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# 消防研究所報告

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## MEMOIR

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# 石油タンク底板に生ずる応力
## ——盛り土に局部的崩壊がある場合——

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（昭和53年11月29日受理）

## 1. 緒　言

石油タンクの破壊は常に貯蔵油の流出を伴う。漏洩，流出した油は火災や環境汚染など大規模災害につながる危険性をはらんでいる。

構造的にみると石油タンクは円筒形側板に底板が溶接されたものであり，油の出し入れなど通常の使用状態ではその変形は軸対称的であると考えられている。このように考えて石油タンクに生ずる応力を解析した研究は少なくない。1~7) ふつう，タンクは盛り土の上に建設される。盛り土は流動性を有し鋼にくらべて圧縮性が大きいため，タンク荷重を受けて局部的な沈下を生じたり，何らかの原因によって流出した油の作用で崩壊を生じたりする。このような場合は通常の使用状態にくらべて部材に生ずる応力値は大きく，破壊の危険度は増すと考えられる。しかしながら，このような状態を想定して応力評価を行った研究は2・3の例8,9)をみるだけである。

本報はアニュラー板直下近傍の基礎盛り土が崩壊した場合に，アニュラー板にどのような応力が生ずるか見積ったものである。*) 基礎盛土の崩壊事例としては，受入れ配管の破口部からの噴射油によるもの，10) 底板に生じた貫通腐蝕部からの漏洩油によるもの，**) 底板に生じたき裂からの噴流によるもの***,11)などがある。

## 2. モデル化

盛り土の一部が局部的に洗堀され，その結果**Fig. 1**で近似的に示されるような盛り土形状になっているものとする。タンク直径を$2a$，液高を$d$，アニュラー板の板厚を$h_b$，側板の板厚†)を$h_s$とする。簡単なため盛り土の崩壊領域はタンクの側板に沿う方向の長さが$L_C$，タンク中心方向の長さが$L_R$とし，この領域内ではアニュラー板は基礎と接していないものとする。更に，盛り土の変形は剛体的であると仮定する。崩壊部のタンク半径方向断面を**Fig. 2**に示す。いま，タンク側板近傍にあるアニュラー板を考えるとき，その変形状態は**Fig. 2**に示されるような断面をもち紙面に垂直方向に

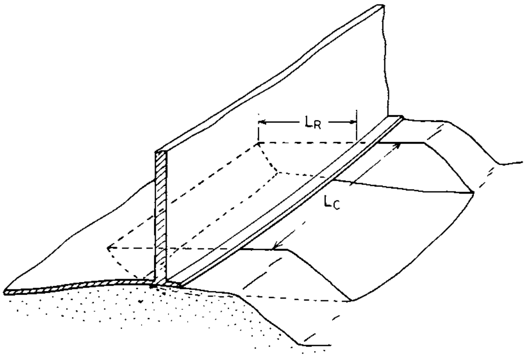

**Fig. 1** Schematic illustration of collapsed part of mound.

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*) タンク底部円形板のうち側板直下に設けられるリング状底板をアニュラー板と言う。小型タンクには通常用いられない。本報の取扱いをアニュラー板のないタンクに適用する場合は底板のアニュラー相当部を考えることにする。

**) 日本鉱業㈱水島製油所重油流出事故（1977年1月）

***) 三菱石油㈱水島製油所重油流出事故（1974年12月）

†) 側板は下段ほど厚板が使用される。ここでは$h_s$として最下段の板の厚さをとる。

十分に長い矩形板におけるものとかなり良い精度で一致する。[7] 本報では$L_R$がタンク半径にくらべて小さい場合を考えるから，上述の矩形板による置きかえを行うことにする。また，盛り土の円周方向崩壊長さは，タンク側板の円周方向全長にくらべて十分小さく，従って崩壊部の存在に起因する側板の局部的沈降は無視できる量であると考える。

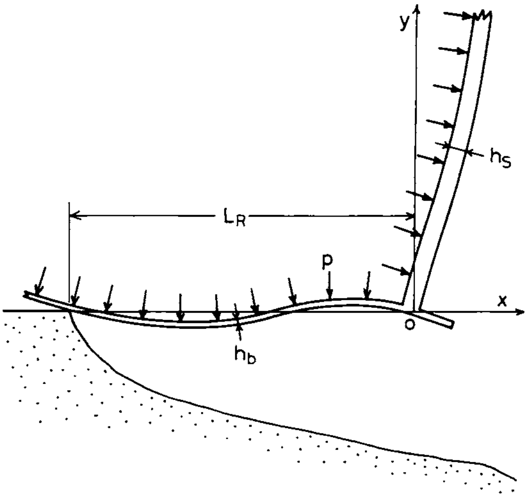

Fig. 2 Radial cross section.

## 3. 理論的解析

**Fig.1**において$L_C \gg L_R$の場合は崩壊部の円周方向中央部におけるアニュラー板の変形挙動に対して長さ$L_C$は影響を与えないと考えられる*)から取扱いが簡単となる。このため，まず$L_C \gg L_R$の場合について解析を行い，次に$L_C$が$L_R$と同程度かそれ以下の場合については$L_C \gg L_R$に対する解析に補正を加えるという方法で考察することにする。

アニュラー板の変形状態を**Fig. 3**に示す。便宜上，

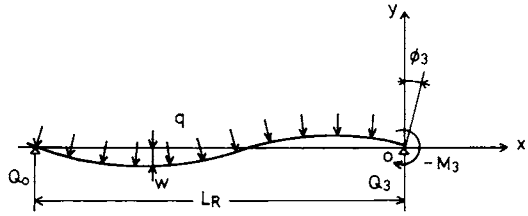

Fig. 3 Deformation of annular plate.

$O-xy$座標をアニュラー板と側板との接合部に原点を有し，タンク半径方向に$x$軸を，タンク上方に$y$軸を有するように設定する。アニュラー板には液圧（これを$q$とする）が作用しており，この反力として$x=-L_R$と$x=0$にそれぞれ$x-y$平面に垂直な方向の単位長さ当り$Q_0$，$Q_3$が作用している。アニュラーは全体として$y$軸方向に力が釣合っているから次第が成立つ。

$$Q_0+Q_3-qL_R=0\,. \tag{1}$$

アニュラー板に生ずるモーメントMは次式のようになる。

$$M=Q_0(L_R+x)-\frac{1}{2}q(L_R+x)^2\,. \tag{2}$$

アニュラー板の変位$w$は次式により与えられる。

$$-EI\frac{\mathrm{d}^2w}{\mathrm{d}x^2}=M\,. \tag{3}$$

ただし，$w$は地盤方向（すなわち$y$軸の負方向）を正としている。(3)式において$E$はヤング率であり，$I$は板厚を$h_b$，幅を1とする板の断面二次モーメントで，次式のように表わされる。

$$I=\frac{h_b{}^3}{12(1-\nu^2)}$$

ここに，$\nu$はポアソン比を表わす。

(2)式を(3)式に代入し，積分すると，

$$-EIw=\frac{1}{6}Q_0x^2(3L_R+x)-\frac{1}{24}q\,x^2(6L_R{}^2$$

$$+4L_Rx+x^2)+C_1x+C_2 \tag{4}$$

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*) **Fig. 1**において，崩壊部のアニュラー板は，崩壊部周辺と側板下端で拘束されていると考えてよい。$L_C \gg L_R$の場合は，円周方向中央部は側板下端と側板から$L_R$だけタンク中心方向にある崩壊縁に近いため，これらからの拘束を受け，一方，距離$L_C$を隔てて対向する崩壊縁は遠いため，それらによる拘束は無視できるからである。

アニュラー板の境界条件は **Fig. 3** により次のように表わすことができる。

$$x=-L_R\ ;\quad w=0\ , \tag{5}$$

$$x=0\ ;\quad w=0\ , \tag{6}$$

$$\frac{\mathrm{d}w}{\mathrm{d}x}=\phi_3\ , \tag{7}$$

$$-EI\frac{\mathrm{d}^2 w}{\mathrm{d}x^2}=-M_3\ . \tag{8}$$

(5), (6), (8)式を満すように $C_1$, $C_2$, $Q_0$ を定めると(4)式は次式のようになる。

$$-EIw=-\frac{q}{24}x(x^3+2L_Rx^2-L_R^3)-\frac{M_3}{6L_R}x$$

$$\cdot(x^2+3L_Rx+2L_R^2)\ . \tag{9}$$

このとき $Q_0$ は次式で表わされる。

$$Q_0=\frac{1}{2}qL_R-\frac{M_3}{L_R}\ .$$

これを(2)式に代入すると底板に作用するモーメントは次のように表わされる。

$$M=-\left(1+\frac{x}{L_R}\right)\left(M_3+\frac{1}{2}qL_Rx\right)\ . \tag{10}$$

側板との接合部（$x=0$）におけるアニュラーの傾斜 $\phi_3$ は，(9)式を(7)式に代入することにより，

$$\phi_3=\frac{L_R}{24D_b}(-qL_R^2+8M_3)\ . \tag{11}$$

ここに，

$$D_b=EI\ .$$

次に側板について考える。側板の変形状態を **Fig. 4** に示す。アニュラー板からの曲げモーメント $M_3$ と側板に作用する液圧とにより決る側板下端部（$y=0$）の傾斜は $x=0$ におけるアニュラー板の傾斜に等しい。この $\phi_3$ は次式のように与えられる。[7)]

$$\phi_3=\frac{1}{D_s}(\xi d+\eta M_3+\zeta)\ . \tag{12}$$

ここに，

$$\xi=\frac{\rho\beta^* h_s^2a^2}{12(1-\nu^2)}\ ,$$

$$\eta=-\frac{1}{2\beta^*}\ ,$$

$$\zeta=-\frac{\rho h_s^2a^2}{12(1-\nu^2)}\ ,$$

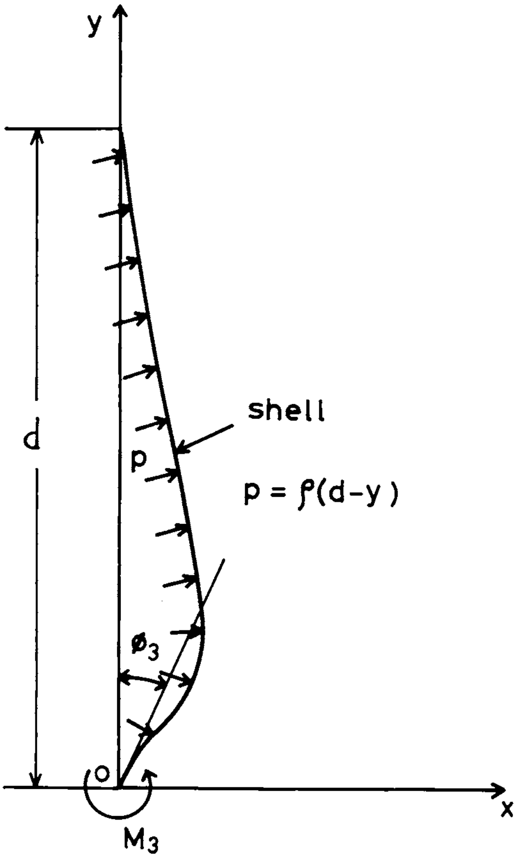

Fig. 4 Deformation of cylindrical shell.

