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A probability-based Monte Carlo life-risk analysis model for fire emergencies

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ABSTRACT

The paper proposes a probability-based Monte Carlo life-risk analysis model for fire emergencies. Based on the hazardous conditions in each compartment of a building and the evacuation path of each occupant, the model calculates the probabilities of injury and death determined by fractional effective doses due to heat and toxic gases, considers the probability of death due to fire spread, and produces the probabilities of injury and death for each occupant. Then these probabilities for all occupants are summed to give the total probabilities of injury and death in a Monte Carlo run, and statistics about the total probabilities of all Monte Carlo runs are produced for each fire scenario. According to the statistics and scenario composition, the expected risks of injury and death in the building are calculated. The model is applied to a life risk analysis of 6- and 12-storey apartment buildings. The results show that for these buildings, injuries and deaths are mainly limited to the rooms of fire origin and the effects of building area and the number of storeys on life risk are slight. The predictions for different layouts are in good agreement with the numbers of injuries and deaths given by Canadian and US statistics.

1. Introduction

Fire safety is an important objective addressed by building codes. In recent years, the application of fire safety engineering tools has resulted in dramatic changes to building regulations in many countries. One of the most important characteristics of the changes is that codes have started to allow fire safety design to conform to performance- or objective-based requirements rather than prescriptive requirements [1]. In performance-based or objective-based codes, acceptable solutions are deemed to automatically meet the performance or objective requirements. Alternative solutions are allowed to replace acceptable solutions. However, the alternative solutions must be demonstrated that their performance is equivalent to or better than that of the corresponding acceptable solution, in addition to meeting other relevant requirements.

Since fire protection systems are rarely perfect and fire events are often random, fire safety performance has to be assessed by means of a risk analysis, which becomes more and more important with the development of performance-based or objective-based codes. However, codes generally do not outline specific methodologies to guide fire risk analyses. Instead, it has been covered in engineering guidelines [2,3], which provide general principles rather than specific details.

Fire risk analysis addresses questions related to fire loss in terms of possible scenarios, and their consequences and likelihoods. Fire risk analysis methods can be categorised in different ways [2,4–6]. According to the completeness and complexity of information provided, they can be classified into three groups: qualitative, semi-quantitative, and quantitative. The qualitative methods address both likelihood and consequences qualitatively. The semi-quantitative methods treat likelihood qualitatively but consequences quantitatively, or treat likelihood quantitatively but consequences qualitatively. The quantitative methods treat both consequences and likelihood quantitatively, and are more comprehensive than the qualitative and semi-quantitative methods. Among the three types of methods, the qualitative and semi-quantitative methods are often not enough to provide sufficient information to demonstrate the equivalency of the fire performance of an alternative solution to that of the acceptable solution it is replacing.

Due to complications in the inputs, calculations and outputs

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Nomenclature

EROD	expected risk of death
EROI	expected risk of injury
f	factor to allow for the increased uptake of toxic gases
FED	fractional effective dose
i	index
N	total number
p	probability of scenario
POD	probability of death of an occupant
POI	probability of injury of an occupant
q	radiant heat flux, kW/m^2
T	temperature, °C
t	time, min
TPOD	total probability of death in a Monte Carlo run
TPOI	total probability of injury in a Monte Carlo run
x	common variable
ϕ	volume fraction

Subscripts

c	convection
e	evacuation
FS	fire spread
g	gas
h	heat
i	index
LO	low oxygen
m	mean
MC	Monte Carlo
O	occupants
r	radiation
S	scenario

involved, more and more quantitative methods use computer models. Some examples of quantitative fire risk analysis models are FiRECAM [7] and FIERAsystem [8] developed in Canada, CESARE-Risk [9] in Australia, CRISP [10] in the UK and B-RISK [11] in New Zealand.

