SIMULATION OF CITY FIRE

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ABSTRACT

The purpose of this study is to develop a physical model of city fire spreading. First, we developed a fundamental model of city fire. Then we made a simulation program of city fire based on the fundamental model. Using the physical model of city fire, risk of fire in urban area can be evaluated in detail.

1. INTRODUCTION

In Japan, the areas crowded with the wooden houses exist. In these areas, buildings are built very close by each other and streets are narrow. When a fire breaks out, there is a danger of spreading easily. Especially in case of an earthquake, there are so many fires break out simultaneously, that fire engines cannot get to all of fires. Even if a fire engine gets to the burning area, crowded houses and narrow streets prevent from fire-fighting activity. About 7000 buildings were burned down in case of the South Hyogo prefecture earthquake in 1995. The disaster measures to these areas are very important.

This paper explains development of the tool for evaluating the fire prevention performance of city area. This is a premise to disaster measures.

2. THE OUTLINE OF THE MODEL OF CITY FIRE

2.1 The unit of fire spread

Generally, city fire is considered to spread from building to building. But, fire is prevented to spread in a building, when it has some fireproofed partitions in it. Such as an apartment constructed by reinforced concrete. It is suitable to describe the city fire that a partitioned area in a building, instead of a building itself. In this model, the term "*Unit*" is defined as the area partitioned by fireproofed wall.

Units in the city can be divided into three types as follows;

Fireproof Unit can be ignited only internal things (e.g. furniture) by heat from outside through its openings. After ignite, the flame or heat can rise only from its openings. After its inside was burned out, it remains same shape as the shape before ignition.

Covered Wooden Unit can also be ignited only internal things by heat from outside through its openings. After ignite, at first, the flame or heat can rise only from its openings (same as *Fireproof Unit*). but its roof is broken down after minutes, and then the outer wall is broken, and finally, it burned down and would not remain the shape.

Uncovered Wooden Unit can be ignited its entire outer wall. Its roof and outer wall fall down immediately after ignition. And then it burns down and does not remain the shape. The *covered wooden units* which are collapsed by earthquake are also in this type.

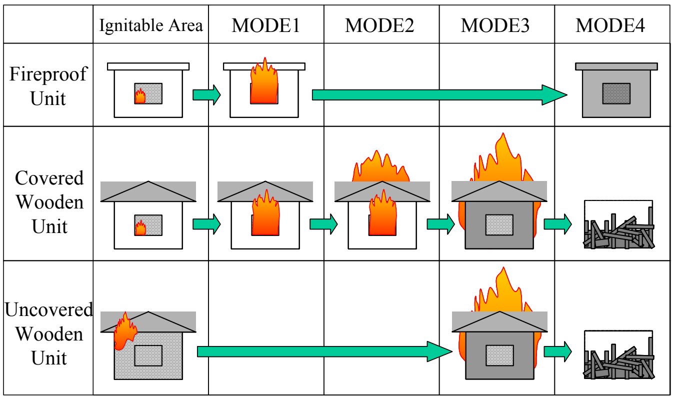


Figure 1: Fire process of the unit

Ignitable area: The area where the unit ignite by receiving heat
MODE0: Condition of unit before ignition
MODE1: Condition of unit with flame rising only from opening
MODE2: Condition of unit with flame rising opening and roof
MODE3: Condition of unit burning the whole
MODE4: Condition of unit after burning out

2.2 Scenario of city fire

City fire can be divided to four phenomena of spreading process. That are; progress of fire of each unit, heat emission from burning unit, heat transmission from unit to another surrounding unit, and temperature rise and ignition of Ignitable area.

Figure 2 shows the relationship among the four phenomena.

