Estimation of Magnitude and Heat Release Rate of Fires Occurring in Historic Buildings-Taking Churches as an Example

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Abstract: Historical buildings often fail to meet today’s building and fire protection regulations due to their structure and space restrictions. For this reason, if such buildings encounter fire, serious damage will be resulted. The fire of the Notre-Dame Cathedral in Paris (Notre-Dame de Paris) in April 2019 highlights the seriousness of this problem. In this study, the historical building of “Tamsui Church” was selected as an example. The Fire Dynamics Simulator (FDS) was adopted to analyze the scale of damage and possible hazards when the wooden seats in the church are on fire, and improvement measures were proposed to ensure that such buildings can be used under safer conditions. It was found that the existing seat arrangement will cause the spreading of fire, and the maximum heat release rate is 2609.88 kW. The wooden roof frame above the fire source will also start to burn at 402.88 s (6.6 min) after the fire, which will lead to a full-scale fire. To maintain the safety of the historical building, it is necessary to add active firefighting equipment (smoke detector and water mist system).

Keywords: simulation; historic buildings; fire magnitude; sustainable buildings; heat release rate

1. Introduction

The issues related to the preservation of cultural heritage have been promoted in the world since the launch of the “Athens Charter” in the 1930s, and the “Venice Charter” in the 1960s, which have made such preservation a universal value all around the globe. Furthermore, the “World Heritage Convention” announced in 1972 and its follow-up documents also established a set of universal value standards and operating norms for practice around the world. When it comes to the 21st century, the scope of preservation has been gradually expanded due to the continuous growth of the concept of holistic preservation. Thus, the direction of the world’s preservation of cultural heritage has been diverted through the integration and investment of various sciences and technologies.

Moreover, the concepts of risk management and disaster prevention have also been applied in the preservation of historic building in recent years, for example, the Blue Shield project led by the United Nations, the “Hoygo Framework for Action 2005–2015, HFA”, the establishment of the Research Center for Disaster Mitigation of Urban Cultural Heritage (University of Leuven and Ritsumeikan University), etc. In addition, Italy’s pioneering in the creation of “The Risk Map of Italian Cultural Heritage” and Japan’s continuous promotion of the Programme on Disaster Risk Management of Cultural Heritage both demonstrate the world’s efforts in heritage preservation. According to the “Venice Declaration on Building Resilience at the Local Level towards Protected Cultural Heritage and Climate Change Adaptation Strategies”, jointly announced by UNESCO, UN-HABITAT and UNISDR, a “from the bottom up” approach was promoted for the reduction of disaster risk and increases in urban resilience in response to the aggravation of urbanization and climate change. In the Third United Nations World Conference on Disaster Risk Reduction (WCDRR) held in Sendai City, Japan, in March 2015, besides evaluating the implementation
of the “Hoygo Framework for Action”, the conference also addressed such important topics as “disaster prevention for cultural heritages”, “disaster reduction with the assistance of science and technology” and “government–community integrated risk management”. Moreover, three pillars for the protection of cultural heritage from disasters were also proposed, which were “non-material assistance”, “material assistance” and “global and region-wide cooperation”. The aforementioned content shows the efforts made by various countries in recent years in the preservation of cultural heritage and the realization of the buildings’ sustainable use.

The incorporation of digital technology into disaster prevention and rescue systems has become a global trend. The “ICOMOS Charter for the Interpretation and Presentation of Cultural Heritage Sites” in 2008 pointed out the importance of expanding the use of digital tools to communicate with all walks of life, while the “Sharjah Initiative” of ICCROM in 2011 emphasized the importance and necessity of geographic information systems (GISs) in the preservation and management of cultural heritage; both of which fully explain the importance of digital technology in the protection of cultural heritage. In addition, the number of devastating fires in important historical buildings around the world this year also illustrates the importance of building fire safety. Through the use of numerical simulation based on FDS, problems can be detected in advance to formulate improvement plans, preventing similar tragedies from happening again.