$$D_s=\frac{Eh_s^3}{12(1-\nu^2)}\ ,$$

$$\beta^*=\left\{\frac{3(1-\nu^2)}{a^2h_s^2}\right\}^{1/4}\ .$$

上式において $\rho$ は貯蔵液の密度を表わす。(11)式と(12)式から $\phi_3$ を消去し，$M_3$ を求めると

$$M_3=\frac{\dfrac{\xi d+\zeta}{D_s}+\dfrac{qL_R^3}{24D_s}}{\dfrac{L_R}{3D_b}-\dfrac{\eta}{D_s}} \tag{13}$$

タンクの形状・寸法，液高および盛り土の崩壊寸法が与えられると $M_3$ は(13)式により計算できる。$M_3$ が定まるとアニュラー板の変位は(9)式により，モーメントは(11)式により計算することができる。

アニュラー板の任意の点における半径方向の曲げ応力 $\sigma_b$ は，その位置のモーメント $M$ により次式のように

与えられる。

$$\sigma_b = \frac{6\,M}{{h_b}^2} \quad . \tag{14}$$

## 4. 計算結果*)

盛り土崩壊部のアニュラー板の変位を**Fig. 5**に示す。

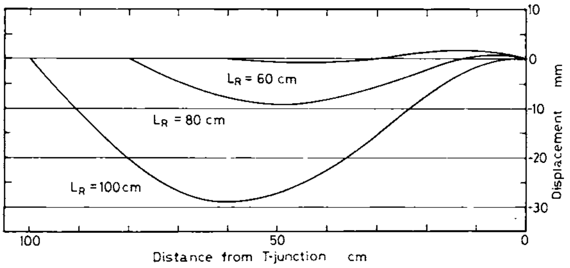

**Fig. 5** Displacement of annular plate. $h_b$ = 12 mm, $h_s$ = 23 mm, a = 30 m, d = 20 m.

図にはタンク中心方向の崩壊長さ$L_R$として60，80および100cmの場合について示してあるが，$L_R$の増大と共に最大変位量は急に大きくなることがわかる。また，側板との接合部におけるアニュラー板の傾斜角度は$L_R$が増大するにつれて次第に減少している。

**Fig. 6**にアニュラー板に生ずる曲げ応力$\sigma_b$を示す。

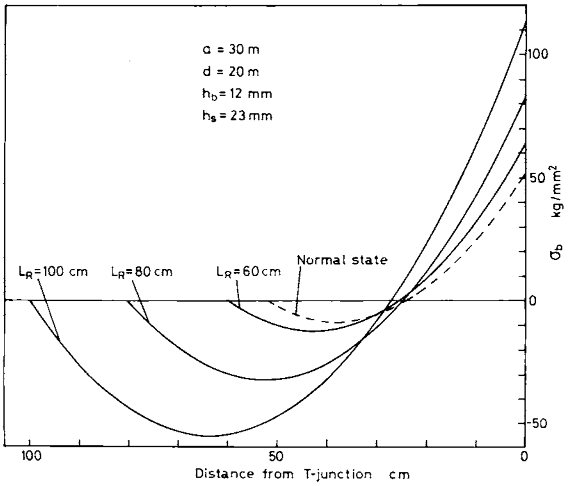

**Fig. 6** Bending stress distribution of annular plate.

$\sigma_b$の正の値はアニュラー板の上面(タンク内側表面)が引張りを受ける場合に対応する。図中の破線は盛り土に崩壊のない場合の曲げ応力分布である。盛り土の崩壊を有する場合の応力分布形状に関しては崩壊のない場合におけるものと同様である。すなわち，接合部タンク内面側に最大値が存在し，接合部からタンク中心方向に向うに従って$\sigma_b$は減少してゆき，やがて下面(基礎に面する表面)が引張り状態となり，極大値に達したのち次第に減少するパターンを示している。そして，接合部の応力（すなわち最大値）は，内部に生ずる極大値より大きな値となっている。しかしながら，崩壊のない場合にくらべて崩壊がある場合の最大値，極大値は大きく，この傾向は$L_R$が長いほど著しいことがわかる。

応力の最大値$\sigma_{bm}$を$L_R$との関係で示すと**Fig. 7**のようになる。図からわかるように，両者の関係は下に凸の曲線となり，$\sigma_{bm}$は$L_R$が大きくなると急激に増加している。

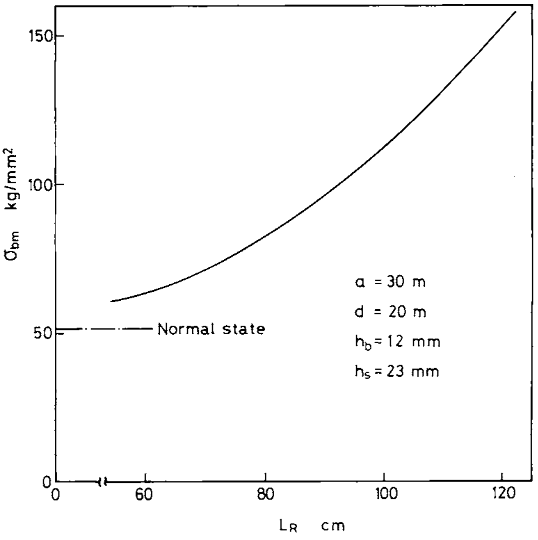

**Fig. 7** Relation between the maximum bending stress $\sigma_{bm}$ and the collapsed length of mound.

タンク半径$a$と$\sigma_{bm}$との関係を**Fig. 8**に示す。崩壊のない正常な場合と同様に直径の大きいタンクほど$\sigma_{bm}$は大きくなることがわかる。

液高$d$と$\sigma_{bm}$との関係を**Fig. 9**に示す。この場合も正常な状態におけるものと同様に液高が高いものほど

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*）貯蔵液の比重は１として計算した。

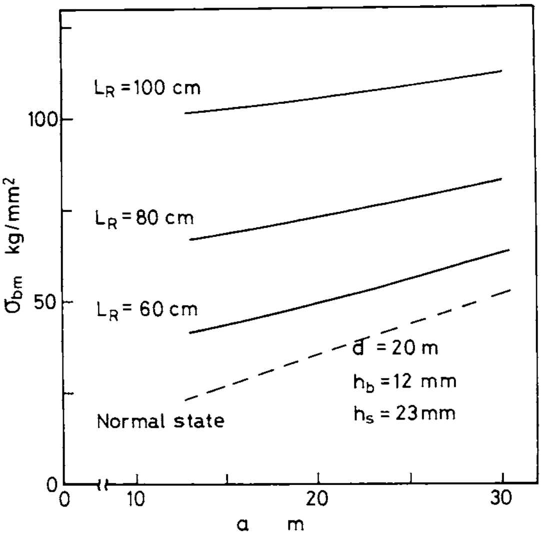


**Fig. 8** Relation between the maximum bending stress $\sigma_{bm}$ and the tank radius a.

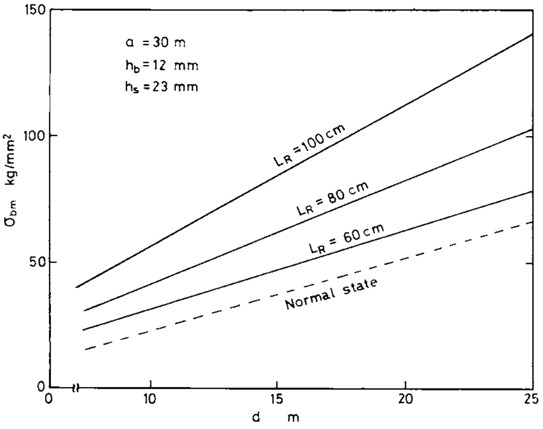


**Fig. 9** Relation between the maximum bending stress $\sigma_{bm}$ and the oil level d.

$\sigma_{bm}$は大きく，増加の割合はほぼ直線的である。直線の勾配は$L_R$の大きいものほど急である。

アニュラー板の板厚$h_b$が$\sigma_{bm}$に及ぼす影響を**Fig. 10**に示す。正常な状態のタンクの場合，$h_b$を小さくしてゆくと$\sigma_{bm}$はかなり大きな値になることが示された7)が，土盛りの崩壊を有するタンクではこの傾向は一層顕著であることがわかる。

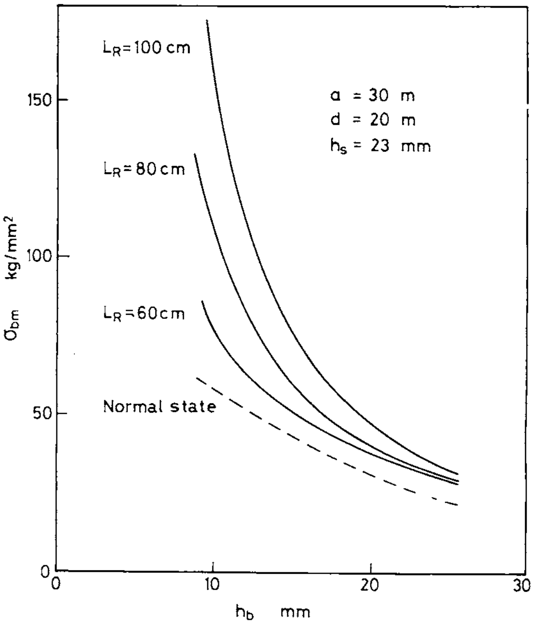


**Fig. 10** Relation between the maximum bending stress $\sigma_{bm}$, and the plate thickness of annular $h_b$.

## 5. 考察

解析の便宜上，**4.**では円周方向崩壊長さ$Lc$が半径方向崩壊長さ$L_R$に較べて十分に長い場合を考えた。ここでは$Lc$が$L_R$と同程度もしくは小さい場合の取扱いについて述べる。

**Fig. 11**に示すような一様圧力$p$を受ける矩形板を考える。辺の長さを$Lc$および$L_R$とし，板の縁は3辺で単純支持(Simply Supported)され，残りの1辺でクランプ(Built In)されているものとする。このような矩形板の解はTimoshenkoら12)によって与えられている。クランプされた辺の中央に原点を持ち，クランプされた辺に一致するように$\xi$軸を，板の面内に$\xi$軸と直角方向に$\eta$軸を持つ直角座標系$0-\xi\eta$を設ける。この座標系において，$\xi=\eta=0$の点の$\eta$方向の曲げ応力を$\sigma$ ($L_R$, $Lc$) と書くことにする。$Lc=\infty$の場合の応力，すなわち$\sigma$ ($L_R$, $Lc=\infty$) に対する$\sigma$ ($L_R$, $Lc$) の比を$\alpha_{clp}$とする。$\alpha_{clp}$の計算値11)を**Fig. 11**に示す。