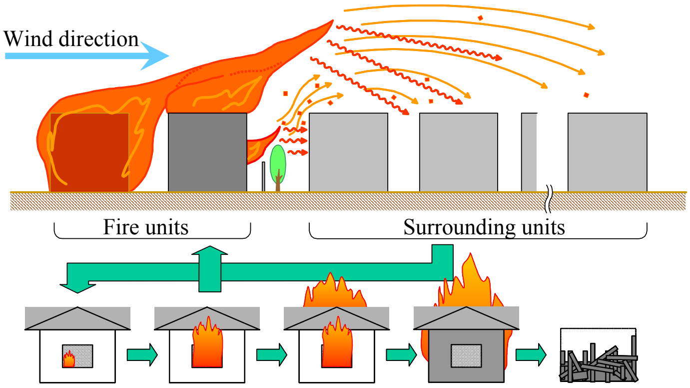


Figure 2: Scenario of city fire

3. PHYSICAL MODEL OF CITY FIRE

The model of city fire also can be divided to four sub-models corresponding to the four phenomena. In this chapter, the outlines of sub-models are described.

3.1 Model of fire progress in a unit

The fire progress is defined by following rules in this model.

- The quantity of heat generation increase in proportion to the second power of time when the unit changes the *MODE*, if it is less than the maximum.
- The maximum of generating heat of each *MODE* (Q_{max1}~Q_{max3}[kW]) is defined by the quantity of combustibles and the size of all openings belonging with the unit.
- It is 1200 seconds later from the time of reaching maximum of *MODE1* (t_{FO1}[s]) that changing to *MODE2*. And it is 1800 seconds later from t_{FO1} that changing to *MODE3*.
- The quantity of heat generation starts decrease when more than 40% of combustibles are burned out (t_p[s]).
- The decreasing speed is constant after t_p.
- The fire finishes the progress when the remains of combustibles are 40% (t_q[s]).

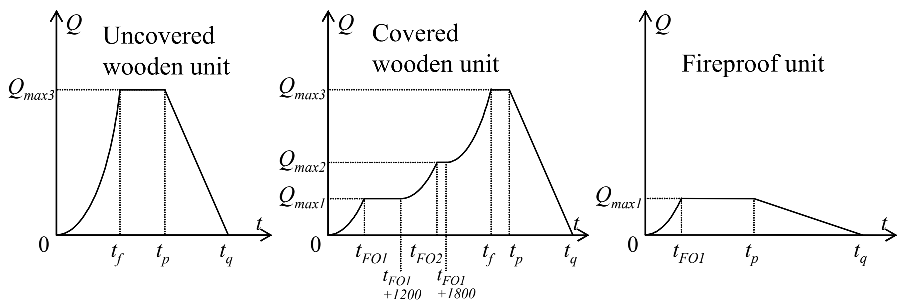


Figure 3: Fire progress curve of each unit

3.1.1 *Quantity of combustibles (W[kg])*

Combustibles are the sum total of fixed combustibles (W_b[kg]) and loading combustibles (W_l[kg]). Fixed combustibles are a structure component or interior material. On the other hand, loading combustibles are clothing, furniture, etc.

There are large difference in quantity of fixed combustibles between wooden building and non wooden building. As for Loading combustibles, the quantity per 1[m^2] (w_l[kg/m^2]) of floor area (A_{floor}[m^2]) is decided by the use of building. (Equation 1)

$$\begin{aligned} &W = W_b + W_l \\ &W_b = 60A_{floor} + 90A_1 && \text{(Wooden unit)} \\ &W_b = 0.5\times 1.5\times H_c\times A_{floor} && \text{(Non wooden unit)} \\ &W_l = w_l\times A_{floor} \end{aligned} \tag{1}$$

A_1: Floor area of the first story[m^2], H_c: Floor height[m]

3.1.2 *Maximum of heat generation*

Q_{max} depends on two elements, one of it is the size of the surface area of combustibles; another one is the quantity of air flowing into the unit through the openings.

The size of the surface area of combustibles (A_f [m^2]) can be found by the following equations.

$$A_f = 0.54 w_l^{1/3} A_{floor} + 2NA_1 + 8A_1^{1/2} H_c + 0.09\left(W_b / A_1\right)^{2/3} A_{floor} \tag{2}$$

N: Number of stories[-]

Considering the height position (Z_n[m]) where internal and external pressure of unit is equal, the balance of air flow can be calculated, assuming the temperature inside unit to be 1073[K] degrees. In the condition shown in figure 4, which is the condition of the unit with one opening, the quantity of air flow (m_{in}[kg/s] or m_{out}[kg/s]), is calculated by equation 3. In other conditions, it can be calculated by the same method. The unit's opening condition is decided by the arrangement of windows and the *MODE* of the unit.