However, fire has been a long-standing major cause of devastating damage to historic buildings. The Notre-Dame de Paris fire that broke out in April 2019 burned out its Gothic spire and wooden attic roof, and the fire lasted until the next day. It was initially estimated that it might take 20 years or more for it to be completely repaired. The devastating fires that have occurred in several important historic buildings all over the world in recent years have manifested the importance of fire safety in buildings. With the assistance of FDS (Fire Dynamics Simulator) [1] numerical simulation, problems of fire concerns can be identified beforehand, and improvement plans can be developed in advance to prevent similar tragedies from happening again. Since full-scale fire experiments are hard to implement on such buildings, the experiments are mostly carried out by computer simulation. In Taiwan, the design based on international standards has been applied in newly-built buildings since 2004, in which building fire scenarios are explored according to fire dynamics to exclude some restrictions arising from architectural techniques and rules, and countermeasures against the hazards are proposed. This method has been employed by many international studies for years. However, studies on fires occurring in historic buildings are relatively rare. With respect to studies on the numerical simulation of historic building fires conducted by foreign experts, Masatake Murahashi and Yasunori Iwaguchi, etc., calculated the locations that could most effectively stop a fire from spreading within historical and traditional areas using tree segmentation. A geographic information system was also incorporated to illustrate the spatial distribution situation, by which dangerous areas vulnerable to fires could be identified and countermeasures could be determined (Masatake Murahashi, etc., 2007) [2]. The physics-based Urban Fire Spread Model (UFSM) developed by Himoto Keisuke and Tanaka Takeyoshi, etc., [3] was applied in the fire spread simulation for traditional buildings in Sanneizaka Preservation District, Kyoto, in order to predict high-risk areas in a fire, and it further highlighted the relationship between the fire safety reinforcement ratio and fire hazards in traditional/historical areas, etc. In addition, countermeasures against fire hazards, such as selection of fire-resistant materials for wooden buildings, etc., were also proposed based on the fire safety reinforcement ratio (Himoto Keisuke, etc., 2006) [4]. In regard to the research on fires in non-historic buildings published in recent years, by focusing on the impact of atrium space during fires, Al-Waked et al. (2021) [5] found that a natural smoke exhaust window installed above the atrium could effectively facilitate the rising of hot air when a fire breaks out, so as to postpone the smoke layer’s descent during a fire and provide more time for evacuation. By comparing the results of full-scale fire experiments and FDS simulations, Vigne et al. (2021) [6] found that the smoke layer temperatures at heights of 10 m and 15 m, obtained
in FDS simulations, were precise (with a difference smaller than 10%), and they verified that grid analysis could ensure the correctness of the simulation results. Xu et al. (2021) [7] tested the sensitivity of smoke detectors in spaces with low ceilings, and discovered that there was a linear relationship between the ceiling height and the response time of smoke detectors—the greater the ratio of the long side to the short side, the slower the smoke detector’s response. Li et al. (2021) [8] compared the results of scale model fire experiments and FDS simulations, and found that the average temperature difference in the upper layer airflow between the two models was within 2 °C, and the overall error was also controlled to within 7%, showing that FDS could be used to predict or represent actual fire scenarios.

The foregoing research is summarized as follows. (1) In Japan, studies have been conducted to discuss and predict fires in regional historical buildings; however, the possible scale of fires has not been assessed. (2) FDS can indeed predict or reproduce the fire scenario. It has been used mostly for temperature and smoke analysis. Through the simulation, one can understand the temperature and smoke flow conditions at different heights. (3) The comparison between the results of FDS and of full-scale experiments evidence that the simulation is accurate when the height is below 15 m. This study is an improvement on the aforementioned research. The major difference is that in the improved fire simulation technology, fire source ignition loss setting is proposed. Under the premise that it is not easy to add firefighting equipment to historical buildings, the maximum heat release rate should be assessed, and can be determined via the ignition loss setting, thus serving as a basis for improvement. The main methods include: (1) analyzing the maximum heat release rate of the fire source through the ignition loss setting of the combustible material, and (2) adding the extended burning setting to see if the scale of the fire is too large to spread. Through the method setting, one can: (1) understand more about realistic fire scale, and (2) formulate an appropriate building hardware improvement strategy, as well as a software risk management mechanism. Due to building structure and space constrains, it is difficult for historical buildings to comply with existing laws and regulations on fire protection. For the objective of sustainable use, how to accurately estimate the scale of fire in the existing space and structure, and the proposal of appropriate improvement methods, are particularly important. It is hoped that these cultural assets can continue to show their values under safer conditions, and better preservation methods can be proposed for such historical buildings.

