Quantitative Analysis of Fire Spreading Potential for Surrounding Areas of Cultural Properties in Kyoto City

Kaoru Matsumiya* and Kiyoaki Oikawa

1 Graduate Student, Graduate School of Science and Engineering, Ritsumeikan University, M. Eng., Japan
2 Professor, Graduate School of Science and Engineering, Ritsumeikan University, Dr. Eng., Japan

Abstract

Many cultural heritage sites exist in the historic city of Kyoto. Wooden buildings account for a majority of these sites, and they exist in a large proportion in the surrounding urban areas. Therefore, protecting Kyoto's cultural properties from fire hazards is a pressing issue in urban planning. Based on this type of problem awareness, this study aims to produce basic documentation related to future disaster-prevention measures for cultural properties.

First, we conducted a field survey of the buildings surrounding cultural properties and compiled critical distance of fire spreading dilated volume fraction (DVF) buffer data for each structure. We calculated the critical distance of fire spreading taking into account the weather conditions of wind speed and direction, and illustrated the DVF buffer using image processing techniques and created a fire spreading graph. We then analyzed the risk of fire spreading to cultural properties from both the macro and micro perspectives according to the number of configuration nodes for the DVF buffer and graph.

We found that the majority of cultural properties at high risk of fire spreading are folk dwellings and Japanese traditional town houses and that many are distributed in areas of high-density wood construction.

Keywords: cultural property buildings; fire spreading; covering volume fraction; dilation; cluster

1. Introduction

1.1 Background and Purpose of the Study

Many cultural heritage sites exist in the historic city of Kyoto, such as temples and shrines. Wooden buildings account for a majority of these sites, and they exist in a large proportion in the surrounding urban areas. Therefore, there is a significant risk of fire spreading in many areas when a fire breaks out and protecting these cultural properties from fire hazards is a pressing issue in urban planning.

To reduce fire hazards in cultural property buildings, it is necessary to understand the fire risk rating for the building itself and to take fire prevention and extinguishing measures, such as the installation of fire-prevention equipment, a fire defense system for self-protection and fire protection guidance. It is also necessary to simultaneously prevent fire spreading from ordinary buildings surrounding the cultural properties. While it is important to promote the fireproofing of surrounding buildings it is time consuming to fireproof a large number of buildings. To adopt effective fire prevention measures, it is essential to accurately understand the current distribution of buildings in the vicinity of the cultural property and take appropriate measures for the prevention of fire spreading, which are appropriate for each area. Ranking each cultural property according to its conflagration hazard index and documenting the ranking is considered an effective step.

On the basis of this type of problem awareness, in this study, we examine the current distribution of ordinary buildings in the vicinity of cultural properties, quantitatively analyze the risk of fire spreading, and rank the individual cultural properties according to the level of risk. On the basis of the results, we seek to produce basic documentation to support future detailed analysis, such as conducting fire spreading simulation for high-risk cultural properties.

1.2 Context of the Study

Several studies have previously been conducted that morphologically address urban fire prevention. The National Institute for Land, Infrastructure and Transport General Technological Development Project (hereafter referred to as the General Project for a Fireproof Town) proposes the Covering Volume Fraction (CVF) method for macro evaluation of the risk of fire spreading in an urban area. Kato et al. developed this CVF concept for the entire country of Japan based on the structure of buildings in each city.
with the known data and then established a critical distance of fire spreading for each building on the basis of structural and wind speed, and direction attributes. They then compared these critical distances of fire spreading by building structural types and by wind speed and direction with the distance between adjacent buildings for all building polygonal data and calculated the probability of individual buildings being burnt down using fire-spreading clusters. Abe et al.\(^5,6,7\) investigated fire prevention measures via urban development prioritization. Discrete optimization according to a network of fire spreading routes can identify buildings that should be developed for maximum improvement in fire prevention. These studies targeted entire prefectures, municipalities, and so on, rather than evaluating the risk of fire spreading concentrated on specific buildings within a region. Matsumiya et al.\(^8\) limited their target study region to the area surrounding a cultural property and categorized buildings as either fire-resistant or non-fire-resistant structures on the basis of their classification on city planning maps as "solid buildings" and "high-rise buildings". They proposed a "deemed non-fire-resistant rate," evaluated the risk of fire spreading in the vicinity of cultural property buildings, and ranked them according to that risk. However, none of these studies provided an accurate database because the structure of the building is only estimated on the basis of the number of stories, and a field survey of each building is omitted. Furthermore, in the study by Kato et al., lengthy numerical calculations using building polygonal data is required for a comparison of the critical fire spreading distance with the distance between adjacent buildings.

