late time.

By the time the temperature has risen to 120 °C, less than 9% of occupants remain in the building. They are mainly occupants on the floors different from the fire origin floors since the times the occupants on the fire origin floors need to evacuate the buildings are 228 s to 1526 s including response times of 200 s to 538 s for scenario S8 and 212 s to 1478 s including response times of 184 s to 502 s for scenario S4. While the longest times are later than the time the temperature has been 120 °C, the thickness of the smoke layer is not thick enough to injure occupants. These indicate that deaths and injuries still happen in the fire origin rooms. This is similar to that in the small residential buildings, as the fire origin rooms do not change.

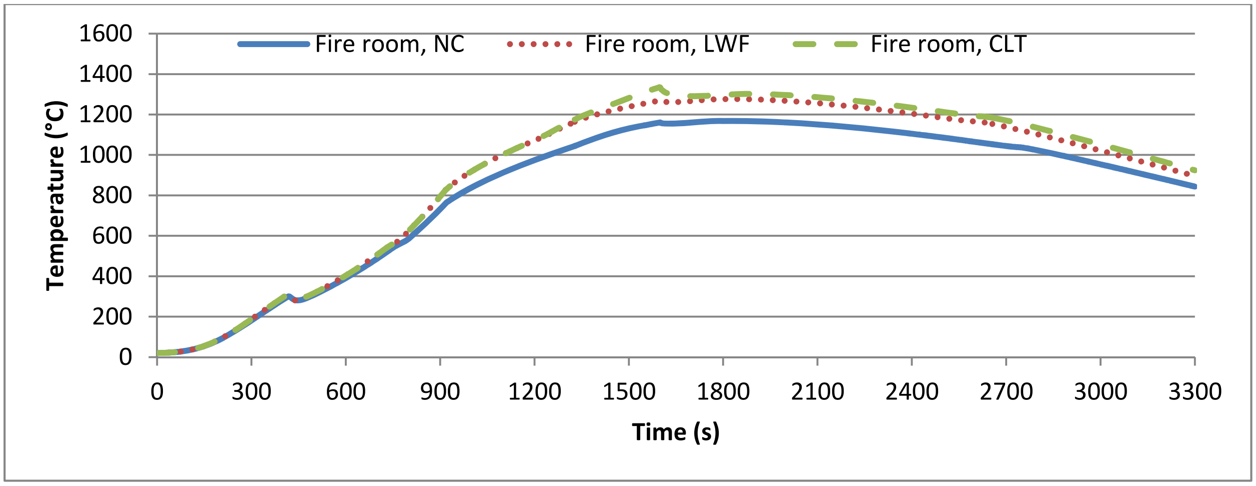

Figure 4.50 Upper layer temperatures in fire origin rooms for scenarios S4 and S8 of large residential buildings

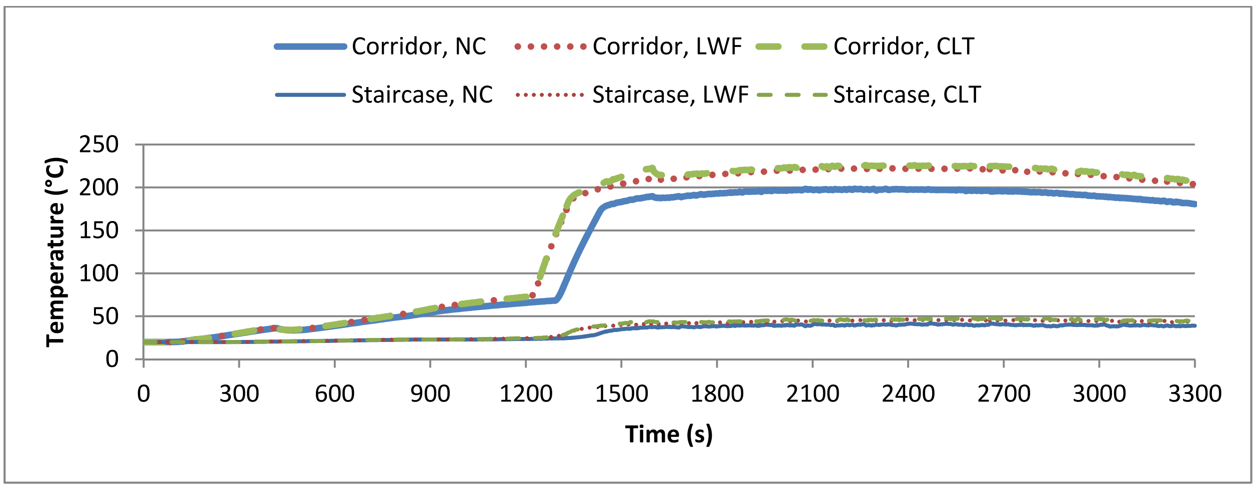

Figure 4.51 Upper layer temperatures in corridors and staircases close to fire origin rooms for scenarios S4 and S8 of large residential buildings

Figure 4.52 compares the maximum and minimum remaining occupants for the daytime scenario S4 and night scenario S8, which do not change with the construction type, because fire development in the three buildings is similar. The evacuation process for the large residential building is similar to that for the small residential buildings. There are also differences. For scenario S4, the times at which 90%, 99%, and 100% of occupants evacuate the buildings are 1096 s, 1862 s and 3064 s. For scenario S8, the three times are 1102 s, 1890 s and 3120 s. The times for 90% of occupants for scenarios S4 and S8 are 124 s and 92 s longer than those for the small residential buildings.

Similar analysis can be made for Scenario S3 and S7. The numbers of deaths and injuries for scenarios S3, S4, S7 and S8 are in agreement with or on the same magnitudes as the statistical data for 2002 Canadian apartment fires (CCFMFC 2007) and 2007 – 2011 US apartment fires (Ahrens 2014).

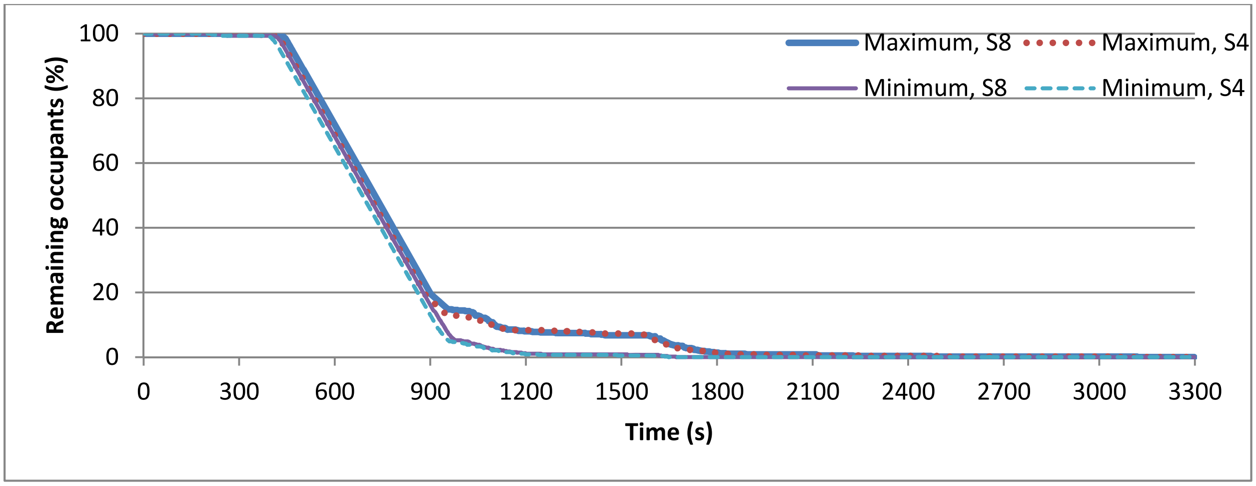

Figure 4.52 Maximum and minimum remaining occupants as a percentage of total occupants for scenario S4 and S8 for NC building

Scenarios S1, S2, S5, and S6 have much milder temperature development due to the activation of sprinklers. As a result, Figures 4.53 and 4.54 show that for scenarios S1, S2, S5, and S6, no fire death or injury is predicted.