2. Method
2.1. Overview of the Building

This study applies the Fire Dynamics Simulator (FDS) developed by the Building and Fire Research Laboratory (BFRL) under the U.S. National Institute of Standards and Technology (NIST) for fire scenario simulations. FDS is the most widely used computer fire simulation software used by fire researchers all over the world in recent years. The FDS ancillary software Smokeview can also be used for follow-up observations and the analysis of simulation results.

The object of simulation is the “Tamsui Church” (Figure 1), which has a wooden ceiling in the interior space (Figure 2). The simulation is mainly focused on estimating the scale of a fire of the wooden seats in the Church (Figure 3 plan view). Through FDS, the possible fire scale, heat release rate, ignition loss and fire spread when the wooden seats in the Church are on fire can be understood, such that improvement measures can be proposed. The burning of a single wooden seat will be investigated first, and then the simulation of larger burning area will be carried out to discuss the possibility of extended burning and the scale of the maximum heat release rate. In general, the size of the fire source in the existing FDS fire simulations is fixed with no ignition loss. The reason for employing such a setting is that (1) this is a more conservative way of carrying out the evaluation; however, the result needs to be improved by adding equipment with higher specifications, and (2) the ignition loss setting is more complicated, making it difficult to carry out the calculation with normal computers and obtain a result. Based on the fact
that it is not easy to add excessive firefighting equipment into historical buildings, the
effect of controlling the number of users and the amount of furniture (fire load) is limited.
Therefore, the greatest value of this study lies in (1) using parallel computing to overcome
the computational challenge, (2) understanding the fire source (wood material) ignition
loss and whether the fire spreads through settings, in order to analyze the maximum heat
release rate and the scale of the fire, and (3) formulating the most appropriate improvement
plans of use restrictions or hardware protection for historical buildings.

Figure 1. Tamsui Church.

Figure 2. Internal space of the church.
2.2. Individual Bench

The individual bench was graphed based on its actual size on the site. The maximum heat release rate of ignition source burnout was set. Existing data were compared and used as the basic information for determining the heat release rate of the bench. The basic prerequisites and conditions for simulation are shown in Table 1. The individual-bench FDS simulation model is illustrated in Figure 4, and the positions of the measuring points are shown in Figures 5 and 6.
2.3. Multiple Benches

Multiple benches and the intervals between them have been graphed based on their actual state on the site. This simulation focused on the analysis of the possibility of fire spreading from the benches and the magnitude of fire, as well as the measurement of the maximum heat release rate, thereby proposing a limit for the use of the building and measures for improvement. The prerequisites and conditions for the simulation are shown in Table 1. The multiple-bench FDS simulation model is illustrated in Figure 7, and the positions of measuring points are shown in Figures 8 and 9.

1. Temperature: when the temperature at measuring points reaches 260 °C, the wood starts to burn (Babrauskas, 2002) [9].
2. Heat radiation: when the heat radiation at measuring points reaches 10 kW/m², the wood starts to burn (Bartlett et al. 2019) [10].
### Table 1. Description of prerequisites and conditions.