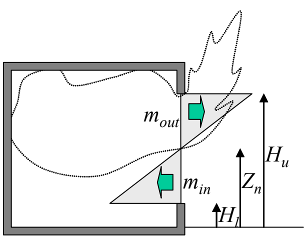


Figure 4: Air flow of a unit with one opening

$$\begin{aligned} m_{out} &= \frac{2}{3}\alpha B\sqrt{2g\rho_{in}\left(\rho_\infty - \rho_{in}\right)}\left(H_u - Z_n\right)^{\frac{3}{2}} \\ m_{in} &= \frac{2}{3}\alpha B\sqrt{2g\rho_\infty\left(\rho_\infty - \rho_{in}\right)}\left(Z_n - H_l\right)^{\frac{3}{2}} \end{aligned} \tag{3}$$

α: Coefficient of air flow[-], B: Width of opening[m],
g: Gravity acceleration[m/s^2], ρ: Density of air[kg/m^3]

Q_{max} is calculated as the minimum value of $100A_f$, and $3200m_{im}$.

3.2 Model of flame shape

The flame shape depends on *MODE*, quantity of heat generation, and wind conditions. And it is described by the direction and length.

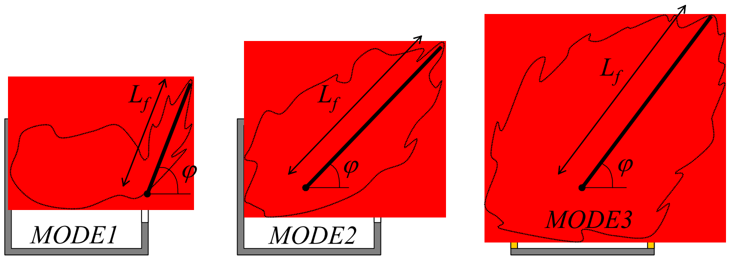


Figure 5: Flame shape of each unit

3.2.1 *Direction of flame*

A horizontal direction of flame is the same direction as a wind. A standup angle from the level surface (set to φ) can be calculated by following equations.

$$\begin{cases} \sin\varphi = 1 & F_r^{\,2} / Q_f^{*\,2/3} \le 0.98^5 \\ \sin\varphi = 0.98\left(F_r^{\,2} / Q_f^{*\,2/3}\right)^{-1/5} & 0.98^5 < F_r^{\,2} / Q_f^{*\,2/3} \le 20 \\ \sin\varphi = 2.6\left(F_r^{\,2} / Q_f^{*\,2/3}\right)^{-2/3} & 20 < F_r^{\,2} / Q_f^{*\,2/3} \end{cases} \tag{4}$$

$$Fr = \frac{U}{\sqrt{gD}}, \quad Q_f^* = Q / \rho_\infty C_p T_\infty g^{1/2} D^{5/2}, \quad D = \begin{cases} 2\sqrt{A_1/\pi} & \text{MODE3 or MODE2} \\ 2\sqrt{A_{op}/\pi} & \text{MODE1} \end{cases}$$

U: Wind speed[m/s], C_p: Specific heat of air[kJ/kgK],
A_{op}: Area of a opening[m^2]

3.2.2 *Length of flame(Lf*[m]*)*

The length of flame while the unit is *MODE1* is calculated by equation 5, and it while the unit is *MODE2* or *MODE3* is calculated by equation 6.

$$L_f = 30 r_f \exp\left\{-132\left(\frac{r_f^{\,5}}{Q^2}\right)^{1/3}\right\} + \left(H_u - Z_n\right) \qquad \text{(MODE1)} \tag{5}$$

$$r_f = \sqrt{(H_u - Z_n)B}$$

$$L_f = 3.3 Q_f^{*\,n} D - 0.5 H_c \quad \begin{cases} n = 2/3 & Q_f^{\,*} < 1.0 \\ n = 2/5 & 1.0 \le Q_f^{\,*} \end{cases} \qquad \text{(MODE2 or MODE3)} \tag{6}$$

3.3 Model of transfer of heat

In this model, the factors of transfer of heat are "*Flame touch*", "*Radiation*", and "*Convection*". Each factor is described below.