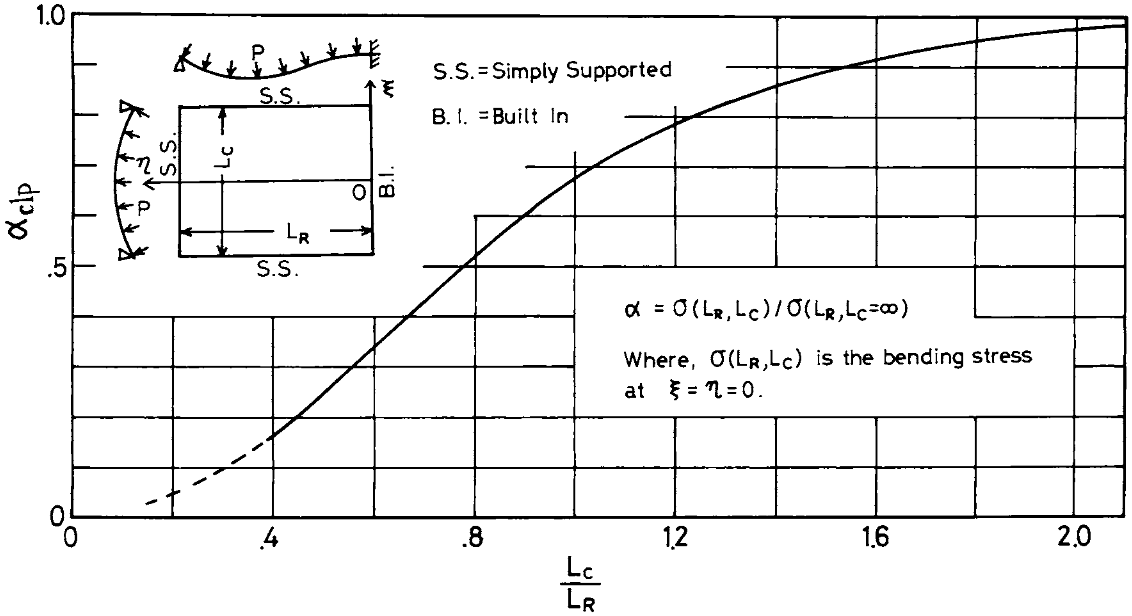


**Fig. 11** Correction factor for the finite width of plate.

この$\alpha_{clp}$を無限板厚（$Lc=\infty$）の解に補正係数として考慮することにより有限板幅の応力を評価することができる。

さて，**Fig. 11**の矩形板において$\xi$軸に沿った縁のクランプという条件を，同縁にモーメント$M_3$が作用しているという条件に置き換え，他の全ての条件をそのままに保持したモデルを考えると，これは**Fig. 1**に示される崩壊土盛り上のアニュラー板に対する条件と全く一致する。このようなモーメント$M_3$が作用する場合についても上述の**Fig. 11**に対すると同様に補正係数を導入し，これを$\alpha_{mt}$と書くことにする。

次に，$\alpha_{mt}$の大きさを考えてみる。**Fig. 11**からわかるように，補正係数は板幅$Lc$が長いほど大きい。クランプされている場合は全板縁にわたり変位が零という条件で拘束されているのに対し，モーメント$M_3$が作用する場合は，幅$Lc$の拘束を受けない見掛上$Lc$を無限大と考えてよい領域，すなわち**Fig. 5**に示されるような側板に近い部分のアニュラー板の浮き上り領域が存在する。このため，クランプの場合より$M_3$が作用する場合の方が補正係数は大きいわけである。すなわち，$\alpha_{clp} \leqq \alpha_{mt} < 1$の関係が存在する。**Fig. 5**に示されるように$L_R$が小さい場合には浮き上り長さは比較的大きく，従って$\alpha_{mt}$は1に近い値をとる。これに対して$L_R$が大きい場合は浮き上り長さが小さくなるため，$\alpha_{mt}$は$\alpha_{clp}$に近づくことになる。また，**Fig. 11**からわかるように，$L_R$に関係なく$Lc/L_R>1.5$に対して，$\alpha_{clp}>0.9$となっているから，このような縦横比に対して$\alpha_{mt}>0.9$が成立する。実際に土盛りが崩壊する様相を想定すると半径方向長さより円周方向長さの方が大きくなりやすいと考えられる。このような点を考慮すると実際的には$\alpha_{mt} \simeq 1$としてよいであろう。

## 6. 結　論

盛り土が崩壊した円筒形石油タンクのアニュラー板に生ずる曲げ応力の大きさについて解析を行った。その結果次の結論を得た。

(1) 最大曲げ応力はアニュラー板と側板との接合部に生じ，タンク内側表面に引張り力が作用する。

(2) 最大曲げ応力は，タンク中心方向崩壊長さが増すと急激に大きくなる。

(3) 最大曲げ応力は，側板に沿う円周方向崩壊長さが

増すと一定値に漸近的に増大する。(円周方向長さ)／(中心方向長さ)＞1.5の範囲では最大曲げ応力は円周方向長さが無限大の場合の応力の0.9倍以上となる。

(4) アニュラー板の板厚を増すと最大応力は急に減少する。

(5) タンク直径，液高を増すと最大応力は，ほぼ直線的に増大する。

本研究は消防研究所における「石油コンビナート等災害防止に関する研究」の一環としての「石油タンク構造部材の経年変化と寿命に関する研究」の一部をなすものである。

## 参考文献

1) Denham J.B. et al：*How to Design* 600,000－*Bbl. Tank, Hydrocarbon Processing*, **47**, 137(1968)

2) 井上威恭：石油タンク，機械設計，**20**，43(1976)

3) 吉田亨，加藤重幸：大型石油タンクの構造欠陥とその対策，金属材料，**16**，58(1976)

4) 河野和間：鋼製円筒タンク底隅角部の応力解析，日本建築学会論文報告集，**245**，53(昭51)

5) 後藤大三：円筒平底タンク隅底部の挙動，圧力技術，**15**，22(1977)

6) 小林信之：円筒タンクの隅底部の応力解析，日本機械学会関西支部第234回講演論文集P.78(昭50)

7) 亀井浅道：大型石油タンクに生ずる応力，消防研究所報告，№46，7(1978)

8) 佐々木康夫，他4名：基礎地盤に部分的な不等沈下がある場合の大型石油貯槽の有限要素法による構造解析，圧力技術，**15**，97(1977)

9) 仲井久雄，他2名，不等沈下したオイル・タンクの有限要素法による構造解析，化学工学論文集，**2**，387(1976)

10) 川崎市コンビナート安全対策委員会：フレキシブルホースの破損原因の推定，安全工学，**17**，297(1978)

11) 亀井浅道，1978年宮城県沖地震による東北石油㈱仙台製油所石油タンク事故概要，消研輯報(投稿中)

12) Timoshenko, S. and Woinowsky－Krieger, S.：*Theory of Plates and Shells*, *McGraw－Hill* (1959)

# Estimation of Stress in an Annular Plate of Cylindrical Oil Storage Tank on a Partially Collapsed Mound

(Abstract)

By Asamichi Kamei

(Received November 29, 1978)

For a cylindrical oil storage tank with partially collapsed mound, bending stress of the annular plate is estimated, and compared with that on a mound without collapse.

From the analysis, the following conclusions are obtained.

(1) The maximum bending stress ($\sigma_{bm}$) for annular plate appears along the T-junction.
(2) The larger the area of the collapsed mound, the higher is the $\sigma_{bm}$.
(3) The $\sigma_{bm}$ is reduced effectively by increasing the thickness of the annular plate.
(4) The $\sigma_{bm}$ increases linearly in proportion to the oil level and the diameter of the tank.

# 都市火災の延焼確率とそのシミュレーション
# （概　　要）

佐々木　弘明，神　忠久

（昭和53年11月30日受理）

冬期間に東京都で発生した火災事例約400件を分類整理し，建物構造をパラメータに，建物間距離の函数として，延焼確率をまとめた。

これに依ると，木造建物と防火造建物の差異は，出火に際して顕著に現われる。

得られた確率を東京都中野区の住宅地域に適用して算出した火災１件当りの延焼棟数は，55％前後の建ぺい率でも，木造建物の混在率が65％で，大火の危険性を指摘している。

# Probability of Fire Spread in Urban Fires and their Simulations

Hiroaki Sasaki and Tadahisa Jin

(Received November 30, 1978)

Simulations of urban fires were tried as an application of probabilistic "Percolation Theory".

By classifying the Fire Incident Reports in Tokyo by building constructions (wooden construction, slow burning construction, fire-proof construction) and wind conditions (velocity, direction), the probability of fire spread was obtained as a function of distance between buildings.

The application of the probability to the actual residential area in Tokyo can estimate the number of burnt buildings per fire incident there, which is found to largely depend upon the building construction ratio.

## 1. Introduction

An application of probabilistic "Percolation Theory"[1] to fire spread modeling was tried by a research group of "Statistical Study of Propagation of Hazard".

The authors took charge of getting the actual probability of fire spread and obtained it by examining the Fire Incident Reports in Tokyo. Further, by using the data, the urban fires were simulated and the averaged number of burnt buildings per fire incident was estimated.

## 2. Probability of fire spread

Besides the distance between buildings, the following items may be supposed as the main factors which have some effect upon the probability of fire spread.

- building construction (wooden constructin, slow burning construction, fire-proof construction)
- building size and shape, window area, number of windows
- indoor construction material
- furniture
- wall, fence
- garden, tree
- weather

These factors may facilitate fire spread or check it, according to circumstances. Taking the building construction as the parameter, the probability of fire spread was gotten as a function of distance between buildings under certain weather conditions.

### *2.1 How to get the probability of fire spread*

1) Weather condition

According to "Statistics of Fire Incidents in Tokyo (1972)"[2], as shown in **Fig. 1**, a overwhelming major portion of building fire incidents are in the winter season. **Fig. 2** is a graph of monthly averaged value of temperature and humidity in Tokyo[3]. Two mean temperatures of January and February are nearly equal and two mean humidities of the same two months are so too. The case is the same in December and March. As the differences of temperatures and humidities among the four months are 3°C and 8%, respectively, and these months may be regarded as averagedly homogenious in the weather. The Fire Incident Reports in Tokyo during the winter season over 3 years of 1971, 1972 and 1973 were surveyed, and the fire incidents were classified.

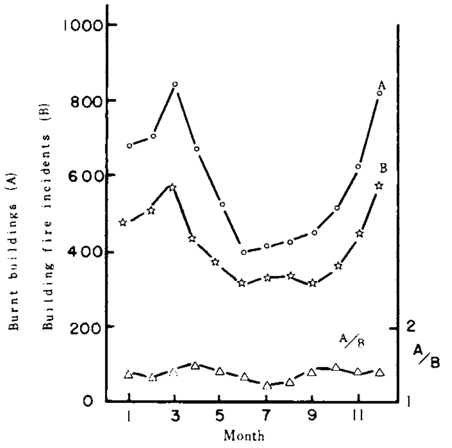


**Fig. 1** Building fire incidents and burnt buildings in Tokyo (1972)

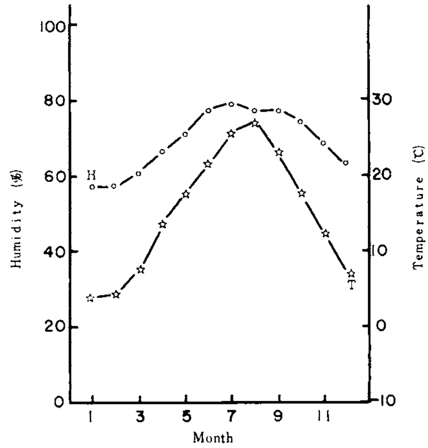


**Fig. 2** Averaged temperature and humidity in Tokyo (1941 – 1960)

2) Adoption of data

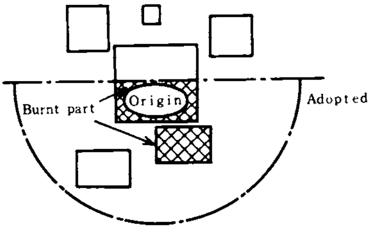
Among the cases of building fire incidents in the Reports, those fulfilling one of the following requirements were adopted.

a) totally burnt, the burnt area over 50 m$^2$

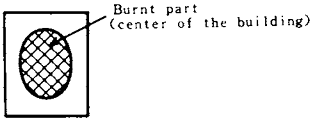
b) partially burnt, the burnt area over 50 m$^2$

In this case the adoption of data was decided in consideration of the circumstances (**ex. 1**, **ex. 2**). The upper part of **ex. 1**, and **ex. 2** where the possibility of fire spread to neighbouring

**Ex. 1** Partially adopted



**Ex. 2** Not adopted



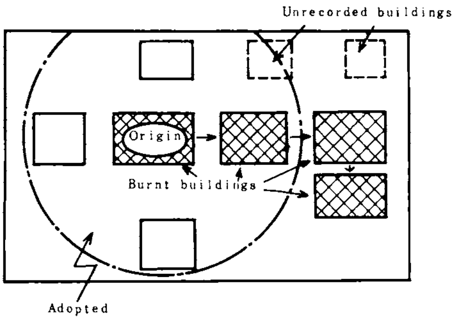
buildings seems to be zero were not adopted.

c) the first neighbouring burnt buildings

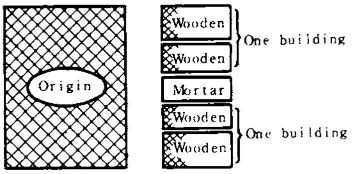
Considering the proper characters of the Reports, the adoption of the first neighbouring burnt buildings only is reasonable, for the unburnt buildings whose number increases as their distances from the origin of a fire increases tend not to be written in it (**ex. 3**).

d) In case the building from which a fire broke out faces several buildings, the buildings of the same construction among the latter were treated as one buiding (**ex. 4**).