| Item                        | Description                                                                 |
|-----------------------------|-----------------------------------------------------------------------------|
| **Designing of grids**      | **Individual-bench simulation** Dimension of the scope: Length 4 × Width 3 × Height 6 m; grid dimensions: mainly 10 × 10 × 10 cm; the part below the height of 2 m was denser; with grid dimensions of 5 × 5 × 5 cm; total: 240,000 grids |
| **Multiple-bench simulation**| Dimension of the scope: Length 12 × Width 12.2 × Height 6 m; grid dimensions: mainly 20 × 20 × 20 cm; the part below the height of 2 m and close to the igniting benches was denser; with grid dimensions of 5 × 5 × 5 cm; total: 802,800 grids |
| **Boundary condition**      | Initial temperature: 25 °C; relative humidity: 40%; no lateral wind speed was set |
| **Combustion reaction**     | \&REAC ID = ‘WOOD_PINE’, FYI = ‘SFPE Handbook, 3rd Ed’, FUEL = ‘REAC_FUEL’, C = 1.0, H = 1.7, O = 0.83, CO_YIELD = 5 × 10 −3 / RADIATIVE_FRACTION = 0.35 / |
| **Setting of ignition source** | Oil pan (size: 0.1 × 0.1 m) ignited and started to burn. The unit area heat release rate was 907.25 kW, and the fire reached its peak 75 s after ignition. The time length of simulation was 3600 s. \&SURF ID = ‘burner’, COLOR = ‘RED’, HRRPUA = 907.25, TMP_FRONT = 300.0 / |
| **Setting of fire spreading to combustibles** | Yellow Pine was set as the structural material of the benches in the church case, and the ignition temperature was set as 260 °C. \&MATL ID = ‘YELLOW PINE01’, FYI = ‘Quintiere, Fire Behavior–NIST NRC Validation’, SPECIFIC_HEAT = 2.85, CONDUCTIVITY = 0.14, DENSITY = 640.0, \&SURF ID = ‘ BENCH ’, HRRPUA = 2500.0, TAU_Q = −200.0, IGNITION_TEMPERATURE = 260.0, BURN_AWAY = .TRUE., BACKING = ‘VOID’, MATL_ID(1,1) = ‘YELLOW PINE01’, MATL_MASS_FRACTION(1,1) = 1.0, THICKNESS(1) = 0.01. |
| **Temperature measuring points above the origin of fire** | \&DEVC ID = ‘TEMPHIGH6 m’, QUANTITY = ‘TEMPERATURE’ / Four points in total at a height of 6 m and spaced at 40 cm intervals |
| **Temperature measuring points above the benches (X axis)** | \&DEVC ID = ‘TEMPX1’, QUANTITY = ‘TEMPERATURE’ / Six points in total at a height of 60 cm and spaced at 40 cm intervals |
| **Temperature measuring points above the benches (Y axis)** | \&DEVC ID = ‘TEMPY1’, QUANTITY = ‘TEMPERATURE’ / Six points in total at a height of 60 cm and spaced at 40 cm intervals |

Note: Settings for the wood fire to spread.
3. Analysis and Discussion

3.1. Individual-Bench Simulation Result

The time taken for the temperature over the four measuring points at a height of 6.0 m on the ceiling to reach 260 °C, required for the ignition of wood, were as follows
(in chronological sequence): Measuring Point #2 (372.87 s), Measuring Point #1 (375.00 s), Measuring Point #3 (375.89 s) and Measuring Point #4 (376.49 s). Clearly, the times taken to reach wood ignition temperature at the four measuring points were very close. This result suggests that the fire would spread to the wood ceiling 372.87 s (6.21 min) after the bench started to burn. If the interior decoration material is not to be changed, there is a need to install appropriate monitoring devices or suppression devices for early-stage fires. Otherwise, it is worth considering that the material of the ceiling should be changed to improve its fire resistance. The highest temperature, which was about 705.26 °C (right above the origin of fire), was reached at the approximate time of 464.40 s (7.74 min) after the fire began. When looking at the positions of the measuring points, there was clearly a relationship between the measured temperature and the distance from the origin of fire, and the measured temperatures over the measuring points, which were spaced at 40 cm intervals only, were very close. The relationship between the temperatures over measuring points and the times is shown in Table 2.