As soon as flame touch to the ignitable area of the unit, it ignites immediately. Heat transfer by radiation (I_r[kW/m^2]) and convection (I_c[kW/m^2]) are evaluated as the sum total of heat flux (I[kW/m^2]).

$$I = I_r + I_c \tag{7}$$

3.3.1 *Flame touch*

The flame shape in here is the pillar of a diameter D, described in equation 4.

3.3.2 *Radiation*

There is many flames while spreading city fire. And in this model, one flame is divided into parts, which are the origin of radiation. The heat flux of radiation from each part of flame can be calculated by equation 8.

$$I = \sum_i \frac{\chi Q_i}{4\pi d_i^{\,2}} \cos\theta_i \tag{8}$$

"i" is the suffix of each part of flames

χ: Constant[-], d: Distance from flames to receiving point[m],

θ: Angle between normal of receiving point and direction to flames[Rad]

If a part of flame is obstructed to see from the receiving point of heat by something (e.g. other unit, something like wall, hedge, or tree), heat is not transferred. As for the wooden obstruction, if flame touch to it, it can be burned out and it does not function as an obstruction.

3.3.3 *Convection*

The temperature rise (ΔT_c[K]) of the location of downwind to flame in a perpendicular section can be calculated by equation 9. And the heat flux of convection under the air temperature is T_c, can be calculated by equation10.

$$\Delta T_c(x,z) = \Lambda^{-s} Fr^{-t}\left[1.7\exp\left\{-1.5^2\left(\frac{z}{x}\Lambda^k Fr^n - 0.37\right)^2\right\} + 0.05\right] \times \left(\frac{Q_c^{\,2} T_\infty}{C_p^2 \rho_\infty^2 g}\right)^{1/3} D^{-1/3} x^{-4/3}$$
$$\Lambda = \frac{U D_c^{\,1/3}}{\left\{Q_c g / \left(C_p \rho_\infty T_\infty\right)\right\}^{1/3}} \tag{9}$$

$$I_c = h\Delta T_c \tag{10}$$

x: horizontal distance[m], z: vertical distance[m],

h: heat transfer ratio[kW/m^{2}K], s, t, k, n: constant,

Q_c: Heat generation effect to convection[kW],

D_c: diameter of a heat generating area[m]

3.4 Model of ignition

In this model, the ignitable area ignites if it is heated and its temperature becomes 593[K] degrees. (Equation 11)

$$T_s > 593 \tag{11}$$

3.4.1 *Temperature rise of ignitable area*

The temperature response of the surface when receiving heat flux is obtained by the following equations. Here, variables are calculated as values of a time section.

$$
\begin{aligned}
&T_s(t) = T_\infty + \Delta T(t) \\
&\Delta T(t) = \frac{1.18 I(t)}{\sqrt{\dfrac{k\rho c}{t_s + \Delta t}} + 1.18 h} \\
&t_s = \frac{k\rho c}{\left\{1.18 \cdot \left(\dfrac{I(t)}{\Delta T(t - \Delta t)} - h\right)\right\}^2}
\end{aligned}
\tag{12}
$$

t: Time[s], $k\rho c$: Heat inertia [kW^2s/m^4K^2],
Δt: Time step of Calculation[s]

4. CASE STUDY

A computer program was created based on the physical model described above. The main data for the program is as follows (table 1).

Table 1: List of input / output data

Input data	
Initial conditions	*Wind condition, Unit breaking out fire,*
Units	*Plan, Unit type, Use, Story, Height, Location*
Openings	*Width, Height, Material*
Hedges, Walls	*Location, Height, Material*
Output data	
Units	*MODE, Total quantity of heat generation*
Flames	*Quantity of heat generation,* *Top and bottom location*
Receiving points	*Temperature, Receiving heat flux*

The figures 5 show the results of the execution of the program. An applied area has 239 units. The wind is blowing by 10[m/s] from north, the upper side of figures. The unit from which the fire breaks out is the northeast side in the burning area at figure 5(a).