In this study, we limit the target study region to the area surrounding a cultural property, create an accurate building structure database by conducting a field survey of the buildings surrounding the cultural property and quantify the risk of fire spreading to the cultural property and surrounding area. Furthermore, on the basis of the CVF concept, we propose a Dilated Volume Fraction (DVF) that takes into account the weather conditions of wind speed and direction characteristic of the area. This method requires less calculation time because an image processing technique rather than numerical calculations is used to compare the critical distance of fire spreading between individual buildings with the distance between adjacent buildings. This method can be regarded as a simplified version of the method proposed by Kato et al.

### 2. Compiling Data by Structure of Cultural Property Buildings and Surrounding Buildings

#### 2.1 Cultural Property Buildings

Many cultural properties exist in Kyoto, including cultural heritage sites listed as world heritage sites, such as those designated as national treasures and important cultural properties by the Law for Protection of Cultural Properties and Kyoto Prefecture and Kyoto City designated cultural properties. We reviewed each type of documentation, such as previous literature and webpages, and compiled a list of tangible cultural properties located in Kyoto that are classified as "buildings." There are a total of 565 cultural properties in this list\(^9\).

In addition, we created building polygonal data that corresponds to each cultural property and created an arrangement plan of these buildings (Fig.1.). The building polygon count for cultural properties is 772, and when collated by name, e.g., temple or shrine name, the count is 236.

![Fig.1. Distribution Map of Buildings Separated into Fire-Resistant and Non-Fire-Resistant](image)

#### 2.2 Compiling a Database by Structural Type for Buildings Surrounding Cultural Properties

To comprehend the risk of fire spreading in the areas surrounding cultural properties, we used CAD to create a building distribution map for fire-resistant and non-fire-resistant buildings, which is based on a 1/2500 city planning map developed by the Kyoto City Planning Bureau. In this planning map, buildings classified as "solid buildings" and "high-rise buildings" are designated as fire-resistant structures, and all other buildings are designated as non-fire-resistant\(^10\). Fig.1. is a distribution map of fire-resistant and non-fire-resistant buildings. There are approximately 480,000 buildings in Kyoto City. Fire-resistant buildings are concentrated around Kyoto Station and in the city center, while numerous non-fire resistant buildings generally exist in other areas.
To accurately estimate the risk of fire spreading in areas surrounding cultural properties, only classifying the buildings as fire-resistant or non-fire-resistant structures is not sufficient. Therefore, we conducted field surveys of the buildings surrounding cultural properties (108,091 buildings) and, on the basis of the results, compiled data by structural type of exposed wooden, wooden, quasi-fire-resistant and fire-resistant (Fig.2.).

We set the scope of the survey at a radius of 200m from the center of the cultural property polygon. In past urban conflagrations, fire spread at a speed of 200 m/h and therefore a distance of 200m is equivalent to the range the fire could possibly spread within 1 hour when there is a conflagration and can be said to be an appropriate numerical value setting.

The survey method entailed walking the area in a 200m radius of the center of the cultural property polygon and visually identifying the four structural types of exposed wooden, wooden, quasi-fire-resistant and fire-resistant buildings and color-coding them on the map (Fig.3.). The details of classification are as follows: "exposed wooden" is a building covered with at least 90% wood on the exterior, "wooden" is a wooden building covered in mortar and siding, "quasi-fire-resistant" is a steel structure building less than 100 m², and "fire-resistant" is a reinforced concrete building or steel structure building more than 100m².

Table 1. lists the number of buildings (polygon count) and area of each building by structural type. This table also provides cultural property aggregate data. We found from this table that in Kyoto non-fire-resistant buildings, (which include cultural properties), exposed wooden buildings, wooden buildings and quasi-fire-resistant buildings, account for more than 80% of the number of buildings and close to 70% of the building areas are significantly greater than the figures for fire-resistant buildings.