Figures 4.55 - 4.57 show that all the three buildings have very low fire risk in terms of death and injury due to the use of sprinklers. Specifically, the expected risk is about 3% of the Canadian statistical value and 9% of the US statistical value in terms of death, and 5% of the Canadian statistical value and 15% of the US statistical value in terms of injury. If sprinklers with higher reliability, 0.97 (shown as CLT-SP in the Figures), instead of general reliability, 0.95, are used, the risk will be reduced further to 60% of the risk for the general sprinklers.

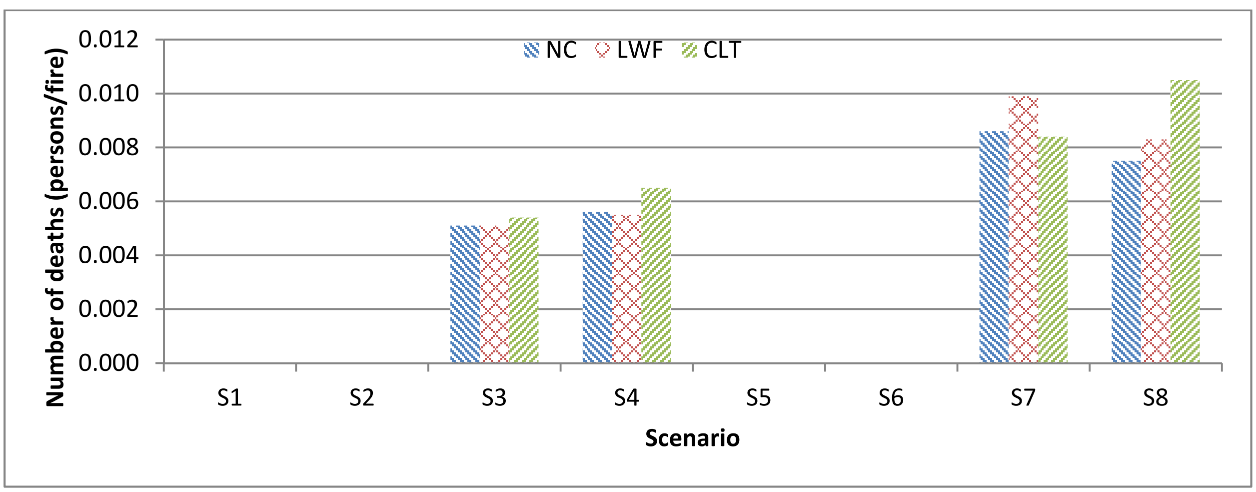

Figure 4.53 Number of deaths for different scenarios in large residential buildings

Figures 4.58 and 4.59 show that the three buildings have relative risks of 0.05 compared to the Canadian statistical value, indicating that all three buildings have similar risk and all are much lower than the reference value. The LWF and CLT buildings show relative risk of 0.95 and 0.96 compared to the NC building. Additionally, the expected risks of death for the three buildings are quite similar. Therefore, the risks of the three buildings are very close.

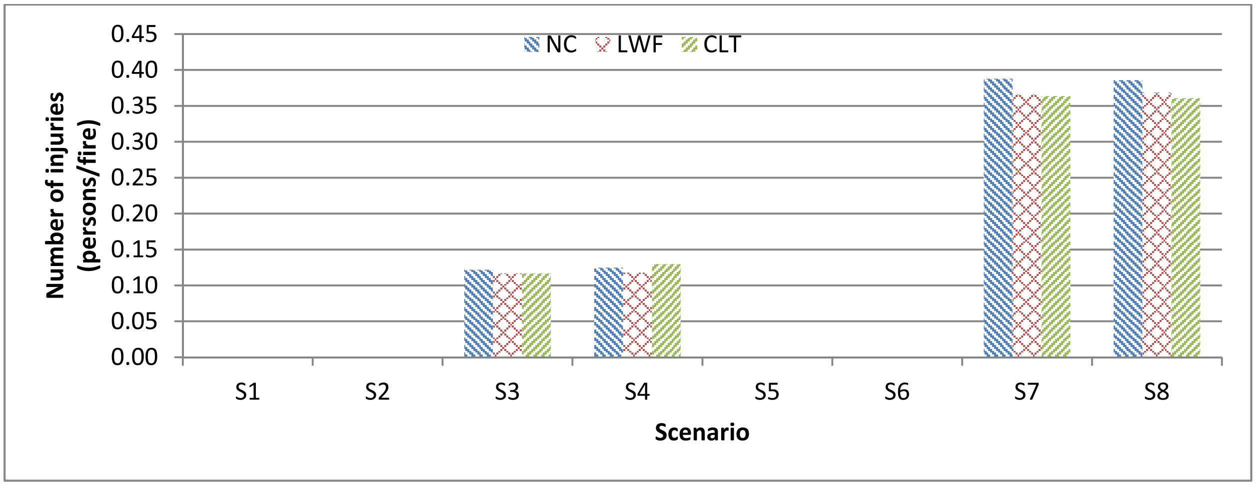

Figure 4.54 Number of injuries for different scenarios in large residential buildings