Originating from collaborative ventures [12], both FiRECAM [7] and CESARE-RISK [9], were developed for apartment and office buildings and shared similar system structures. FiRECAM [7] uses a probabilistic model to calculate occupant response and a deterministic model to calculate occupant evacuation following the calculation of fire development in the various scenarios, and then calculates the life risk of occupants as the combined probability of fractional incapacitating dose and assumed probability of hazard from high temperatures. A two-zone model is used to predict smoke movement in the corridor on the fire origin floor and a one-zone model is used elsewhere [13]. The model calculates the probability of death based on the effects of heat and toxic gases, as well as fire spread to the location of the occupants. It does not consider the effect of randomness in the evacuation process and the life risk of occupants. As an extension of FiRECAM, FIERAsystem [8] was developed for light industrial buildings with a primary focus on warehouses and aircraft hangars.

CESARE-Risk [9] adopts a three-realisation method to calculate the expected risk to life. The results produced by the method were claimed to be much better than those produced by a single realisation. However, it is unclear whether the model can reproduce results similar enough to those generated by Monte Carlo methods, which can simulate practical situations to a good degree.

CRISP [10] is similar to FiRECAM and CESARE-Risk to some extent. It uses random methods to produce possible fire scenarios but states Monte Carlo simulations are too massive and time consuming to be possible. Fractional Effective Dose (FED) is used to determine life risk with the assumed threshold death and injury FEDs of 1 and 0.1 respectively. The risk of death or injury is defined as ratio of the number of people affected to the number exposed.

B-RISK [11] allows the user to perform Monte Carlo simulations by using randomly sampled parameters according to input distributions. In addition to the calculation of fractional effective dose, reduced visibility is also taken as a hazard. However, these parameters are calculated for a fixed position in a specific room. While egress paths can be specified by the user, the life hazard of occupants calculated by using this method is problematic due to the high randomness of human behavior.

The present paper proposes a probability-based Monte Carlo life-risk analysis model, which has been integrated into a fire risk analysis model CUrisk [14] being developed at Carleton University. The model is applied in life risk analyses of 4 typical 6- and 12-storey non-combustible apartment buildings compliant with the National Building Code of Canada [1]. The results produced by the model are in agreement with statistics.

2. Brief summaries of relevant sub-models of the fire risk analysis model CUrisk

The fire risk analysis model CUrisk [14] consists of a number of sub-models, among which the important ones are system, scenario generation, fire growth and smoke movement, occupant response, fire spread, occupant evacuation and life-risk analysis sub-models.

The system sub-model controls the calculation process of the entire model and produces the final results based on the intermediate results generated by other sub-models. The scenario generation sub-model converts the user-input scenarios into the format that other sub-models use, and can accommodate multi-scenario calculations.

The fire growth and smoke movement sub-model [15–17] adopts a two-zone approach to predict the heat release rate, temperature and concentrations of oxygen, carbon monoxide, and carbon dioxide in each zone, and interface height in each compartment of a building. The model considers heat released from both room contents and a combustible structure and is applicable to the full fire process including growth, fully developed and decay stages.

The effect of openings on fire growth and smoke movement is considered by using leakage fractions, which mean the ratios of the leakage areas on windows or doors to their integral areas. The initial leakage fractions of windows and doors are specified by the user. The windows will break and the leakage fractions will be changed to 1 for a room when the temperature and pressure difference meet the following condition

$$\frac{T-20}{300-20}+\frac{abs(\Delta p)}{1500}\geq 1 \tag{1}$$

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 windows.

The leakage fraction of a door will start to linearly increase once the door in a fire has received the same amount of heat as it has when it has been exposed in the standard fire for a time duration equivalent to its fire protection rating. The fraction will increase to 1, after the door receives 50% more heat. The calculation is based on the energy-based time equivalent approach for evaluating fire resistance [18].

The time delay from the fire initiation to the time when the fire department starts to suppress the fire consists of three parts: notification time, response time, and setup time. The notification time is assumed to be the minimum of the times at which smoke detectors or sprinklers activate or the fire is large enough to be perceived by occupants. The other two parts are based on statistics and are given in