### 3. Concept of the Fire Spreading Process Model

#### 3.1 Overview of Fire Spreading Model CVF in Previous Studies

In this study, the fire spreading process model is based on CVF recommended as a macro evaluation technique for fire spread risk in the General Project for a Fireproof Town. With this concept the critical distance of fire spreading between adjacent buildings is defined and if the distance between adjacent buildings exceeds the critical distance of fire spreading it is deemed that the fire will not spread. When the distance between adjacent buildings is less than the critical distance of fire spreading, the risk of fire spread is evaluated according to the collective building cluster or cluster content (area/number of buildings, Fig.4.).

This means that if fire breaks out in one building of the buildings in the cluster, all buildings in the cluster will be destroyed, i.e., the probability of the buildings that make up the cluster being destroyed by fire is equal to the probability of fire breaking out in the cluster.

#### 3.2 Setting the Critical Distance of Fire Spreading for CVF

In the General Project for a Fireproof Town, the
values of the standard scale for critical distance of fire spreading for a building fire are 12m for exposed wooden, 6m for wooden, 3m for quasi-fire resistant, and 0m for fire-resistant structures. This is known as the typical fire spreading rate equation for urban fire spreading and is based on the model type of Hamedan, Horinouchi, and Murosak. The critical distance of fire spreading increases depending on the time that elapses after the outbreak of fire and the wind speed. The critical distances calculated from each fire spreading rate equation by structure are as follows: Hamedan type (exposed wooden): Horinouchi type (wooden): Murosak type (quasi-fire-resistant) = 4:2:1 irrespective of the time that elapsed after the outbreak of fire and the wind speed. In this case, the critical distance of fire spreading is isotropic (identical in all directions).

With the CVF in the General Project for a Fireproof Town, when a buffer of half the critical distance of fire spreading is created around the plane of the subject building, it is expressed as the buffer area ratio for the district, including buildings. Sections where the buffer overlaps are duplicated and are not counted.

4. DVF Approach and Analysis Based on the Dilation of the Building Arrangement Plan

4.1 Setting the Critical Distance of Fire Spreading Taking into Account Wind Speed and Direction

The General Project for a Fireproof Town and previous studies by Kato et al. etc. presented an effective model for the evaluation of fire spreading risk. In this study, we further developed the aforementioned method and plotted a DVF fire-spreading graph. First, we consistently established the critical distance of fire spreading by building structure irrespective of the effect of wind after an outbreak of fire. However, in reality, the critical distance of fire spreading varies according to wind speed and direction. For example, the critical distance of fire spreading in the leeward direction becomes a stretched oval shape (Fig.5.). A model formula for critical distance of fire spreading that recognizes weather conditions as area characteristics and incorporates wind speed and direction is recommended by the Non-Life Insurance Rating Organization of Japan based on the set values from the General Project for Fireproof Town. This is the critical distance of fire spreading that we adopted in this study. In this case, the critical distance of fire spreading $d_*$ is calculated by the following formula according to building width $A$ (the square root of the building area), structure, and wind speed.

$$ d_* = k \cdot A' \quad (I) $$

Here $k$ and $r$ are the parameters determined by the movement of the flames according to the building structure and wind speed.

According to statistics from the Meteorological Agency, the most frequent annual wind direction is generally from the north, specifically, in February when there are many fire hazards, the most frequent wind direction is also north. Accordingly, we set the wind direction for the study as north (Table 2.). The average annual wind speed is 1.7m/s, but we referred to the average wind speed during past urban conflagrations of 8–10m/s, and set the wind speed on the safe side at 10 m/s. We used a curved line that forms an oval shape (windward and windside are equidistant), and set the parameters $k$ and $r$ on the basis of reference literature (10) as shown in Table 3.9

4.2 Definition of DVF

In this study, we developed the CVF concept and plotted a n o v a l - s h a p e d critical distance of fire spreading around a building plane using critical distance of fire spreading incorporating the wind speed and direction as area characteristics and measured the area of the oval line. With image processing technology, the circumferential enlargement of the figure using structural elements is called dilation. The CVF buffer is equivalent to structural elements made circular in dilation. In contrast, because wind direction is considered in this study, the structural elements become oval-shaped in dilation. This enlarged oval-shaped area is the building buffer for "DVF" (hereafter referred to as DVF buffer, Fig.6.). DVF is the ratio of the district area to the buffer area surrounded by the critical distance of fire spreading converted to an oval shape from the circle in Fig.3.