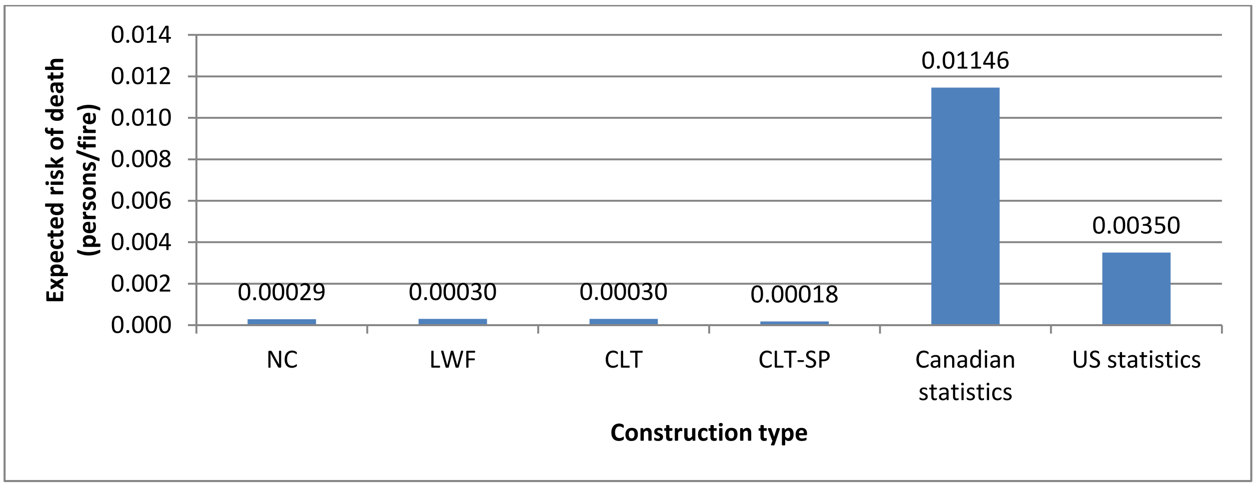

Figure 4.55 Expected risk of death for large residential buildings

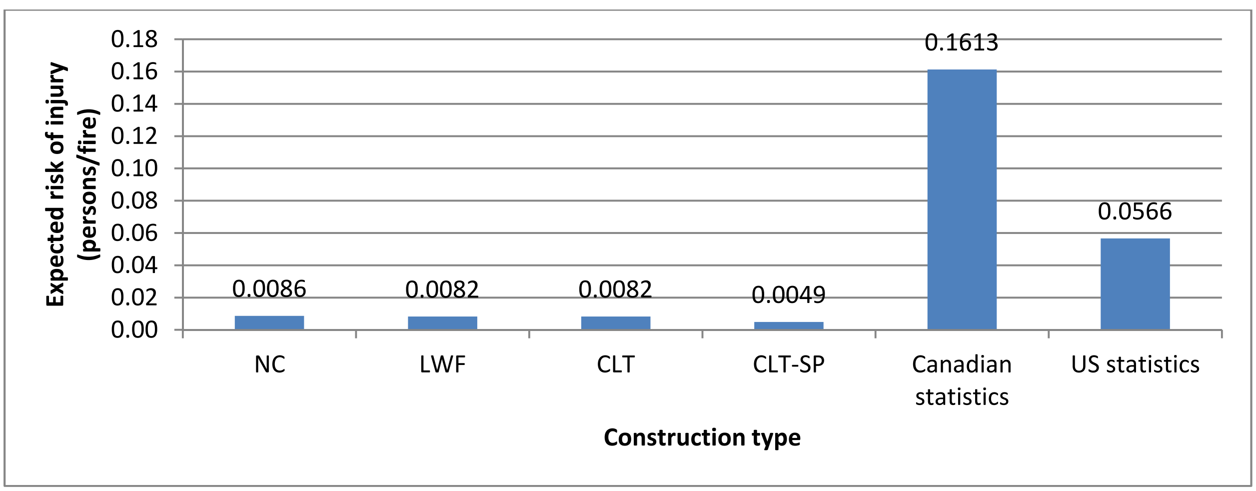

Figure 4.56 Expected risk of injury for large residential buildings

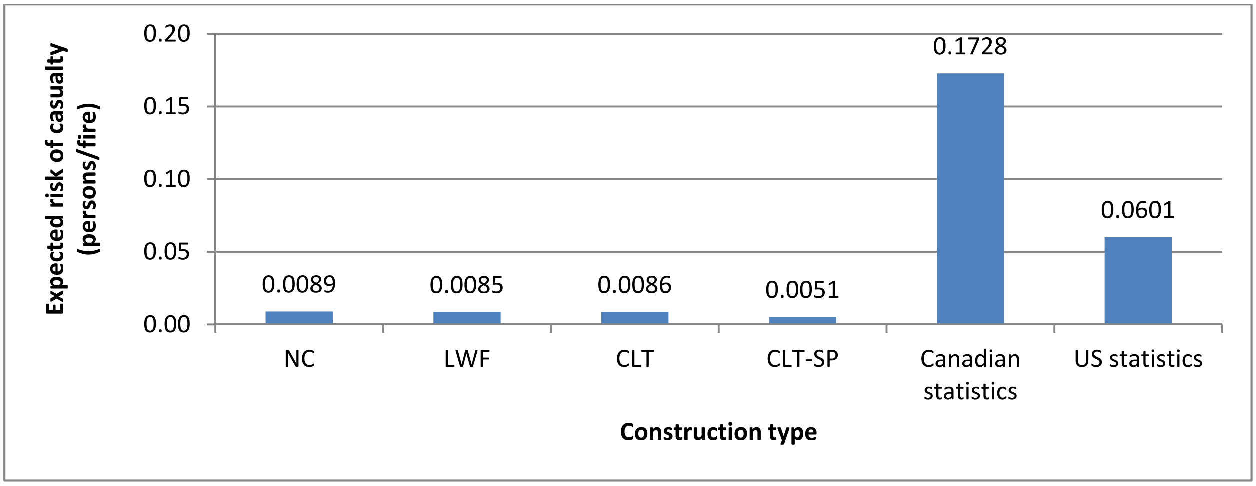

Figure 4.57 Expected risk of casualty (death or injury) for large residential buildings

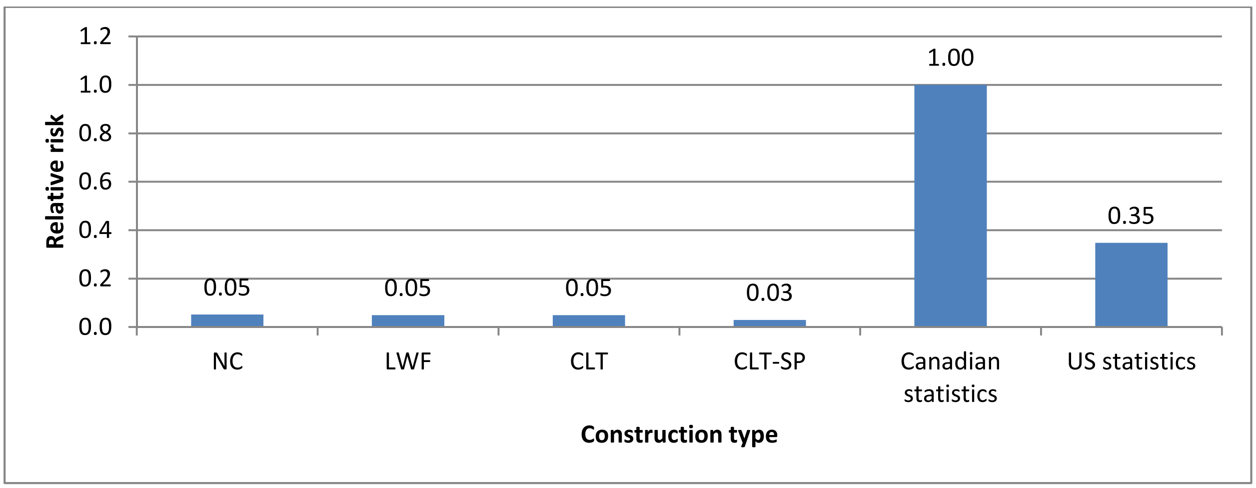

Figure 4.58 Relative risk of casualty for large residential buildings compared to Canadian statistics