Units colored light gray denote *MODE0* units, short lines and circles with hatch are describing flames, the circles are expressing the quantity of heat generation, and the lines describes the direction and length of flames.

Units rising flame from wall denote *MODE1* units, and units rising flame from the center of each unit denote *MODE2* or *MODE3* units.

Units colored dark gray denote *MODE4* units.

5. CONCLUSION

Using this simulation program, the city performance against city fire can be evaluated. And it helps us to find where the weak point against fire in the city is and how to improve the city.

The factors to control city performance against fire are mainly listed below, which can be evaluated by this simulation program.

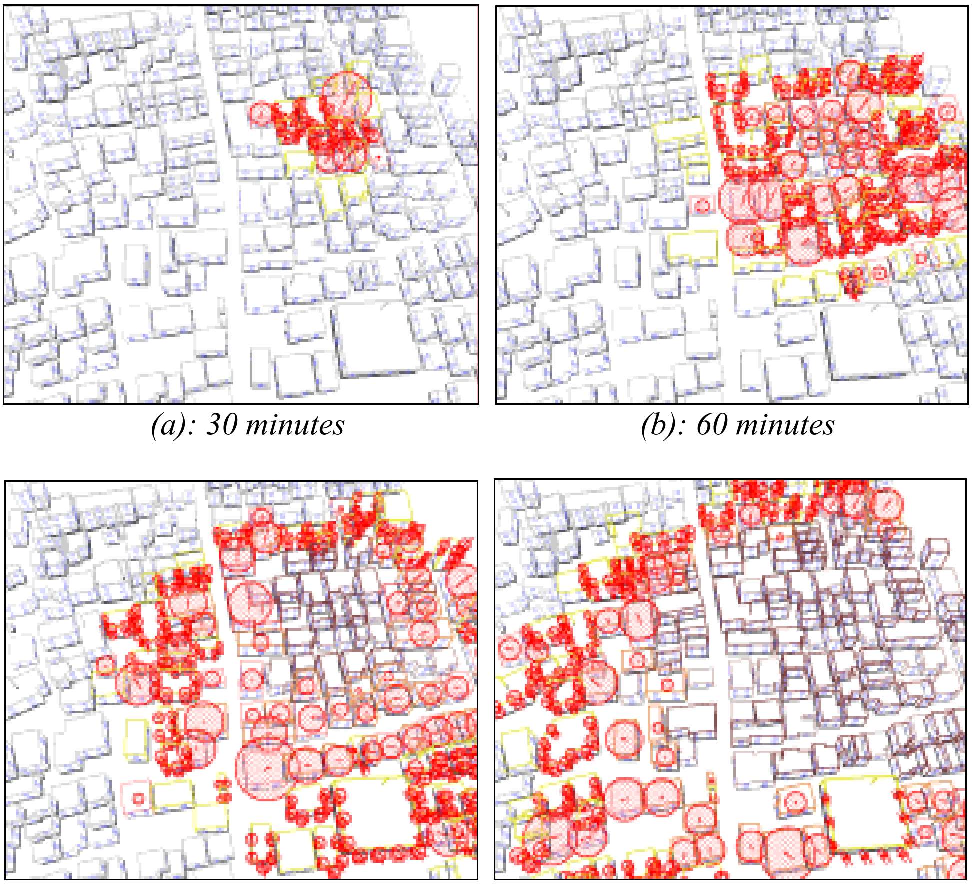
- Performance of walls or a roof of a unit to resist fire
- Relative distance among units
- Location and size of openings in a unit
- Performance of Obstructions (e.g. fences, hedges, walls, and trees)

From now on, a detailed model is added and it improves to a better program, and verification of accuracy will be continued

ACKNOWLEDGEMENT

This study is based on joint research of Building Research Institute and National Institute for Land and Infrastructure Management, as a part of the research project of Ministry of Land, Infrastructure and Transport: "Development of assessment and countermeasure technology for disaster prevention in town planning".

Thanks are due to the member of this project for valuable advice.



(a): 30 minutes *(b): 60 minutes*

(c): 90 minutes *(d): 120 minutes*

Figure 5: Conditions of fire spreading in each 30 minutes after outbreak