Creating the DVF buffer becomes complex on a continuous surface, therefore, digital processing based on the image processing technique was used. Here the building plane was divided into 50 cm square pixels and "half" of the length of the critical distance

\[ Table 2. Wind Direction and Speed in Kyoto-city \]

| Month | Wind dir. | Wind speed |
|-------|-----------|------------|
| Jun.  | W         | 1.5        |
| Aug.  | NNE       | 1.8        |
| Dec.  | NNE       | 1.9        |
| Jan.  | N         | 1.9        |
| Feb.  | N         | 1.7        |
| Mar.  | N         | 1.9        |
| Apr.  | N         | 1.8        |
| May   | NNE       | 1.6        |

\[ Table 3. Parameters by Structure \]

| Structure          | $k$  | $r$  | $k$  | $r$  |
|--------------------|------|------|------|------|
| Exposed wooden     | 3.79 | 0.49 | 0.41 | 0.41 |
| Wooden             | 2.03 | 0.46 | 0.24 |      |
| Quasi-fire-resistant | 1.28 | 0.35 | 0.05 |      |
of fire spreading expressed in equation I was applied, producing dilation for building structure and scale (building area). The length was halved for the same reason as that for CVF. The critical distance of fire spreading was determined from the damage side of the building structure. When fire spread between buildings of different structural types, the average critical distance of fire spreading value was used. It was assumed that fire spreads in both directions if each building is fire side\(^7\) when the distance between adjacent buildings is smaller than the critical distance of fire spreading (Fig.4.). Moreover, it was assumed that when the fire-resistant structures are on fire the exterior of the structure is not affected. In this study, to be on the safe side the cultural property itself was judged to be an exposed wooden structure.

The above parameters were applied to an actual building arrangement plan and the DVF buffer was calculated. An example of the logical union of sets is shown in Fig.7. The yellow areas on the diagram are DVF buffers (excluding the building). As with CVF, DVF refers to the value by dividing the DVF buffer and non-fire-resistant) buildings (exposed wooden, wooden and quasi-fire-resistant) area by the area of the object domain. DVF represents the collective status of buildings to which fire is likely to spread. DVF shows that a fire that occurs within a cluster is likely to spread to all buildings within that cluster over time. A large DVF within a cluster means that the area density of each building cluster (fire spreading cluster) within the object region is high. That is, DVF can be understood to be the macro evaluation numerical value that represents the probability of fire spreading within the entire region around the cultural property\(^8\).

### 4.3 Extracting the areas at risk of fire spreading using DVF

We calculated DVF for the area surrounding the object cultural properties and ranked them (Table 4.). The results indicate that Myoken Temple had the highest DVF at 82.8%, followed by the Funaoaka Ryokan at 80.8%. It is apparent from Fig.7, that there are many non-fire-resistant buildings in these two areas which are densely developed. Therefore, the DVF buffer areas are also large and there is a high risk of fire spreading.

We color-coded the degree of risk on the basis of the DVF ranking (Fig.8.). Considering all districts within Kyoto City, the risk is high in parts of Kamigyo and Higashiyama Wards. There are many temples in these districts and more wooden buildings compared to other areas. It is acknowledged that these two districts are vulnerable to fire.

### 5. Creating a Fire Spreading Graph and Measuring the Number of Buildings that Constitute the Cluster

#### 5.1 Creating a Fire Spreading Graph on the Basis of DVF Data

The fire spreading graph \(V^g\) showing the risk of fire spreading is created on the basis of the DVF data. Assuming that when the DVF buffers (dilation of half of the critical distance of fire spreading) between two buildings intersect, fire will spread from one building to another. The building polygon is replaced with nodes (vertices) on a graph, connected by an edge (line segment). This operation is conducted for all buildings within the target region, including the cultural property, and the fire spreading graph \(V^g\) is created (Fig.9.). The connected components on the fire spreading graph represent the collective building groups or clusters. When a fire breaks out in one of these clusters, all buildings within that cluster will be destroyed by fire unless fire fighting activities are performed. In other words, the buildings in the cluster “share a common destiny.” If a cluster with a cultural property is selected from the graph, it is possible to include the extent of fire spreading risk to the cultural property itself.
property (Fig.10.). Note that when multiple cultural properties with the same name exist at the same location, their nodes are connected to only one node.