**Ex. 3** First neighbouring buildings adopted



**Ex. 4**



The building constructions were classified into 3 groups: wooden construction, mortar construction (slow burning construction), concrete construction (fire-proof construction). Very few cases where fires broke out in concrete buildings or spread to concrete buildings were found. From the above-mentioned result the possibility of fire spread from or to concrete buildings was presumed to be zero.

f) The wind velocity in the course of fire spread was assorted into 2 groups: 0 – 2.5 m/s, 2.6 – 5.0 m/s. In the former case, the fire spread is assumed to be undirectional (isotropic) and as to the latter case, the data were assorted into smaller groups according to the directions of fire spread: the windward direction, the leeward direction, the direction perpendicular to that of the wind (the sideward direction). The fire incidents in which the wind velocity is larger than 5.1 m/s were excluded from the classification for their small number. The percentage of the building fire incidents at the wind velocity below 5 m/s to the total building fire incidents is 73%.

## *2.2 Findings*

The results of choice and arrangement of the fire incidents satisfying the above-mentioned requirements were tabulated in **Tables 1** through **4. Figures 3a** through **6d** show the probability according to different parameters: the wind velocity, the direction of fire spread, the building construction. The number of the fire incidents adopted is shown in **Table 5**.

When the number of the burnt buildings is put as $i$, and that of unburnt ones as $j$, the probability $P$ of fire spread is expressed as $i/(i+j)$.

The data were divided by every meter of the distance between buildings or every 2 m or more in case few data were found.

Table 1 Probability of fire spread at the wind velocity 0 – 2.5 m/s

| | | Distance to neighbouring buildings (m) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 0 ~1.0 | 1.1 ~ 2.0 | 2.1 ~ 3.0 | 3.1 ~ 4.0 | 4.1 ~ 5.0 | 5.1 ~ 6.0 | 6.1 ~ 8.0 |
| Wooden | Burnt | 95 | 51 | 30 | 26 | 15 | 11 | 8 |
| ⇩ | Unburnt | 19 | 25 | 24 | 14 | 16 | 13 | 22 |
| Wooden | Probability | .83 | .67 | .56 | .65 | .48 | .46 | .27 |
| Wooden | Burnt | 31 | 21 | 11 | 15 | 6 | 3 | 7 |
| ⇩ | Unburnt | 10 | 8 | 8 | 9 | 9 | 11 | 15 |
| Mortar | Probability | .76 | .72 | .58 | .63 | .40 | .27 | .32 |
| Mortar | Burnt | 15 | 8 | 5 | 3 | 1 | | — |
| ⇩ | Unburnt | 9 | 11 | 10 | 8 | 11 | | — |
| Wooden | Probability | .63 | .42 | .33 | .27 | .09 | | — |
| Mortar | Burnt | 38 | 18 | 10 | 3 | 1 | 0 | — |
| ⇩ | Unburnt | 17 | 22 | 11 | 10 | 14 | 7 | — |
| Mortar | Probability | .69 | .45 | .48 | .23 | .07 | .00 | — |

Table 2 Probability of fire spread in the leeward direction at the wind velocity 2.6 – 5.0 m/s

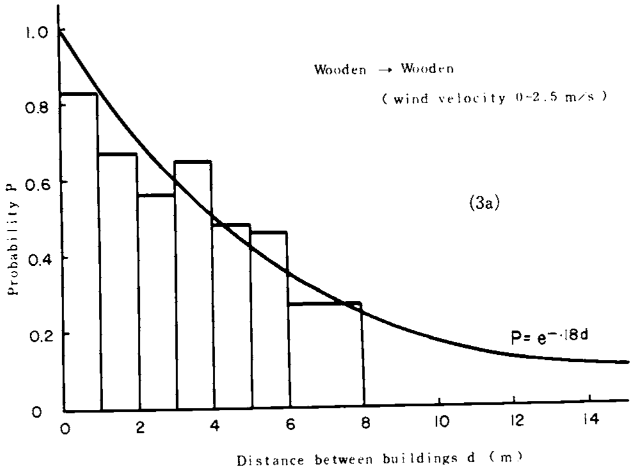
| | | Distance to neighbouring buildings (m) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 0 ~ 1.0 | 1.1 ~ 2.0 | 2.1 ~ 3.0 | 3.1 ~ 4.0 | 4.1 ~ 5.0 | 5.1 ~ 6.0 | 6.1 ~ 8.0 |
| Wooden | Burnt | 26 | 19 | 10 | 8 | 5 | 3 | 6 |
| ⇩ | Unburnt | 2 | 3 | 5 | 5 | 1 | 2 | 9 |
| Wooden | Probability | 93 | .86 | .67 | .62 | .83 | .60 | .40 |
| Wooden | Burnt | 21 | 13 | 5 | 8 | | 2 | 5 |
| ⇩ | Unburnt | 0 | 3 | 2 | 5 | | 2 | 5 |
| Mortar | Probability | 1.00 | .81 | .71 | .62 | | .50 | .50 |
| Mortar | Burnt | 6 | 4 | — | 2 | | 1 | 1 |
| ⇩ | Unburnt | 3 | 3 | — | 1 | | 2 | 3 |
| Wooden | Probability | .67 | .57 | — | .67 | | .33 | .25 |
| Mortar | Burnt | 17 | 6 | 9 | | 1 | 1 | 1 |
| ⇩ | Unburnt | 4 | 6 | 3 | | 1 | 1 | 3 |
| Mortar | Probability | .81 | .50 | .75 | | .50 | .50 | .25 |

Table 3 Probability of fire spread in the sideward direction at the wind velocity 2.6 – 5.0 m/s

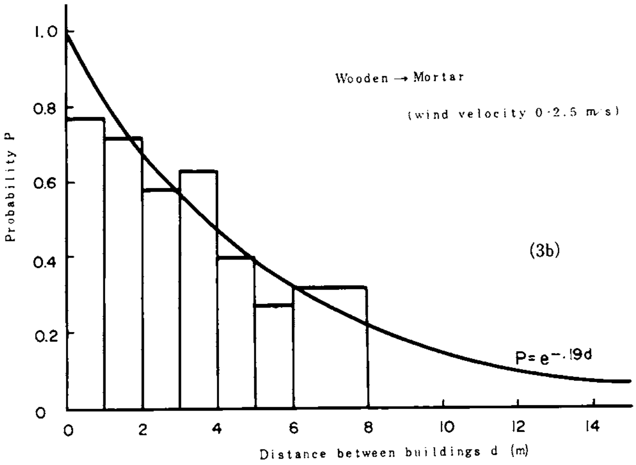
| | | Distance to neighbouring building (m) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 0 ~ 1.0 | 1.1 ~ 2.0 | 2.1 ~ 3.0 | 3.1 ~ 4.0 | 4.1 ~ 5.0 | 5.1 ~ 6.0 | 6.1 ~ 8.0 |
| Wooden | Burnt | 39 | 38 | 19 | 6 | 9 | 5 | — |
| ⇩ | Unburnt | 11 | 6 | 9 | 5 | 6 | 6 | — |
| Wooden | Probability | .78 | .86 | .68 | .55 | .60 | .45 | — |
| Wooden | Burnt | 30 | 9 | 11 | 3 | 3 | | — |
| ⇩ | Unburnt | 4 | 5 | 5 | 5 | 6 | | — |
| Mortar | Probability | 88 | .64 | .69 | .38 | .33 | | — |
| Mortar | Burnt | 7 | 5 | 3 | 1 | 0 | 0 | — |
| ⇩ | Unburnt | 5 | 4 | 2 | 2 | 1 | 4 | — |
| Wooden | Probability | .58 | .56 | .60 | .33 | .00 | .00 | — |
| Mortar | Burnt | 38 | 8 | 5 | 2 | | 0 | — |
| ⇩ | Unburnt | 17 | 4 | 5 | 6 | | 2 | — |
| Mortar | Probability | .69 | .67 | .50 | .25 | | .00 | — |

**Table 4** Probability of fire spread in the windward direction at the wind velocity 2.6 – 5.0 m/s

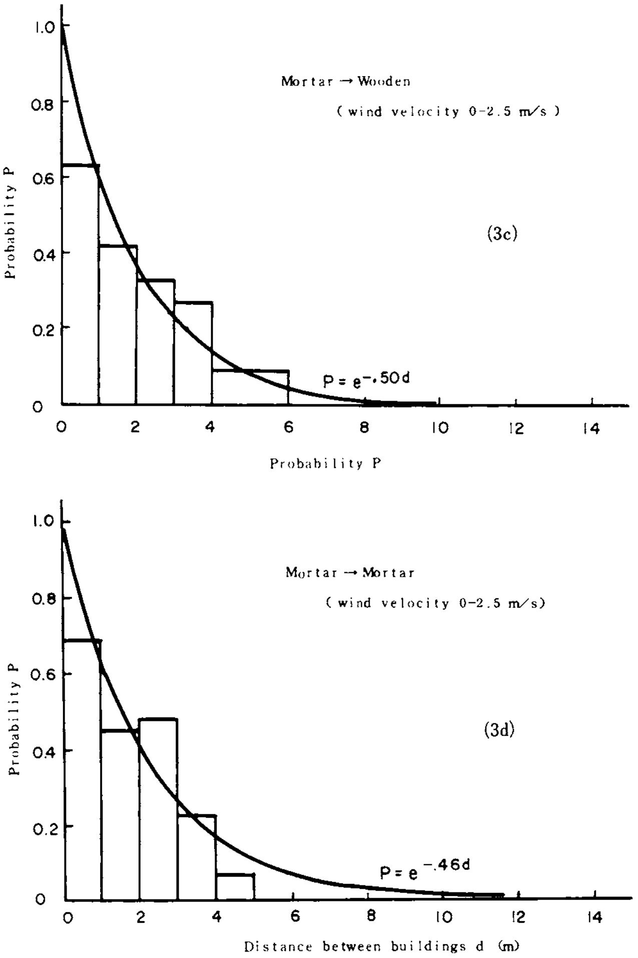
| | | Distance to neighbouring building (m) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 0~1.0 | 1.1~2.0 | 2.1~3.0 | 3.1~4.0 | 4.1~5.0 | 5.1~6.0 | 6.1~8.0 |
| Wooden<br>⇩<br>Wooden | Burnt | 23 | 20 | 8 | 6 | 6 | 3 | |
| | Unburnt | 6 | 5 | 6 | 6 | 6 | 7 | |
| | Probability | .79 | .80 | .57 | .50 | .50 | .30 | |
| Wooden<br>⇩<br>Mortar | Burnt | 14 | 9 | 7 | 2 | 3 | | 2 |
| | Unburnt | 4 | 6 | 4 | 2 | 6 | | 4 |
| | Probability | .78 | .60 | .64 | .50 | .33 | | .33 |
| Mortar<br>⇩<br>Wooden | Burnt | 6 | 1 | 1 | | — | — | — |
| | Unburnt | 2 | 6 | 7 | | — | — | — |
| | Probability | .75 | .14 | .13 | | — | — | — |
| Mortar<br>⇩<br>Mortar | Burnt | 14 | 5 | 1 | 2 | 0 | 0 | — |
| | Unburnt | 4 | 7 | 3 | 10 | 2 | 3 | — |
| | Probability | .78 | .42 | .25 | .17 | .00 | .00 | — |