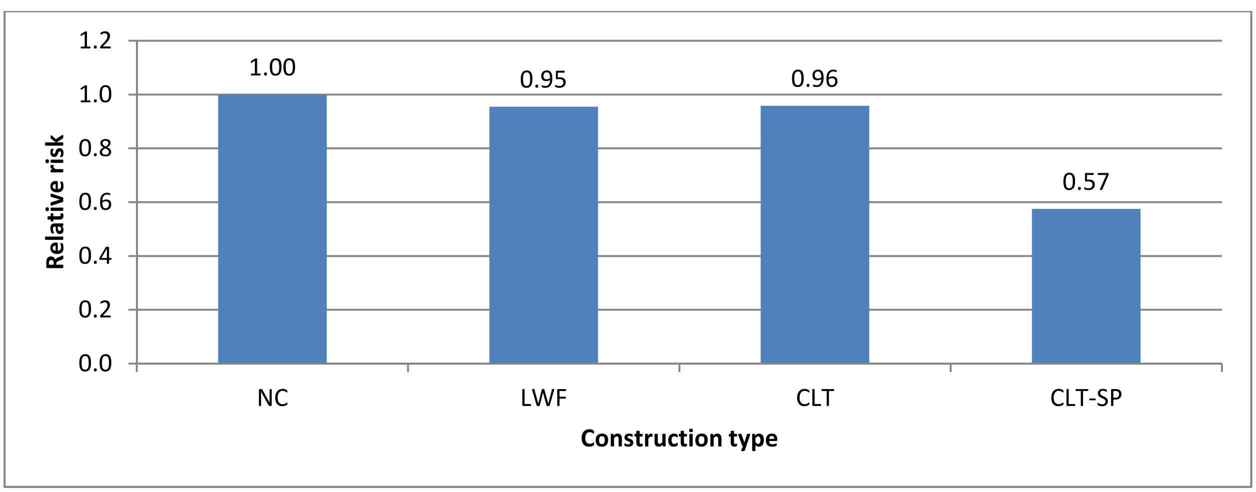

Figure 4.59 Relative risk of casualty for large residential buildings compared to non-combustible construction

The large residential buildings have very close risk to that of the small residential building. Larger area and occupant load do not change fire risk significantly.

4.3.3 Twelve-Storey Residential Buildings

Fires in the high residential buildings with the layout shown in Figure 2.2 (R12-NC, R12-CLT, R12-CLT-BCN and R12-CLT-D45) have been simulated. These buildings are called NC, CLT, and CLT-D45 buildings in this section. CLT-BCN means the CLT building with balconies and CLT-D45 the CLT building with suite doors with 45 min fire protection rating. More details of these buildings are given in Tables 3.1 and 3.2. The event tree is given in Figures 3.2 and 3.4. Simulation results are shown in Figures 4.60 – 4.69.

Figures 4.60 and 4.61 show the temperature development of the fire origin rooms, corridors and staircases close to the fire origin rooms for scenarios S4 and S8. The effect of a balcony on fire development inside the building is not considered and therefore the temperature development of the CLT-BCN building is the same as that of the CLT building. Sprinklers in both scenarios fail to activate. The difference between the two scenarios is that S4 happens during the day and S8 at night. Figure 4.62 shows the maximum and minimum remaining occupants as a percentage of total occupants in all Monte Carlo evacuation processes for scenarios S8 and S4.

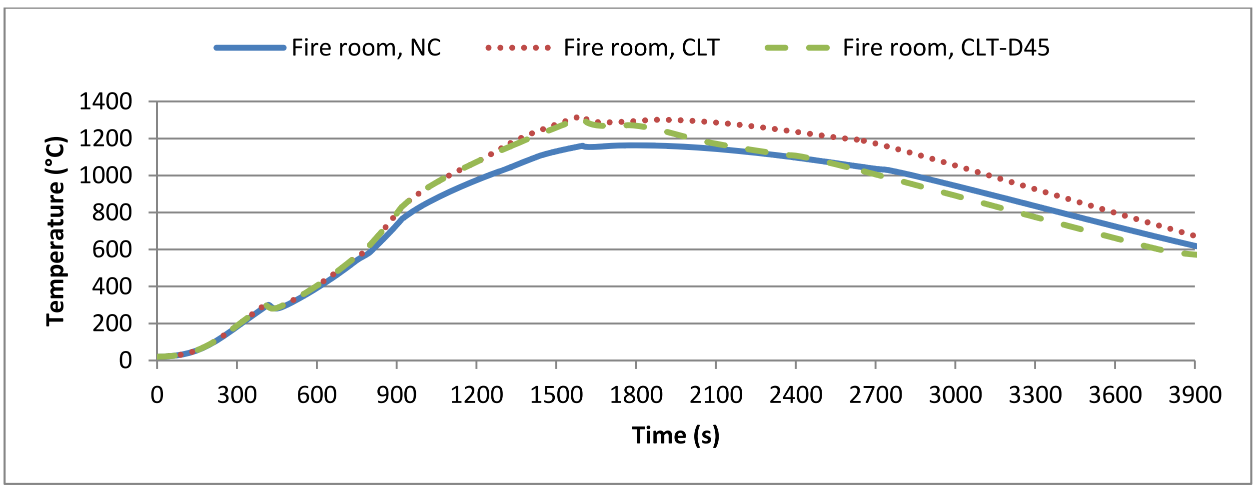

Figure 4.60 Upper layer temperatures in fire origin rooms for scenarios S4 and S8 of high residential buildings

The temperatures in the staircases are always under 120 °C. The temperatures in the corridors are lower than 120 °C within 1266 s for the CLT building, 1358 s for the NC building, and 1800 s for the CLT-D45 building. The times for the CLT and NC buildings and the smoke temperatures in the corridors and the staircases are the same as for the large-area 6-storey residential CLT and NC buildings, as both buildings have the same plan layout. For the CLT-D45 building, the time at which the corridor reaches 120 °C is delayed about 9 min compared to the time of the CLT building due to the suite doors with 45 min fire protection rating, which is longer than the 20 min fire protection rating of general doors. Due to the late failure of the door, the temperature in the corridor of the CLT-D45 building is lower than that in the CLT building. The longer failure time and the lower temperature provide longer safe evacuation time.

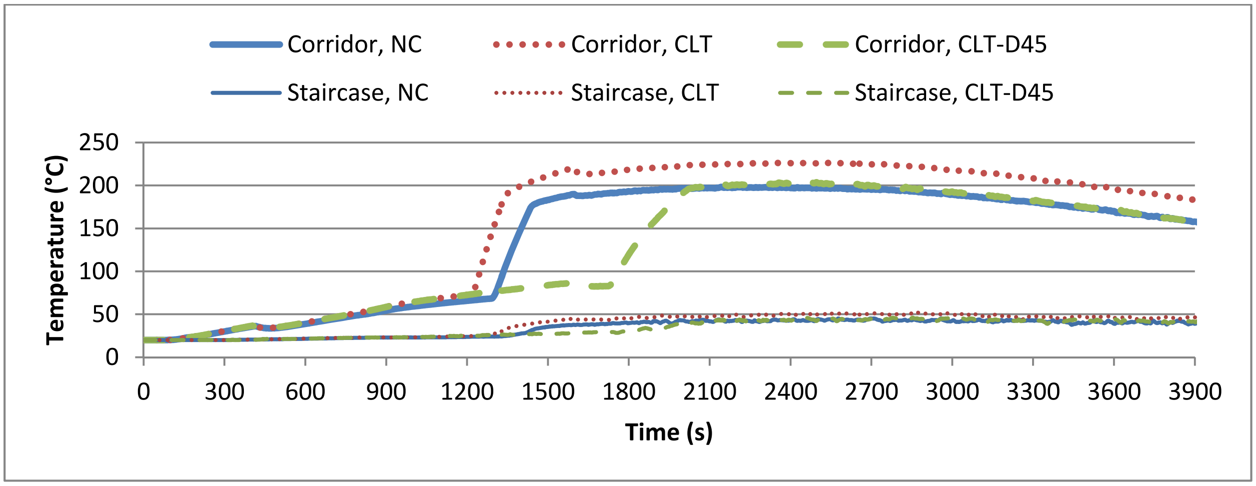

Figure 4.61 Upper layer temperatures in corridors and staircases close to fire origin rooms for scenarios S4 and S8 in high residential buildings