| No. of Measuring Points | #1        | #2        | #3        | #4        |
|-------------------------|-----------|-----------|-----------|-----------|
| The highest temperature (°C) | 685.49    | 705.26    | 703.25    | 685.66    |
| The time measured (s)   | 453.60    | 464.40    | 460.80    | 453.60    |
| Time to reach 260 °C (s) | 375.00    | 372.87    | 375.89    | 376.49    |

The simulation result for a single seat shows that under the constraint of such space conditions (the height is only 6 m), even if a single seat burns, it will cause the ceiling to reach the ignition temperature of wood, which only takes about 6.21 min to burn. Therefore, fire detection equipment is very important in the initial stage of fire to provide the required early warning. It is also noted that the highest temperature occurred at 7.74 min, indicating that the fire grew extremely fast. For this reason, adding the appropriate active fire-extinguishing equipment for the initial stage of the fire would be necessary to delay the spread of the fire, allowing firefighters to have enough time to put out the fire and carry out the rescue (the time for firefighters in Taiwan to arrive at the scene and begin to carry out rescues is approximately 6 to 8 min after the report).

3.2. Multiple-Bench Simulation Result

The highest temperatures over the four measuring points at a height of 6.0 m on the ceiling all exceeded the ignition temperature for wood (260 °C). The times taken were as follows: Measuring Point #2 (402.88 s), Measuring Point #3 (405.85 s), Measuring Point #1 (406.02 s) and Measuring Point #4 (407.46 s). This shows that the ceiling was about to ignite and burn. The time taken and the highest measured temperatures are shown in Table 3. In addition, the temperatures over benches ahead of and behind, as well as on the left and right of, the ignited benches also reached the ignition temperature for wood (260 °C). The times taken for benches positioned at the front, back, left and right to reach 260 °C were about 478.97 s, 488.10 s, 680.00 s and 687.53 s, respectively (the times taken for the fire to spread towards the benches on the left/right were longer because this was the longer side of the bench). The heat radiation level shows that the time required for the heat radiation to reach 10 kW/m² (necessary for wood ignition) was even shorter in this simulation, as the benches were very close to each other. It was also proven that if the wooden benches were on fire, under their current spatial arrangement, an extensive fire scenario seemed almost unavoidable, and it only took five minutes for the fire to spread around. Therefore, appropriate adjustments of monitoring devices and firefighting equipment for early-stage fires are imperative. Other relevant data are summarized in Table 4, and detailed section views of the bench temperatures are illustrated in Figures 10–12.
Table 3. The greatest temperatures and durations measured at 6.0 m (position on the ceiling) above the multiple benches (origin of fire).

| No. of Measuring Points | #1     | #2     | #3     | #4     |
|-------------------------|--------|--------|--------|--------|
| The highest temperature (°C) | 1016.22 | 999.82 | 1034.37 | 1015.48 |
| The time measured (s)    | 575.00 | 565.00 | 575.00 | 575.00 |
| Time to reach 260 °C (s) | 406.02 | 402.88 | 405.85 | 407.46 |

Table 4. The greatest temperatures and durations measured over the benches in front of and behind, and on the left/right of, the multiple benches (origin of fire).

| Measuring Point Position (Relative to the Origin of Fire) | Front (Y2) | Back (Y5) | Left (X1) | Right (X9) |
|---------------------------------------------------------|------------|-----------|-----------|------------|
| The highest temperature (°C)                           | 1205.66    | 1254.17   | 1308.78   | 1410.59    |
| The time measured (s)                                  | 665.00     | 575.00    | 930.00    | 940.00     |
| Time to reach 260 °C (s)                               | 488.10     | 478.97    | 680.00    | 687.53     |
| Time to reach the thermal radiation level of 10 kW/m² (s) | 328.20     | 369.60    | 513.30    | 499.80     |

Note: The positions of Y2, Y5, X1 and X9 are shown in Figure 9.

Figure 10. Multiple benches on fire simulation: temperature section view of benches in front of and behind the igniting benches (X axis) at the time of 402.88 s.