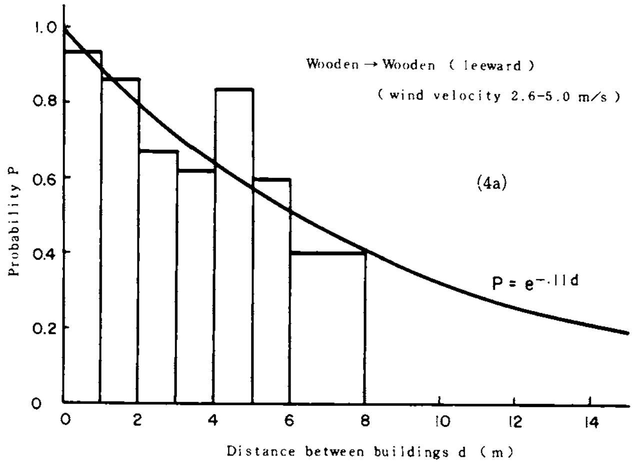
(3a)

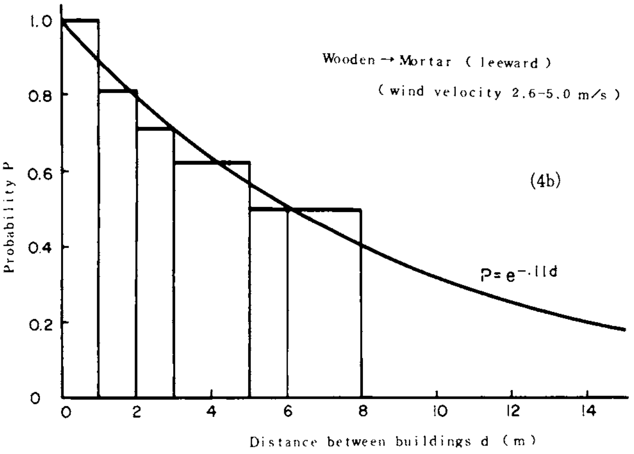


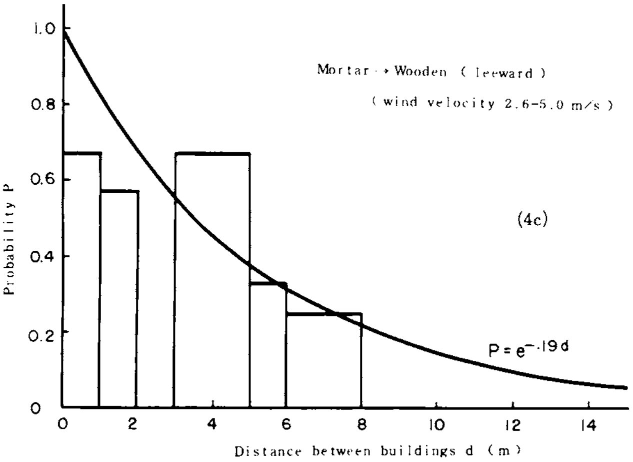
(3b)

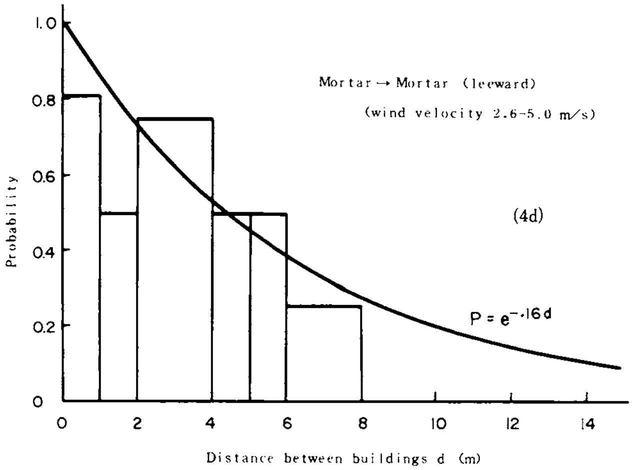


Figs. 3a-d Probability by building construction at the wind velocity 0 – 2.5 m/s

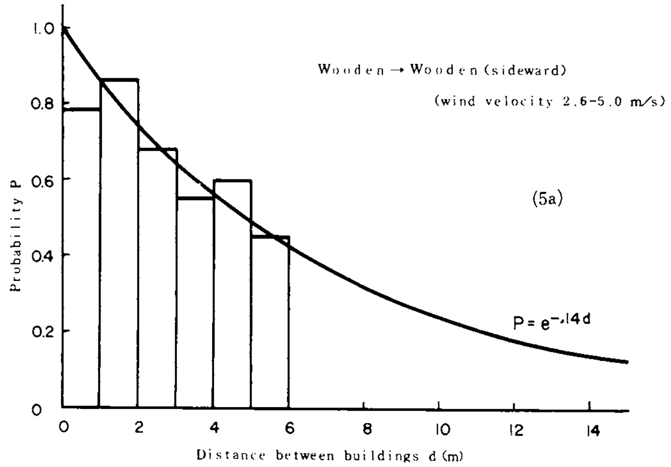




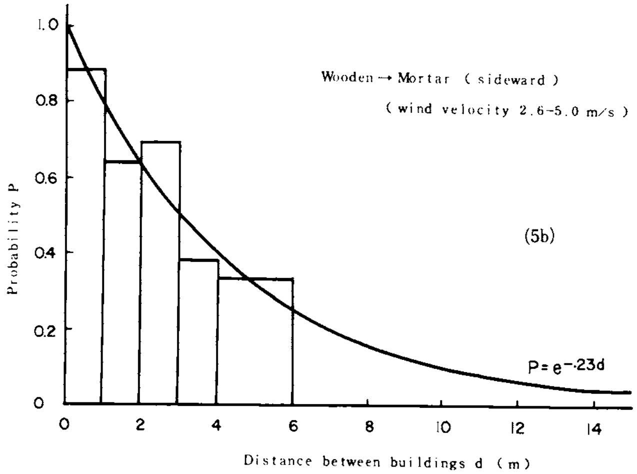




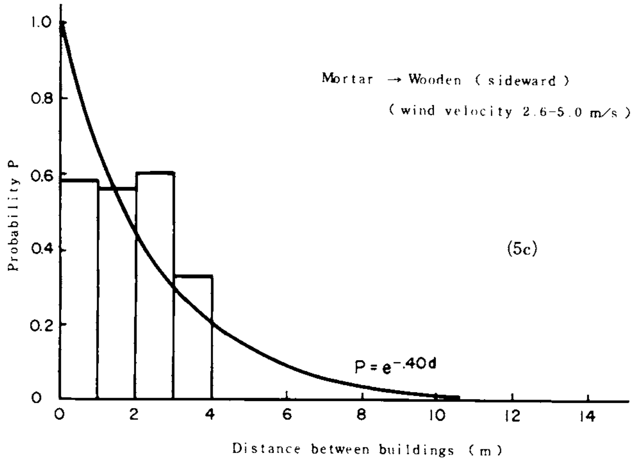
**Figs. 4a-d** Probability by building construction at the wind velocity 2.6 – 5.0 m/s in the leeward direction


Wooden → Wooden (sideward)
(wind velocity 2.6-5.0 m/s)
P = e^{-.14d}
Probability P
1.0
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
Distance between buildings d (m)

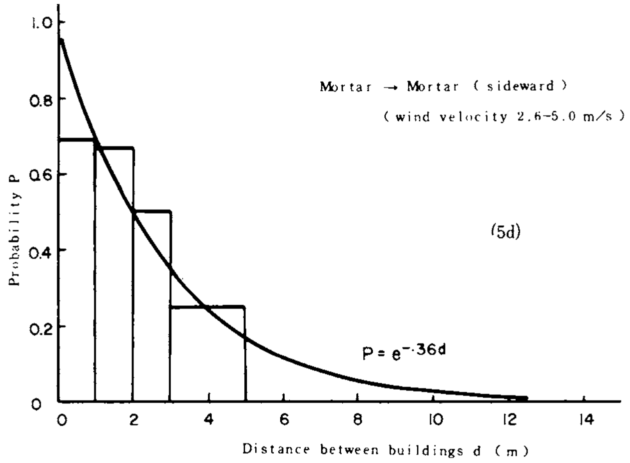
(5a)


Wooden → Mortar ( sideward )
( wind velocity 2.6-5.0 m/s )
P= e^{-.23d}
Probability P
1.0
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
Distance between buildings d ( m )

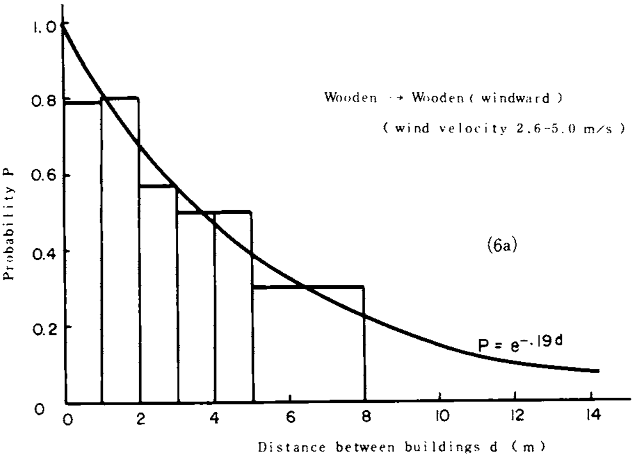
(5b)

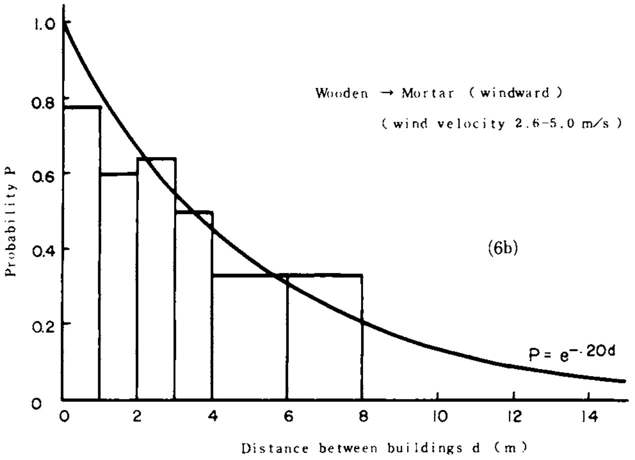

Mortar → Wooden ( sideward )
( wind velocity 2.6-5.0 m/s )
P = e^{-.40d}
Probability P
1.0
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
12
14
Distance between buildings ( m )