By the times the smoke temperatures of the corridors have risen to 120 °C, less than 29% of occupants remain in the buildings. This percentage is evidently higher than that for the large-area 6-storey residential buildings. They are mainly occupants on the floors different from the fire origin floors since the times the occupants on the fire origin floors need to evacuate the buildings are 228 s to 1544 s including response times of 200 s to 538 s for scenario S8 and 212 s to 1528 s including response times of 184 to 502 s for scenario S4. These numbers are similar to those of the large-area 6-storey residential buildings. While the longest times are later than the time the temperature has been 120 °C, the thickness of the hot smoke layer is not thick enough to injure occupants. These indicate that deaths and injuries still happen in the fire origin rooms. This is similar to the case in the large 6-storey residential buildings, as the fire origin rooms do not change.

Figure 4.62 compares the maximum and minimum remaining occupants for the daytime scenario S4 and night scenario S8, which do not change with the construction type, because fire development in the three buildings is similar. The evacuation process for the high residential building is similar to that for the large-area 6-storey residential buildings except for longer evacuation times. For scenario S4, the times at which 90%, 99%, and 100% of occupants have evacuated the buildings are 1478 s, 1958 s and 3802 s. For scenario S8, the three times are 1496 s, 1982 s and 3812 s. The times for 90% of occupants for scenarios S4 and S8 of the high residential buildings are 382 s and 394 s longer than for the large residential buildings due to higher occupant load.

Similar analysis can be made for Scenario S3 and S7. The numbers of deaths and injuries for scenarios S3, S4, S7 and S8 are in agreement with or on the same magnitudes as the statistical data for 2002 Canadian apartment fires (CCFMFC 2007) and 2007 – 2011 US apartment fires (Ahrens 2014).

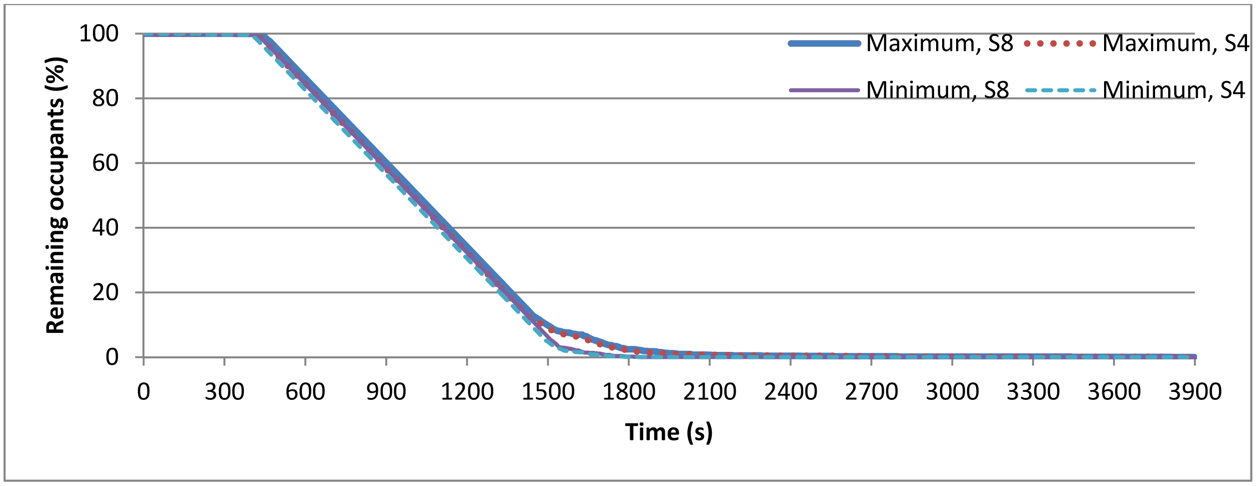

Figure 4.62 Maximum and minimum remaining occupants as a percentage of total occupants for scenarios S4 and S8 for NC building

Scenarios S1, S2, S5, and S6 have much milder temperature development due to the activation of sprinklers. As a result, Figures 4.63 and 4.64 show that for scenarios S1, S2, S5, and S6, no fire death or injury is predicted.

Figures 4.65 - 4.67 show that all the four buildings have very low fire risk in terms of death and injury due to the use of sprinklers. Specifically, the expected risk is about 3% of the Canadian statistical value and 9% of the US statistical value in terms of death, and 5% of the Canadian statistical value and 15% of the US statistical value in terms of injury. If sprinklers with higher reliability, 0.97 (shown as CLT-SP in the Figures), instead of common reliability, 0.95, are used, the risk will be reduced further to 60% of the risk for the general sprinklers.

In the studies, no death or injury due to fire spread is predicted. As a result, the numbers of deaths and injuries for different scenarios and the expected risks of casualty for all scenarios of the CLT-BCN building are quite similar to those of the CLT building. Balconies do not show effect on reducing fire risk for these buildings.

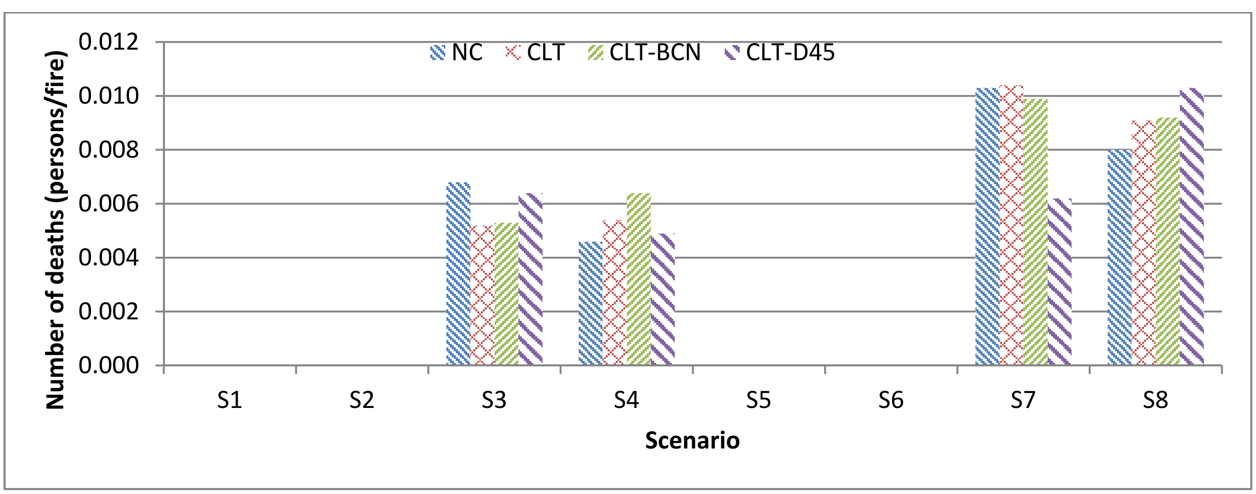

Figure 4.63 Number of deaths for different scenarios of high residential buildings