5.2 Clusters Containing Cultural Properties and their Node Order

It is considered that the greater the number of nodes in a cluster with a cultural property, the higher the risk of fire spreading. We ranked the fire spreading clusters with cultural properties on the graph in descending order based on the number of nodes in the cluster (Table 5.). The target areas with the most nodes including the cultural property were Funaoka Ryokan with 862, Tondaya with 727 and Myoken Temple with 631. In these cases, there is little difference between the total number of nodes for the area and the number of nodes including the cultural property. As can be seen in the example of Funaoka Ryokan (Fig.9.), this is not restricted to the area around the cultural property, because there are non-fire-resistant buildings grouped in all areas within the target area.

In contrast, there are 22 cultural property clusters for which the number of nodes is 1 (graph of the cultural property only), and in this case there are no non-fire-resistant buildings within the critical distance of fire spreading. The risk of fire spreading in these areas is extremely low. For example, in the case of Senbon Shakado, although the total number of nodes is extremely high (801), there is open space surrounding the cultural property and the number of nodes including the cultural property is 1 (Table 5., Fig.9.). Although the cultural property is in an area densely populated with wooden buildings, the risk of fire spreading from the surrounding area is small because the open space acts as a firebreak belt. This example suggests that safety can be guaranteed by implementing thorough fire prevention measures for the cultural property itself.

Fig.11. is a diagram color-coded based on the number of nodes including the cultural property. In the entire Kyoto City, although parts of Kamigyo and Nakagyos have a high number of nodes, there are few nodes in the central shopping district with its bustling streets and the Sakyo District, home to the Kyoto University campus, suggesting that these areas are considered relatively safe.
Further, there are 186 target areas where the number of primary nodes is less than 10 for example, including cultural properties where the primary number of nodes is 0 (the number of nodes including the cultural property is 1). These areas account for approximately 82% of the total city area. In other words, regardless of how many configuration nodes increase to the secondary order or above, if fire breaks out or spreads from non-fire-resistant buildings within the primary order categories, it is possible to avoid fire spreading to the cultural property. In such situations, it is also thought to be relatively easy to take measures against fire spreading.

In contrast, many of the cultural properties with at least 11 configuration nodes of the primary order (41 areas) are located in areas densely populated with wooden buildings. When fire breaks out in these areas, the risk of a large-scale fire is markedly higher. To address this problem, it is necessary to adopt measures against fire spreading as soon as possible.

It will be an effective fire-proof countermeasure to refer to the fire spreading graph and protect the cultural property buildings from ordinary buildings in their vicinity by isolating them at their primary connection points. To be more specific, fire protection trees, fire protection walls, water spray-type water screen fire protection systems, etc. should be installed.

6. Comprehensive Analysis of the Vulnerability of a Cultural Property to Fire Spreading

By comprehensively analyzing the risk of fire spreading to a cultural property according to the analysis described above, it is possible to separately identify the vulnerability to fire spreading to the cultural property for the entire area surrounding the cultural property (from the macro perspective, within the radial distance of 200m) as well as for the area in the vicinity of the cultural property (from the micro perspective). DVF values can be used for the former and the number of nodes with cultural property for the connected components from the fire-spreading graph for the latter. The distribution map shown in Fig.12 provides the results of this comprehensive analysis. It is also possible to understand the safety and risk from the micro and macro perspectives by broadly classifying the results into four categories according to the magnitudes of the values.

Type I with many nodes and a high DVF ratio indicates areas where the risk of fire spreading in both proximity to the culture property and entire area surrounding it is extremely high. Among these sites, the cultural property at the highest risk is "Funaoka Ryokan".

Type II with many nodes and a low DVF ratio indicates areas where the risk of fire spreading in the areas in the vicinity of the cultural property is high. For example, this applies to "Sumiya".

Type III with few nodes and a low DVF ratio indicates areas where the risk of fire spreading in both the areas in the vicinity of the culture property and the entire area surrounding the cultural property is low. The site at the safest level is "Oharano Shrine."