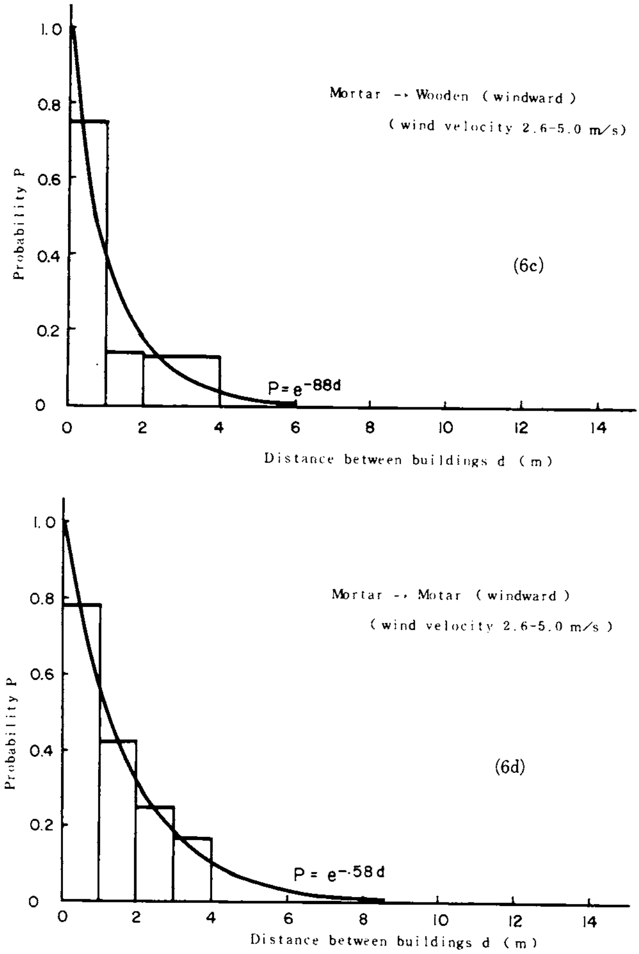
(5c)



Figs. 5a-d Probability by building construction at the wind velocity 2.6 – 5.0 m/s in the sideward direction







**Figs. 6a-d** Probability by building construction at the wind velocity 2.6 – 5.0 m/s in the windward direction

**Table 5** Number of fire incidents adopted

| Year | | 1971 | | | | 1972 | | | | 1973 | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Month | | 1 | 2 | 3 | 12 | 1 | 2 | 3 | 12 | 1 | 2 | 3 | |
| Wind velocity | 0 – 2.5 m/s | 21 | 19 | 23 | 19 | 11 | 7 | 17 | 17 | 21 | 17 | 16 | 191 |
| | 2.6 – 5.0 m/s | 18 | 32 | 17 | 19 | 24 | 11 | 10 | 10 | 18 | 17 | 24 | 215 |

The probability $P$ of fire spread is expressed as a function of the distance between buildings $d$ as follows, considering the following conditions

a) $P = 1$ when $d = 0$.

b) Radiation from a fire decreases in inverse proportion to the square of distance and when the temperature of the building receiving radiation is less than the threshold temperature of ignition, fire spread is impossible.

c) Brands which are another cause of fire spread are known to be effective even at a distance.

The simplest exponential function exp (*–cd*) were taken as the probability function and the values of parameter *c* were obtained by the least squares method.

*C*-values obtained in this way were tabulated in **Table 6** according to the building constructions and the wind velocity.

**Table 6** *C*-values by building construction and wind velocity

| Wind velocity / Building construction | 0 ~ 2.5 m/s | 2.6 ~ 5.0 m/s | | |
|---|---|---|---|---|
| | | Leeward | Sideward | Windward |
| Wooden → Wooden | 0.18 | 0.11 | 0.14 | 0.19 |
| Wooden → Mortar | 0.19 | 0.11 | 0.23 ( 0.15 ) | 0.20 |
| Mortar → Wooden | 0.50 | 0.19 | 0.40 | 0.88 ( 0.62 ) |
| Mortar → Mortar | 0.46 | 0.16 | 0.36 | 0.58 |

See the text as to the values in parentheses

The table may tell that two sorts of fire spreads, from wooden building to wooden one, and from wooden building to mortar one are equivalent, and other two sorts of fire spreads, from mortar building to wooden one and from mortar building to mortar one, are equivalent too.

According to **Table 6**, *c*-values of fire spread from wooden building to wooden one and from wooden building to mortar one are 0.18 and 0.19, respectively, at the wind velocity 0 – 2.5 m/s. At the wind velocity 2.6 – 5.0 m/s, the *c*-values are 0.11 and 0.11 in the leeward direction, 0.19 and 0.20 in the windward direction, respectively. But in the sideward direction, they are somewhat different such that 0.14 and 0.23, respectively. In this direction, however, the data in **Table 3** is deficient in number and unreliable. Considering that the *c*-value in the sideward direction should lie between those in the windward direction and in the leeward direction and that the *c*-value from wooden building to mortar one should be equal to or more than that from wooden building to wooden one by 0.01, the *c*-value from wooden building to mortar one at the wind velocity 2.6 – 5.0 m/s in the sideward direction may be estimated at about 0.15. In the same way, comparing the *c*-values from mortar building to wooden one and from mortar building to mortar one, they are 0.50 and 0.46 at the wind velocity 0 – 2.5 m/s, and at the wind velocity 2.6 – 5.0 m/s, 0.19 and 0.16 in the leeward direction, 0.40 and 0.36 in the sideward direction, respectively. Then two *c*-values may be regarded as almost the same.

In the windward direction, they are a little different such that 0.88 and 0.54. In this case too, examples from mortar building to wooden one are too small in number and unreliable **(Table 4)**. The *c*-value from mortar building to wooden one is larger than that from mortar building to mortar one by 0.04, and 0.62 may be reasonable as the *c*-value from mortar building to wooden one at the wind velocity 2.6 – 5.0 m/s in the windward direction.

As for the differences of *c*-values by the constructions of the building burnt by fire spread in case the buildings from which fires originated are wooden, the *c*-value of the mortar building is equal to or larger than that of the wooden building by 0.01 and in case the buildings from which fires originated are mortar, conversely, the *c*-value of mortar building is smaller than that of wooden building by 0.04. But the percentages of the differences of *c*-values 0.01 and 0.04 to their absolute values are about 5 and 10% and not an appreciable difference, considering the accuracy of the probability of fire spread.

In short, a mortar building on fire is not easier to spread fire to neighbouring buildings than a wooden building on fire, and in case of catching fire a mortar building is nearly equivalent to a wooden building.

### *2.3 Characters of probability of fire spread*

The characters of the probability may be evident by considering how to get the probability, but it is not needless to ascertain them, because the limit of application of it would become clear.

1) Averaged features

The probability inevitably has the following three averaged features which may be clear from how to get it. First; as fire incidents occurred during four months were adopted, the probability are weather-conditionally averaged. Second; the probability was got from fire incidents occurred in Tokyo which has a great area, and so the probability does not show the local features of fire-occurring places. Third; the adopted incidents extended over 3 years during which Tokyo may have changed, and so the probability are averaged in time.

2) The tendency of the probability of fire spread

The Fire Incident Reports are originally the records of burnt things, and unburnt buildings are apt to be neglected and not to be recorded in them. This causes the obtained probability to be larger than the real one. As the distance from the building which started a fire increases, the number of surrounding buildings increases and the number of unwritten buildings also increases. As a natural result, the probability at a larger distance can be larger than the real one. On the other hand, when a building is on fire, fire fighting is active, and water is poured not merely on burning buildings, but also on surrounding unburning ones to prevent fire spread. This leads to the smaller probability than the real one. It is impossible to separate this effect of discharge from others.

3) Burnt area

The number of burnt buildings is less than several in most of examples recorded in the Fire Incident Reports. The probability gained above is inapplicable to large-scale fires which naturally have the larger probability.

4) Probability and fire spread velocity

The probability gained can only decide whether the fire spread is possible or not, and no relation between the probability and the time required for fire spread is gotten.

5) Weather

The data were classified according to the weather conditions recorded in the Fire Incident Reports. They were observed in the meteorological observatory of Tokyo or in fire stations. Places and times of observation are mostly far from those of outbreaks of fire, therefore the weather conditions recorded do not necessarily coincide with those of the spots. For the reason, data assorted by the windward direction, the sideward direction and the leeward direction may be partly mixed together, and data classified by the wind velocity are so too. Consequently, the differences of the probability of fire spread by the wind velocity and the wind directions are smaller than real ones.

## 3. Simulation of urban fires

When one simulates urban fires, using the probability of fire spread gained as a function of distance between buildings, one needs to know another factor, that is, the distribution of distance $d$ between buildings. Each district has its own distribution. The average value of $d$ in the district with low building-to-land ratio is large and that in a densely built-up district is small. For a simple simulation, one can use the probability $P$ corresponding to the mode of the distribution.

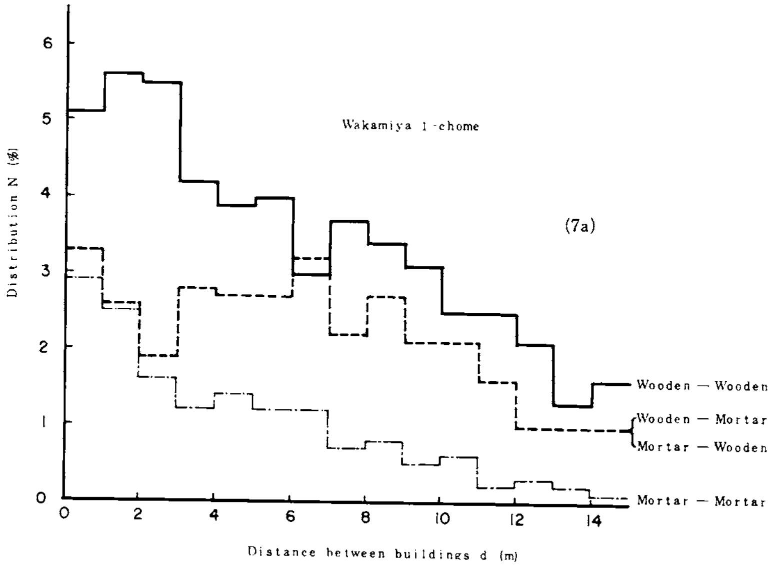
### *3.1 Distribution of distances between buildings*