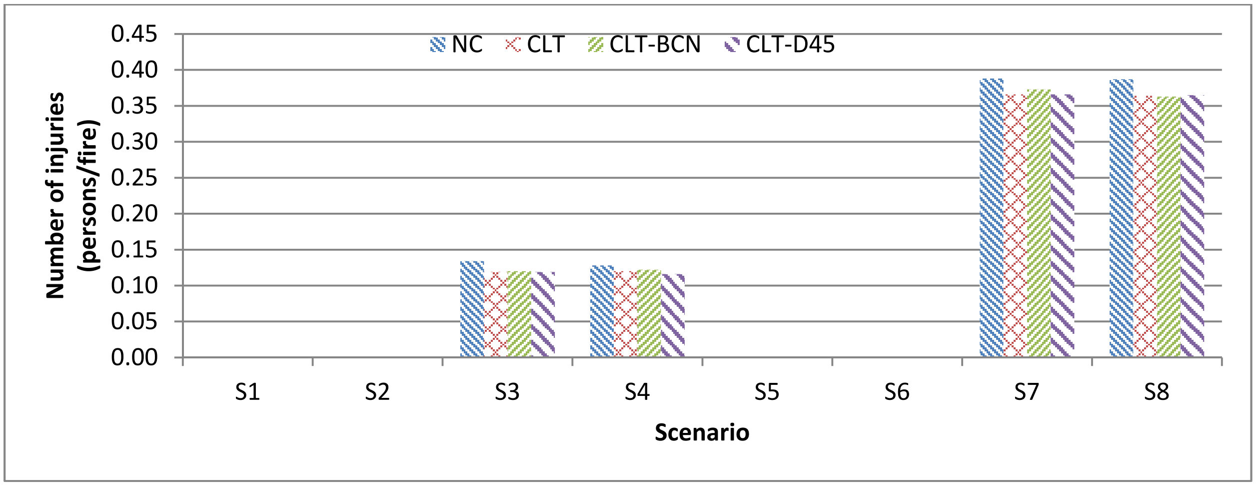

Figure 4.64 Number of injuries for different scenarios of high residential buildings

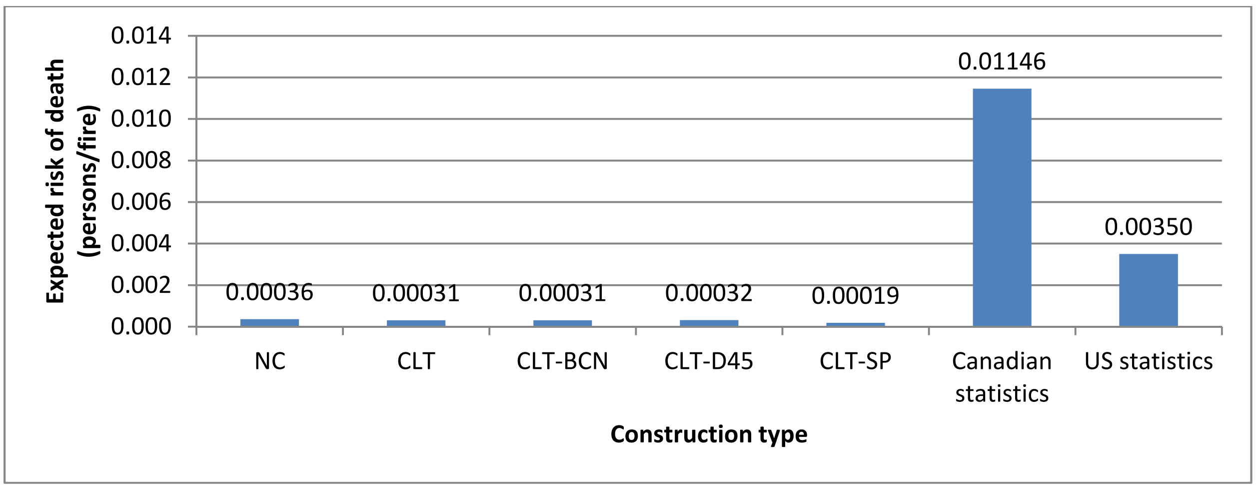

Figure 4.65 Expected risk of death for high residential buildings

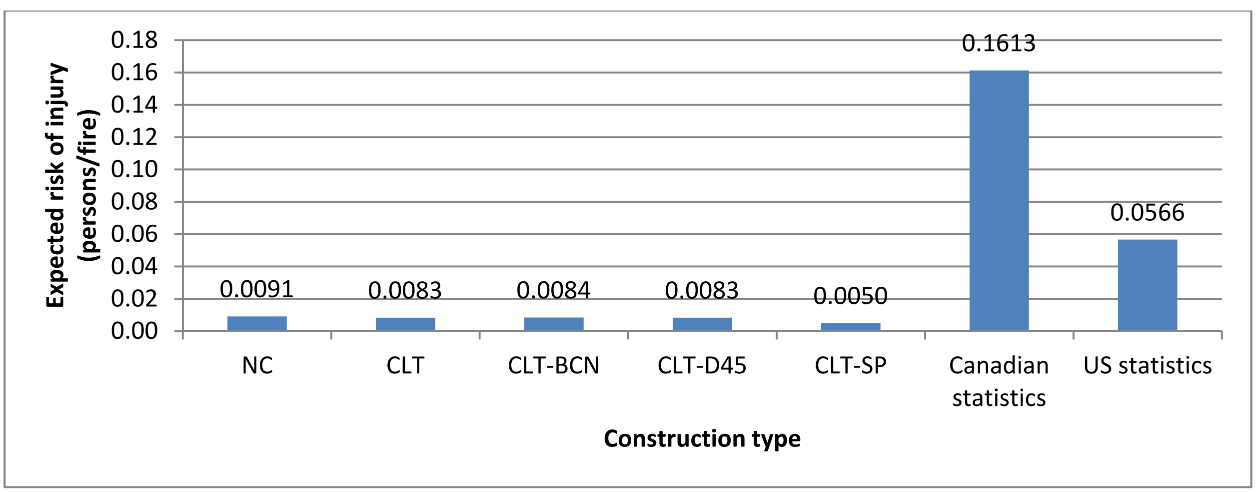

Figure 4.66 Expected risk of injury for high residential buildings

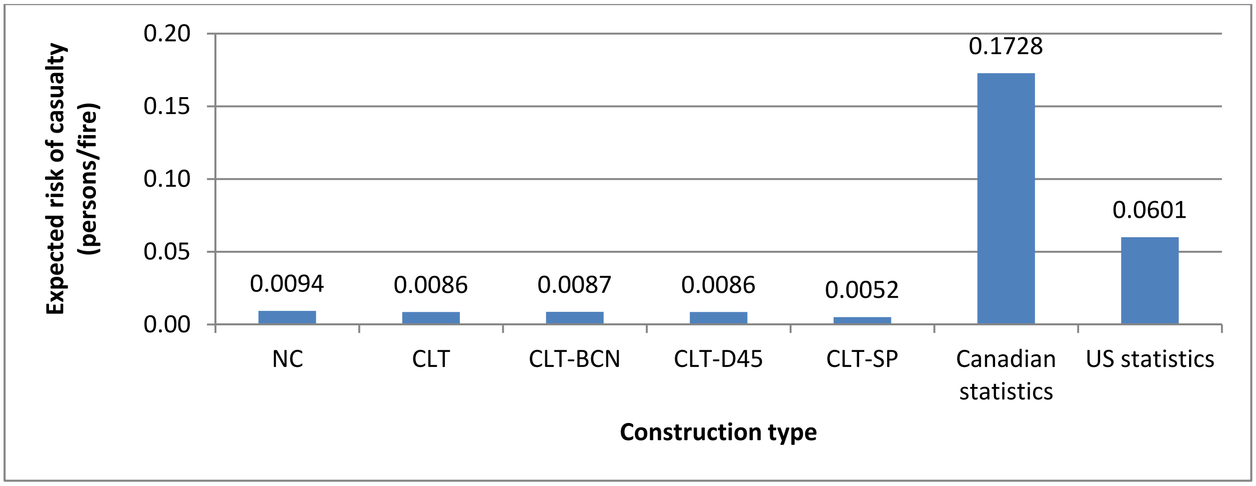

Figure 4.67 Expected risk of casualty (death or injury) for high residential buildings