Type IV with few nodes and a high DVF ratio indicates areas where the risk of fire spreading in the entire area surrounding the cultural property is high. For example, this applies to the "Okutanike Residence."

7. Conclusion

In this study, we conducted field surveys of areas surrounding cultural properties in Kyoto and created a database by building structural types. In the analysis process, we calculated the critical distance of fire spreading taking into account the wind speed and direction as area characteristics and suggested DVF buffers developed through image processing technology. Further, we created a fire-spreading graph on the basis of DVF data and analyzed the risk of fire spreading to a cultural property from both a macro and micro perspective according to the number of...
configuration nodes on the DVF data and the graph. This quantified the cultural properties and surrounding areas at risk of fire spreading. It was found that the majority of cultural properties at risk of fire spreading are folk dwellings and Japanese traditional town houses and many of them are located in areas densely populated with wooden buildings.

In future studies, we would like to better understand the risk of fire spreading from a micro perspective by conducting a simulation of fire spreading for those cultural properties that this study identified as at high risk of fire spreading. This will lead to suggestions for measures to prevent fire spreading to specific cultural properties.

**Notes**

1. The breakdown of cultural properties is: 14 World Heritage sites, 40 national treasures, 200 important cultural properties, 174 nationally registered cultural properties, 41 prefecture designated cultural properties, 6 prefecture registered cultural properties, 67 city designated cultural properties, and 23 city registered cultural properties.

2. A solid building refers to a building with a reinforced or steel framed concrete structure that has at least two floors. High-rise buildings can also be regarded as fire-resistant structures; accordingly, “solid buildings” and “high-rise buildings” are fire-resistant buildings and all other buildings can be determined to be non-fire-resistant buildings.

3. Due to the fact that the scope of the survey was set to a radial distance of 200m from the center of the cultural property polygon. For large-scale cultural properties there are two cases where there are fewer buildings in the surrounding urban area within the radial distance of 200m (1) The site is very large but the building itself is small, with extensive open space surrounding the building. (2) The building itself is large and accounts for most of the area within radial distance of 200 m. Case (1) is not an issue because it is determined that there is no risk of fire spreading to the cultural property from surrounding urban areas. With Case (2), in spite of the close proximity of the cultural property to surrounding buildings, it is thought that since there are not many surrounding buildings within the target survey region, a sufficient amount of materials are not available to determine the risk of fire spreading.

4. The distance between adjacent buildings is defined as the minimum distance from one building polygon to the surrounding building polygons.

5. The critical distance of fire spreading refers to the maximum distance that fire might spread between buildings. The value for this parameter is determined by the building structural type.

6. For example, the leeward critical distance of fire spreading d\(^b\) for the exposed wooden building, with width A=5m is obtained by the equation d\(^b\)=5.14 A\(^{-5.5}\).41=9.94335.

7. Assuming that a fire control service is not available, when oval-shaped dilation is applied to a critical distance of fire spreading according to structure and building area, buildings that are even partly included in the DVF buffer can be regarded as buildings to which fire spreading is caused from dilation-processed buildings (fire-causing buildings). In reality, the critical distance of fire spreading varies depending on the structure of the building subject to damage, but it is known that buildings even with a high fire protecting performance catch fire through openings. Consequently, the critical distance of fire spreading was determined by the structural and scales of the building under conditions of anisotropy of fire spreading routes. To avoid this, dilation was applied to a distance of half the critical distance of fire spreading and when the DVF buffers mutually overlapped, it was assumed that whichever building was on the fire-causing side, the other building would catch fire. This type of concept is derived from the General Project for a Fireproof Town.

8. DVF, as with CVF, is based on the critical distance of fire spreading when fire breaks out in one building. When the fire breaks out in a group of buildings, the critical distance of fire spreading is greater from the building cluster on the fire-causing side, but the increase in critical distance of fire spreading that accompanies the fire spreading is not considered here.

9. The area encompassed by Oike-dori Street to the north, Gojo-dori Street to the south, Kawai-machi-dori Street to the east and Horikawa-dori Street to the west.

10. To conduct a relative analysis, the average DVF values and number of nodes are used as the separator line for convenience.

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