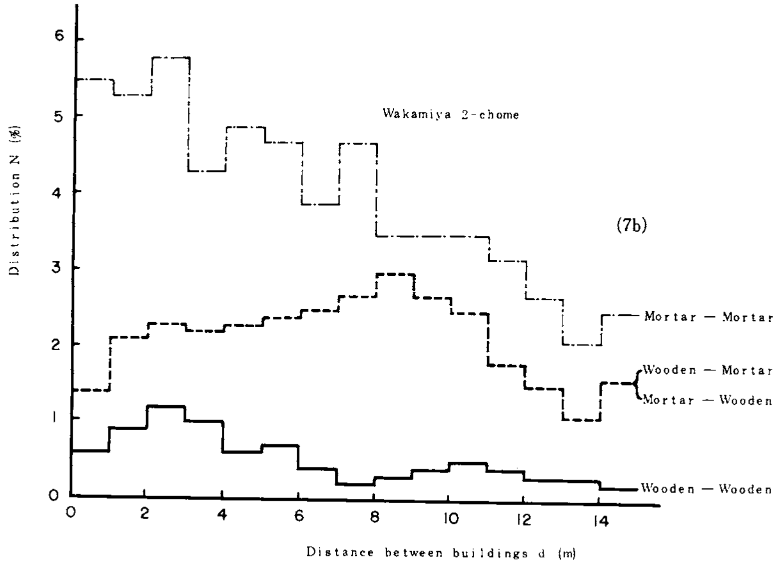
As types of residential districts in Tokyo, Wakamiya 1-chome, Wakamiya 2-chome and Owada 1-chome of Nakano Ward may be chosen. As shown in **Table 7**, the building-to-land

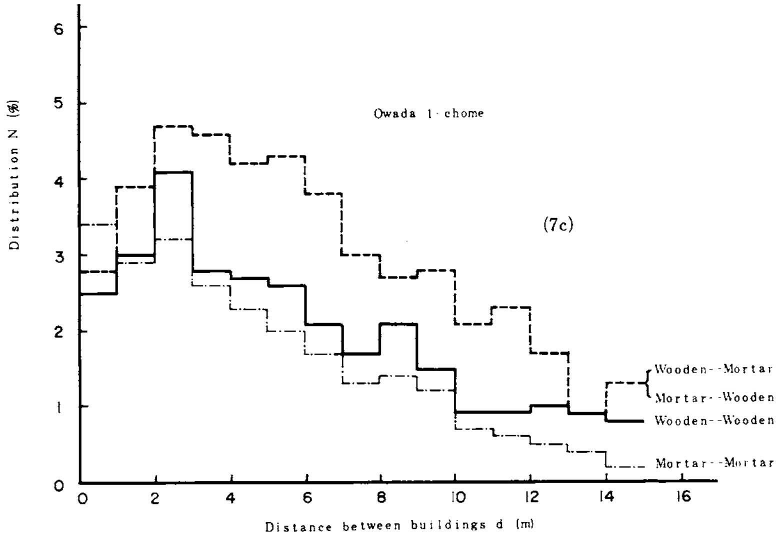
**Table 7** Building construction ratio and number of burnt buildings per fire incident

| Town | Building –to–land ratio | Building construction | Number of burnt buildings/incident | | |
|---|---|---|---|---|---|
| | | | Building construction | Wind velocity | |
| | | | | 0–2.5 m/s | 2.6–5.0 m/s |
| Wakamiya 1–chome | 55% | Wooden 65% | Wooden | 5.8 | 23.0 |
| | | Mortar 33% | Mortar | 3.1 | 11.4 |
| | | Concrete 2% | Concrete | 0 | 0 |
| | | | Total | 8.9 | 34.8 |
| Wakamiya 2–chome | 52% | Wooden 23% | Wooden | 0.3 | 1.0 |
| | | Mortar 75% | Mortar | 1.6 | 3.4 |
| | | Concrete 2% | Concrete | 0 | 0 |
| | | | Total | 1.9 | 4.4 |
| Owada 1–chome | 56% | Wooden 52% | Wooden | 3.2 | 11.1 |
| | | Mortar 47% | Mortar | 2.9 | 10.1 |
| | | Concrete 1% | Concrete | 0 | 0 |
| | | | Total | 6.1 | 21.2 |

ratios of these town are almost the same, i.e. about 55%$^{4)}$. Also, their ratios of concrete buildings lie between 1% and 2%, meanwhile those of mortar buildings are about 20%, 50% and 70%, respectively. It is convenient to compare the influences of ratio of mortar buildings upon the fire incident scale. The distributions of the distance between neighbouring buildings of the towns gained according to Regional Construction Map of Tokyo$^{4)}$ are shown in **Figs. 7 (a)** through 7 (c). The distance means the minimum length of line connecting the walls of neighbouring buildings. Data of distance more than 16 m are discarded.







Figs. 7a-c Distribution of distance between buildings of the towns

### *3.2 Simulations of fire spread*

For simplicity of the simulation, the buildings are arranged in regular squares. Fire spread was assumed to be possible in directions of nearest neighbouring buildings, i.e., 4 directions. The number of buildings for the simulation is 441 = 21 x 21. A fire is assumed to break out from the center (11, 11). The probability of fire spread weight-averaged by the distribution of the distance between neighbouring buildings in the above-mentioned three towns (**Table 8**) was

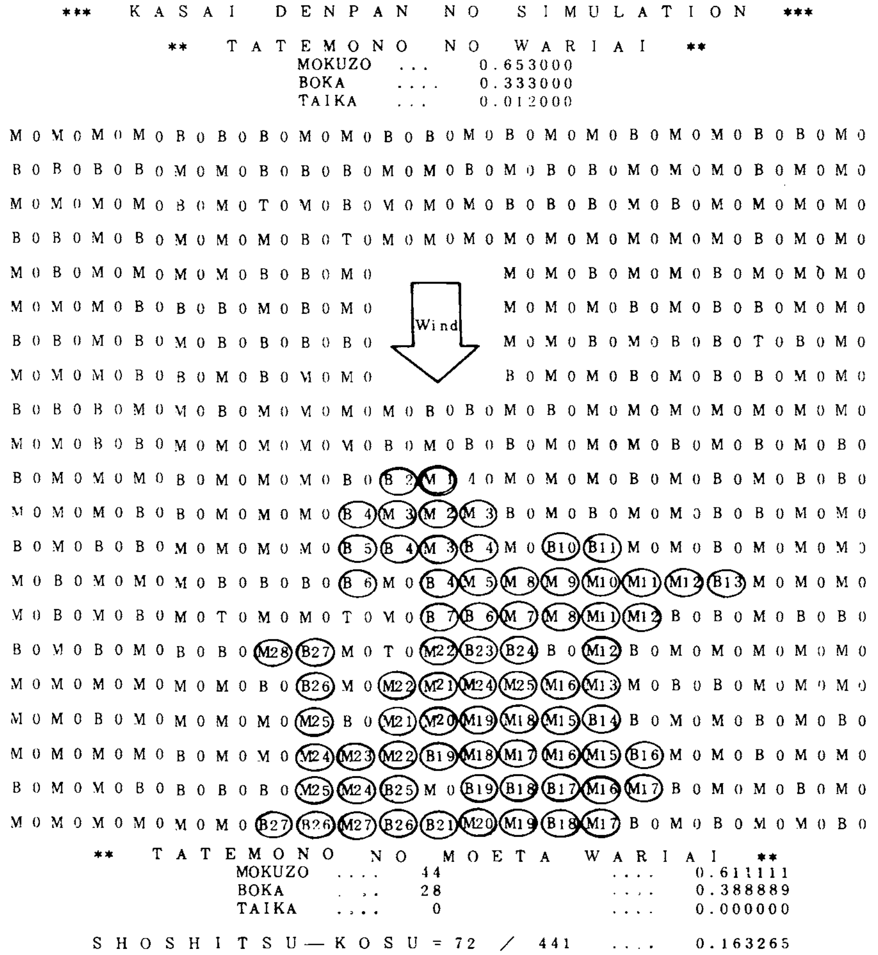
**Table 8** Probability of fire spread weight-averaged by the distribution of the distance between buildings

| Town | Building construction | Wind velocity | | | |
|---|---|---|---|---|---|
| | | 0 2.5 m/s | 2.6 5.0 m s | | |
| | | | Leeward | Sideward | Windward |
| Wakamiya 1 chome | Wooden → Wooden | 0.44 | 0.61 | 0.50 | 0.42 |
| | Wooden → Mortar | 0.39 | 0.53 | 0.45 | 0.37 |
| | Mortar → Wooden | 0.17 | 0.38 | 0.21 | 0.12 |
| | Mortar → Mortar | 0.30 | 0.56 | 0.36 | 0.26 |
| Wakamiya 2 chome | Wooden → Wooden | 0.45 | 0.62 | 0.51 | 0.44 |
| | Wooden → Mortar | 0.33 | 0.48 | 0.39 | 0.31 |
| | Mortar → Wooden | 0.11 | 0.33 | 0.15 | 0.09 |
| | Mortar → Mortar | 0.19 | 0.44 | 0.24 | 0.15 |
| Owada 1 chome | Wooden → Wooden | 0.46 | 0.62 | 0.52 | 0.44 |
| | Wooden → Mortar | 0.39 | 0.54 | 0.46 | 0.38 |
| | Mortar → Wooden | 0.16 | 0.35 | 0.20 | 0.13 |
| | Mortar → Mortar | 0.26 | 0.53 | 0.32 | 0.21 |

used. The building construction ratio was taken according to **Table 6** and the arrangement of buildings was renewed on every calculation. Procedures of calculation are as follows.

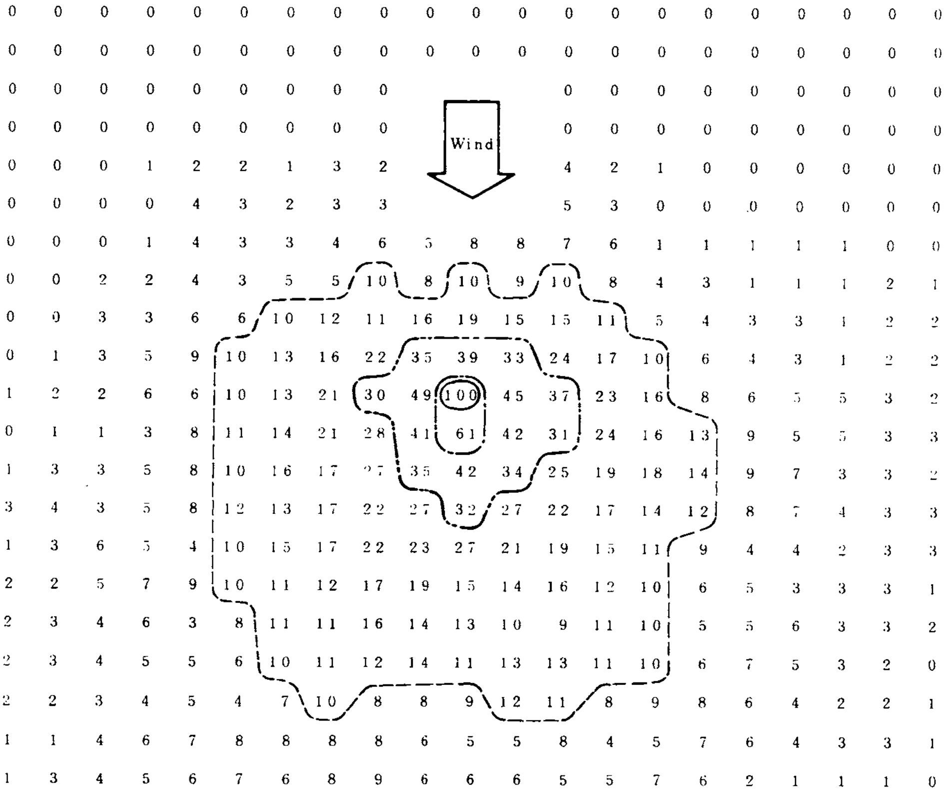
1) Decision of arrangement of building constructions by random numbers
2) Combination of neighbouring buildings leading to its probability of fire spread
3) Decision of possibility of fire spread from first burning building to neighbouring buildings by random numbers
4) Decision of possibility of fire spread from newly burning buildings
5) Recurrence of the same procedure as 4)