Figures 4.68 and 4.69 show that the three buildings have relative risks of 0.05 compared to the Canadian statistical value, indicating that all three buildings have similar risk and all are much lower than the reference value. The CLT, CLT-BCN, and CLT-D45 buildings show relative risk of 0.91 to 0.92, compared to the NC building. Additionally, the expected risks of death for the four buildings are quite similar. Therefore, the risks of the four buildings are very close.

The high residential buildings have very close risk to that of the large-area and small-area 6-storey residential buildings. Higher height, larger area and occupant load do not change fire risk significantly.

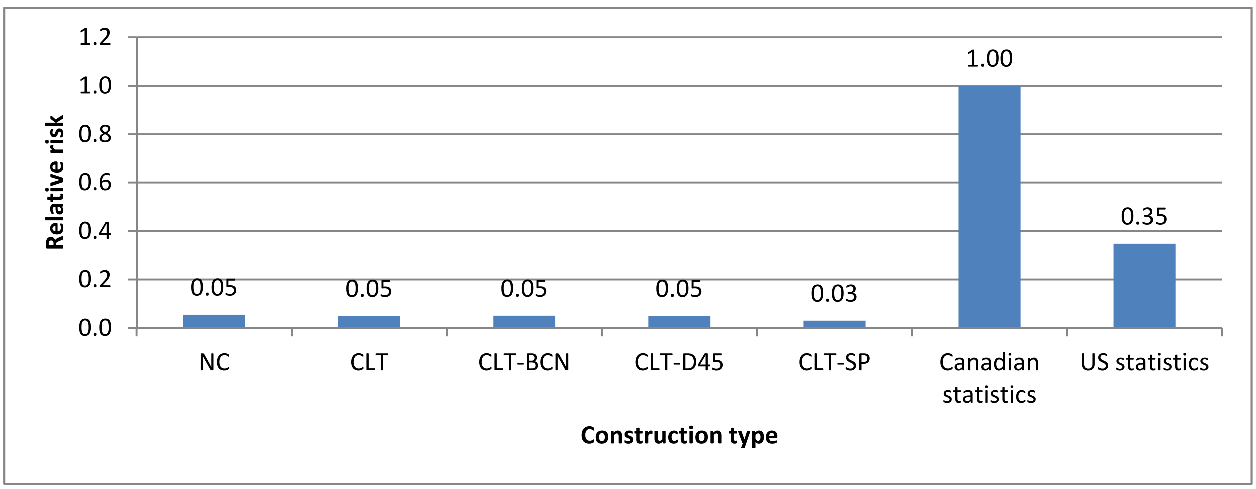

Figure 4.68 Relative risk of casualty for high residential buildings compared to Canadian statistics

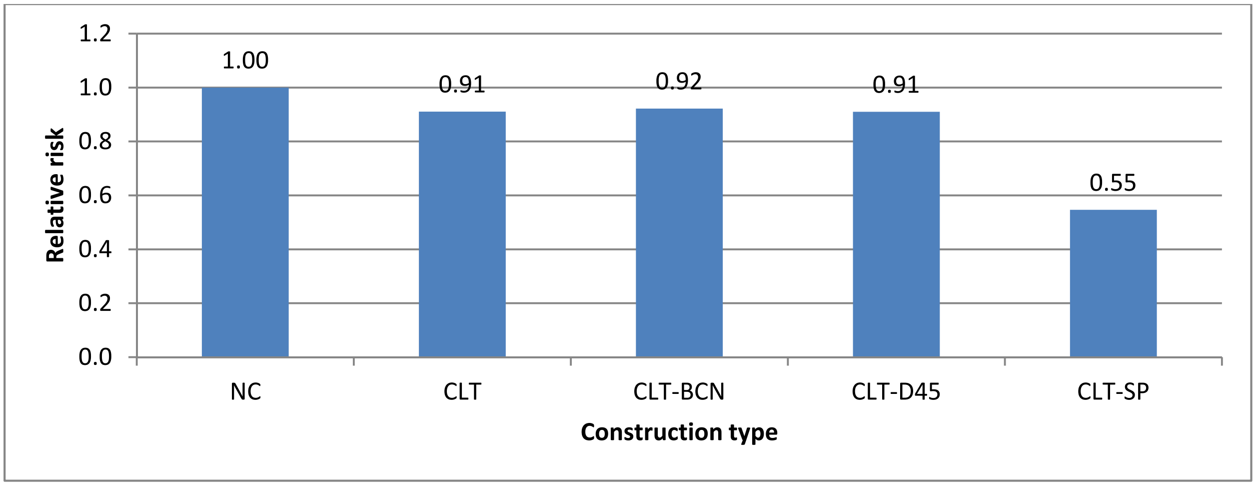

Figure 4.69 Relative risk of casualty for high residential buildings compared to non-combustible construction

5 Summary and Conclusions

The life risks of the office and residential buildings are summarised in Tables 5.1 and 5.2.

For all the compartmented buildings including small-area and large-area 6-storey office and residential buildings and 12-storey residential and compartmented office buildings, life risks and the difference between life risks of the buildings with different constructions, areas and heights are very low. In these buildings, life risk is limited to occupants in the fire origin rooms. All deaths and injuries in these buildings are attributable to heat and toxic gases in the fire origin rooms rather than fire or smoke spread.

For the 12-storey open floor concept office buildings, due to uncontrolled smoke movement and very long evacuation time, high concentration toxic gases in the staircases can injure occupants not in the fire origin regions. For this design, the effect of the construction type on the expected risk of injury is insignificant. While the expected risks are similar to those for the compartmented buildings, high occupant load may be a concern. Wider exits can reduce the expected risk of injury significantly.

Meanwhile, comparison between the numbers of deaths and injuries of scenarios with and without suitable fire protection systems show the importance of fire protection systems in reducing life risk from fire in all buildings. Sustaining the reliability of fire protection systems through proper design, installation, inspection, and maintenance is important to achieve life safety objectives.

In the case studies, all parameters used are applicable to typical occupants and buildings conforming to building codes. For example, 5 s is used as the time needed to awaken sleeping occupants. Occupants are assumed to be healthy occupants consisting of half adult people and half seniors. The results and conclusions are sensitive to the scenario selection. Therefore, they cannot be applied to occupants whose conditions are far from these, such as buildings containing many seniors and/or disabled persons.