One of results of calculations is shown in **Fig.** 8 (Wakamiya 1-chome, wind velocity 2.6 – 5.0 m/s). The numbers enclosed with circles in **Fig.** 8 show the order of burning. M, B and T indicate wooden, mortar and concrete buildings, respectively. The numbers 0 indicate unburnt ones. **Fig.** 8 shows that buildings on the windward are unburnt, that fire spreads fanwise on the leeward and attain the lower end of the figure. The results are shown in **Table 7**. The larger



```
***  KASAI  DENPAN  NO  SIMULATION  ***

          **  TATEMONO  NO  WARIAI  **
                MOKUZO  ...    0.653000
                BOKA    ....   0.333000
                TAIKA   ...    0.012000

M 0 M 0 M 0 M 0 B 0 B 0 B 0 M 0 M 0 B 0 B 0 M 0 B 0 M 0 M 0 B 0 M 0 M 0 B 0 B 0 M 0
B 0 B 0 B 0 B 0 M 0 M 0 B 0 B 0 B 0 M 0 M 0 B 0 M 0 B 0 B 0 M 0 M 0 M 0 B 0 M 0 M 0
M 0 M 0 M 0 M 0 B 0 M 0 T 0 M 0 B 0 M 0 M 0 M 0 B 0 B 0 B 0 M 0 B 0 M 0 M 0 M 0 M 0
B 0 B 0 M 0 B 0 M 0 M 0 M 0 B 0 T 0 M 0 M 0 M 0 M 0 M 0 M 0 M 0 M 0 M 0 B 0 M 0 M 0
M 0 B 0 M 0 M 0 M 0 M 0 B 0 B 0 M 0             M 0 M 0 B 0 M 0 M 0 B 0 M 0 M 0 M 0
M 0 M 0 M 0 B 0 B 0 B 0 M 0 B 0 M 0             M 0 M 0 M 0 B 0 M 0 B 0 B 0 M 0 M 0
B 0 B 0 M 0 B 0 M 0 B 0 B 0 B 0 B 0             M 0 M 0 B 0 M 0 B 0 B 0 T 0 B 0 M 0
M 0 M 0 M 0 B 0 B 0 M 0 B 0 M 0 M 0             B 0 M 0 M 0 B 0 M 0 B 0 B 0 M 0 M 0
B 0 B 0 B 0 M 0 M 0 B 0 M 0 M 0 M 0 M 0 B 0 B 0 M 0 B 0 M 0 M 0 M 0 M 0 M 0 M 0 M 0
M 0 M 0 B 0 B 0 M 0 M 0 M 0 M 0 M 0 B 0 M 0 B 0 B 0 M 0 M 0 M 0 B 0 M 0 B 0 M 0 B 0
B 0 M 0 M 0 M 0 B 0 M 0 M 0 M 0 B 0 B 2 M 1 4 0 M 0 M 0 M 0 B 0 M 0 B 0 M 0 B 0 B 0
M 0 M 0 M 0 B 0 B 0 M 0 M 0 M 0 B 4 M 3 M 2 M 3 B 0 M 0 B 0 M 0 M 0 B 0 B 0 M 0 M 0
B 0 M 0 B 0 B 0 M 0 M 0 M 0 M 0 B 5 B 4 M 3 B 4 M 0 B10 B11 M 0 M 0 B 0 M 0 M 0 M 0
M 0 B 0 M 0 M 0 M 0 B 0 B 0 B 0 B 6 M 0 B 4 M 5 M 8 M 9 M10 M11 M12 B13 M 0 M 0 M 0
M 0 B 0 M 0 B 0 M 0 T 0 M 0 M 0 T 0 M 0 B 7 B 6 M 7 M 8 M11 M12 B 0 B 0 M 0 B 0 B 0
B 0 M 0 B 0 M 0 B 0 B 0 M28 B27 M 0 T 0 M22 B23 B24 B 0 M12 B 0 M 0 M 0 M 0 M 0 M 0
M 0 M 0 M 0 M 0 M 0 M 0 B 0 B26 M 0 M22 M21 M24 M25 M16 M13 M 0 B 0 B 0 M 0 M 0 M 0
M 0 M 0 B 0 M 0 M 0 M 0 M 0 M25 B 0 M21 M20 M19 M18 M15 B14 B 0 M 0 M 0 B 0 M 0 B 0
M 0 M 0 M 0 M 0 B 0 M 0 M 0 M24 M23 M22 B19 M18 M17 M16 M15 B16 M 0 M 0 B 0 M 0 M 0
B 0 M 0 M 0 B 0 B 0 B 0 B 0 M25 M24 B25 M 0 B19 B18 B17 M16 M17 B 0 M 0 M 0 B 0 M 0
M 0 M 0 M 0 M 0 M 0 M 0 B27 B26 M27 B26 B21 M20 M19 B18 M17 B 0 M 0 B 0 M 0 M 0 B 0

      **  TATEMONO  NO  MOETA  WARIAI  **
             MOKUZO  ....   44          ....   0.611111
             BOKA    ...    28          ....   0.388889
             TAIKA   ....    0          ....   0.000000

   SHOSHITSU—KOSU = 72 / 441           ....   0.163265
```

**Fig. 8** One of results of fire spread simulation ratio of mortar building makes the number of burnt buildings smaller whether it blows or not. The result shows a good possibility of a conflagration in Wakamiya 1-chome even at the wind velocity 0.5 m/s where the ratio of wooden building is 65%. At the wind velocity 2.6 – 5.0 m/s, the number of burnt buildings in Wakamiya 2-chome is much smaller than those in Wakamiya 1-chome and in Owada 1-chome, for the ratio of mortar buildings from which fire spreads with smaller probability of fire spread is large. Burning patterns calculated are quite different from each other and the numbers in **Table 7** are the averages of 100 calculations. The number in **Fig. 9** shows how many times a particular building was burnt in so many calculations (in Wakamiya 1-chome, wind velocity 2.6 – 5.0 m/s). The distribution of buildings burnt more than 10 times is almost egg-shaped on the leeward.



| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 1 | 2 | 2 | 1 | 3 | 2 | | | | 4 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 4 | 3 | 2 | 3 | 3 | | | | 5 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 1 | 4 | 3 | 3 | 4 | 6 | 5 | 8 | 8 | 7 | 6 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| 0 | 0 | 2 | 2 | 4 | 3 | 5 | 5 | 10 | 8 | 10 | 9 | 10 | 8 | 4 | 3 | 1 | 1 | 1 | 2 | 1 |
| 0 | 0 | 3 | 3 | 6 | 6 | 10 | 12 | 11 | 16 | 19 | 15 | 15 | 11 | 5 | 4 | 3 | 3 | 1 | 2 | 2 |
| 0 | 1 | 3 | 5 | 9 | 10 | 13 | 16 | 22 | 35 | 39 | 33 | 24 | 17 | 10 | 6 | 4 | 3 | 1 | 2 | 2 |
| 1 | 2 | 2 | 6 | 6 | 10 | 13 | 21 | 30 | 49 | 100 | 45 | 37 | 23 | 16 | 8 | 6 | 5 | 5 | 3 | 2 |
| 0 | 1 | 1 | 3 | 8 | 11 | 14 | 21 | 28 | 41 | 61 | 42 | 31 | 24 | 16 | 13 | 9 | 5 | 5 | 3 | 3 |
| 1 | 3 | 3 | 5 | 8 | 10 | 16 | 17 | 27 | 35 | 42 | 34 | 25 | 19 | 18 | 14 | 9 | 7 | 3 | 3 | 2 |
| 3 | 4 | 3 | 5 | 8 | 12 | 13 | 17 | 22 | 27 | 32 | 27 | 22 | 17 | 14 | 12 | 8 | 7 | 4 | 3 | 3 |
| 1 | 3 | 6 | 5 | 4 | 10 | 15 | 17 | 22 | 23 | 27 | 21 | 19 | 15 | 11 | 9 | 4 | 4 | 2 | 3 | 3 |
| 2 | 2 | 5 | 7 | 9 | 10 | 11 | 12 | 17 | 19 | 15 | 14 | 16 | 12 | 10 | 6 | 5 | 3 | 3 | 3 | 1 |
| 2 | 3 | 4 | 6 | 3 | 8 | 11 | 11 | 16 | 14 | 13 | 10 | 9 | 11 | 10 | 5 | 5 | 6 | 3 | 3 | 2 |
| 2 | 3 | 4 | 5 | 5 | 6 | 10 | 11 | 12 | 14 | 11 | 13 | 13 | 11 | 10 | 6 | 7 | 5 | 3 | 2 | 0 |
| 2 | 2 | 3 | 4 | 5 | 4 | 7 | 10 | 8 | 8 | 9 | 12 | 11 | 8 | 9 | 8 | 6 | 4 | 2 | 2 | 1 |
| 1 | 1 | 4 | 6 | 7 | 8 | 8 | 8 | 8 | 6 | 5 | 5 | 8 | 4 | 5 | 7 | 6 | 4 | 3 | 3 | 1 |
| 1 | 3 | 4 | 5 | 6 | 7 | 6 | 8 | 9 | 6 | 6 | 6 | 5 | 5 | 7 | 6 | 2 | 1 | 1 | 1 | 0 |

**Fig. 9** Frequency of burning of buildings in case fires originate from the same building 100 times (wind velocity 2.6 – 5.0 m/s)

## 4. Considerations

As mentioned in §2.3, the probability of fire spread is of averaged character in the following three points: weather condition, place and time. Therefore, simulations using the probability of fire spread do not always accord with actual fire incidents. It may seem much better to classify the data into smaller groups, but it would make each classified data too small in number and then unavailable in statistics. When fire incidents would be classified into smaller groups, for instance, by the weather condition, it would be necessary to make the area wider or the term longer for increasing number of data in the group. That is, the weather condition, the area and the term have a kind of uncertainty relation with each other. These features of the probability make the results of the simulation just available for relative comparison of regional fire danger.

The probability obtained in this way is on small fire incidents, and that on large-scale fires is presumed to be much larger. Jin5) investigated in detail the record of the conflagration accompanying the Kanto Great Earthquake of 1923 and got the probability for large-scale fires. Tachibana6) took into consideration the superposition effects of radiation from flames to calculate the probability for large-scale fires.

The simulations using the probability of fire spread can get no ever-changing patterns of fire spread. But if one comprehends changes in time of flame of burning building and of state of ignition of neighbouring buildings, one will be able to find the probability as a function of distance and time.

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## References

1) Hori, M.: "Theory of Percolation and its Applications" NIPPON TOKEIGAKKAI-SHI **3**, 19 (1972) (in Japanese)
2) Tokyo Fire Department: "Statistics of Tokyo Fire Department" (1972) (in Japanese)
3) Tokyo Astronomical Observatory: "RIKANENPYO" (1973) (in Japanese)
4) Tokyo Fire Department: "On Urban Circumstances in Tokyo" (1973) (in Japanese)
5) Jin, T.: "Probability of Fire Spread on Large-scale Fires" KASAI **106**, 36 (1977) (in Japanese)
6) Tachibana, F.: "Fire Spread and Regional Characteristics" Research Seminar of Japanese Association of Fire Science and Engineering (1976) (in Japanese)

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