Based on the above summary, the following conclusions are made:

- Life safety performance of buildings depends more on the design solutions as a whole rather than the selection of construction type. Properly designed and protected combustible buildings do not impose higher life risk to occupants than non-combustible buildings.
- In compartmented buildings, casualties can be contained in the fire origin room. But in open floor concept buildings, casualties will not be limited to occupants in the fire origin region. For buildings with high occupant load, this may be a concern.

Active protection systems including smoke detectors, smoke alarms, sprinkler systems, and central alarm systems should be designed, installed, inspected, and maintained properly to maintain good performance.

Table 5.1 Summary of life risks of office buildings

Construction	Expected risk of injury (persons / fire)	Expected risk of casualty (persons / fire)	Relative risk compared to Canadian statistics
6-storey, 2976 m^2, non-combustible office building	0.0041	0.0046	0.08
6-storey, 2976 m^2, light wood frame office building	0.0046	0.0051	0.09
6-storey, 2976 m^2, cross laminated timber office building	0.0041	0.0047	0.08
6-storey, 3936 m^2, non-combustible office building	0.0034	0.0040	0.07
6-storey, 3936 m^2, light wood frame office building	0.0033	0.0040	0.07
6-storey, 3936 m^2, cross laminated timber office building	0.0029	0.0034	0.06
12-storey, 2916 m^2, non-combustible office building with open floor	0.0039	0.0039	0.07
12-storey, 2916 m^2, cross laminated timber office building with open floor	0.0044	0.0044	0.07
12-storey, 2916 m^2, cross laminated timber office building with open floor and balconies	0.0041	0.0041	0.07
12-storey, 2916 m^2, cross laminated timber office building with wood frame separation	0.0046	0.0058	0.10
12-storey, 2916 m^2, cross laminated timber office building with open floor and wider exits	0.0009	0.0009	0.02

Table 5.2 Summary of life risks of residential buildings

Construction	Expected risk of death (persons / fire)	Expected risk of injury (persons / fire)	Expected risk of casualty (persons / fire)	Relative risk compared to Canadian statistics
6-storey, 1152 m^2, non-combustible residential building	0.00032	0.0087	0.0090	0.05
6-storey, 1152 m^2, light wood frame residential building	0.00033	0.0084	0.0087	0.05
6-storey, 1152 m^2, cross laminated timber residential building	0.00029	0.0083	0.0086	0.05
6-storey, 1728 m^2, non-combustible residential building	0.00029	0.0086	0.0089	0.05
6-storey, 1728 m^2, light wood frame residential building	0.00030	0.0086	0.0085	0.05
6-storey, 1728 m^2, cross laminated timber residential building	0.00030	0.0082	0.0086	0.05
12-storey, 1728 m^2, non-combustible residential building	0.00036	0.0091	0.0094	0.05
12-storey, 1728 m^2, cross laminated timber residential building	0.00031	0.0083	0.0086	0.05
12-storey, 1728 m^2, cross laminated timber residential building with balconies	0.00031	0.0084	0.0087	0.05
12-storey, 1728 m^2, cross laminated timber residential building with doors of 45 min fire protection rating	0.00032	0.0083	0.0086	0.05

References

Ahrens M. 2007. U.S. experience with smoke alarms and other fire detection/alarm equipment. Quincy (MA): National Fire Protection Association.

Ahrens M. 2012. Home structure fires. Quincy (MA): National Fire Protection Association.

Ahrens M. 2014. Smoke Alarms in U.S. home fires. Quincy (MA): National Fire Protection Association.

[BSSB] Building and Safety Standards Branch. 2012. British Columbia Building Code 2012. Victoria (BC): Building and Safety Standards Branch, Office of Housing and Construction Standards.

Bwalya AC, Sultan MA, Bénichou N. 2004. A pilot survey of fire loads in Canadian homes. Ottawa (ON): National Research Council Canada. Report No.: Research Report No. 159.

Canadian Codes Centre [Internet]. 2015. National Research Council Canada; [modified: 2015 Mar 17; cited 2015 Mar 27]. Available from: http://www.nrc-cnrc.gc.ca/eng/solutions/advisory/codes_centre_index.html

[CCBFC] Canadian Commission on Building and Fire Codes. 2010. National fire code of Canada 2010. Ottawa (ON): National Research Council of Canada.

[CCFMFC] Council of Canadian Fire Marshals and Fire Commissioners. 2007. Annual Report 2002: Fire Losses in Canada. Ottawa (ON): Council of Canadian Fire Marshals and Fire Commissioners.

[CEN] European Committee for Standardization. 2002. EN 1991-1-2:2002 (E). Eurocode 1: actions on structures - Part 1-2: general actions - actions on structures exposed to fire. Brussels: European Committee for Standardization.

Hall JR Jr. 2005. Fire in the US and Canada. Quincy (MA): National Fire Protection Association.

Hall JR Jr. 2012. U.S. Experience with sprinklers. Quincy (MA): National Fire Protection Association.

Karlsson B, Quintiere JG. 1999. Enclosure fire dynamics. New York: CRC Press LLC.

Karacabeyli E, Lum C. 2014. Technical guide for the design and construction of tall wood buildings in Canada. Pointe-Claire (QC): FPInnovations; Report No.: Special Publicaion SP55E.

Kodur VKR, Pakala P, Dwaikat MB. 2010. Energy based time equivalent approach for evaluating fire resistance of reinforced concrete beams. Fire Safety Journal, 45: 211–220.

Li X, Zhang X, Hadjisophocleous G. 2013. Fire risk analysis of a 6-storey residential building by CUrisk. Procedia Engineering, 62: 609-617.

Li X, Rao P, Zhang X, Hadjisophocleous G. 2015a. A case study on the effect of building construction type, height and area on the building fire risk using the fire risk assessment model Curisk. In: Fire and Materials 2015; 2015 February 2 – 4; San Francisco.

Li X, Zhang X, Hadjisophocleous G. 2015b. The effects of fire protection design options and construction types on the overall building fire risk. In: IFireSS 2015; 2015; Coimbra, Portugal. (Accepted)

Mailvaganam S, Yung D, Prencipe M. 1992. Ontario fire loss statistics for the risk-cost assessment model. Ottawa (ON): National Research Council Canada. Report No.: Internal Report No. 622.

NFPA. 2013. NFPA 13: Standard for the Installation of Sprinkler Systems. 2013 Edition. Quincy (MA): NFPA.

[NRCC] National Research Council Canada. 2013. Full-scale fire resistance tests on cross-laminated timber [Internet]. Ottawa (ON): National Research Council Canada; [modified: 2013 Feb 20; cited 2015 Mar 27]. Available from: http://www.nrc-cnrc.gc.ca/ci-ic/article/v17n4-4

[USFA] U.S. Fire Administration, National Fire Data Center. 2006. Structure fire response times. Topical Fire Research Series. 5: 1-5.

Zalok E. 2011. Validation of methodologies to determine fire load for use in structural fire protection. Final Report. Quincy (MA): National Fire Protection Association.

Zhang X, Li X, Hadjisophocleous G. 2012.An improved two-layer zone model applicable to both pre- and post-flashover fires. Fire Safety Journal, 53: 63-71.

Zhang X, Li X, Hadjisophocleous G. 2013. A probabilistic occupant evacuation model for fire emergencies using Monte Carlo methods. Fire Safety Journal, 58: 15-24.

Zhang X, Li X, Hadjisophocleous G. 2014. A probabilistic occupant response model for fire emergencies. Fire Safety Journal, 68: 41-51.