Figure 11. Multiple benches on fire simulation: temperature section view of benches in front of the igniting benches (Y1 axis) at the time of 405.85 s.
Figure 12. Multiple benches on fire simulation: temperature section view of benches behind the igniting benches (Y2 axis) at the time of 407.46 s.

Compared with the individual-bench model, the highest temperature measured in the multiple-bench model was higher, and the slope of its heating curve was sharper due to the fire spread over the benches (Figure 13). Since it is probably difficult to reduce the number of users and to increase the distance between the benches under the current conditions of use, the provision of appropriate monitoring devices or firefighting equipment for early-stage fires would be a favorable option, to prevent fire accidents from happening in historic buildings. If the current conditions of use are to be maintained, it is most urgent to increase monitoring devices and firefighting equipment for early-stage fires.

Figure 13. Fire Development Curve.

The maximum heat release rate of the multiple benches measured at 2965 s (49.4 min) was 2609.88 kW. The heat release rate by the end of the simulation (3600 s) was 2459.81 kW, showing a drop of 5.8% only. The heat release rate of the multiple benches dropped in a slow manner due to the fire spreading, which would lead to extensive damage to the building.

Based on the simulation of multiple seats, it is noted that the burning spread towards the seats in the front and at the back faster than the spread towards the seats on the left and
right sides. About 8 min after the fire started, the fire spread to the seats in the front and at the back, expanding the scale of the fire. At this time, if firefighters fail to arrive at the scene to control the spread of the fire, the result will be devastating. Eight minutes is about the typical arrival time of firefighters. However, if the road in front of the building is too small for fire trucks to enter, a water source must be direct towards the scene of the fire manually, which will delay the rescue time. Therefore, adding appropriate active fire extinguishing equipment for the initial stage of a fire is essential. Based on the current situation, it is also very difficult to reduce the number of seats and increase the spacing between seats. However, the space in historical buildings is often restricted, and the structure has its limitations, making the installation of regular firefighting equipment difficult and bringing about challenges for the operator regarding how to create balance between the usage and safety of the building.

3.3. Analysis of Fire Magnitude

The previous discussion pointed out that both individual-bench and multiple-bench fires could reach the temperature of 260 °C, the temperature required for the wood ceiling to ignite, and proposed that relevant monitoring devices and firefighting equipment should be appropriately deployed. However, the required size and effective capacity of the equipment depend on the magnitude of the fire. Since historic buildings have their limitations in terms of space, which thus induce significant difficulties in installing equipment pipelines, it is more important to investigate the actual magnitude of fire in advance, which is exactly the purpose of this study. The possible magnitudes of fire based on individual-bench and multiple-bench simulations are explained as follows:

(1) The maximum heat release rate (HRR) of the individual bench was 1159.78 kW, which occurred at 3025 s (50.4 min). This shows that the heat release rate of the benches adopted in this study’s simulations was not as high as the HRR values listed in Table 1, as the benches did not contain other flammable foam materials, even though they were bigger (a 4- to 5-seat width of 240 cm);

(2) The maximum heat release rate of the multiple benches was 2609.88 kW, which occurred at 2965 s (49.4 min), when five benches were on fire at the same time. The maximum heat release rate was about 2.25 times that of an individual bench;

(3) The heat release rates in both simulations started dropping gradually at around 3000 s (about 50 min), yet the decline in the heat release rate of the multiple benches was relatively slow due to the fire spreading over the benches. By the end of the simulations (3600 s), the HRR of the individual bench had dropped to 787.15 kW (showing a decrease of 32.1% compared to the highest value), while the HRR of the multiple benches was 2459.81 kW (showing a decrease of 5.8% compared to the highest value).

By analyzing the simulated fire magnitudes, we see that the magnitude of a real fire occurring in this space would be relatively small, which significantly reduces the required degree of increase in fire monitoring devices and firefighting equipment for early-stage fires. When the bench(es) is (are) on fire, if the monitoring system can detect the location of the origin of fire before 328.2 s (the time at which the fire spreads to the benches 45 cm ahead of the igniting bench(es)), and the notification mechanism can be activated and the fire put out, the likelihood of an extensive fire would be effectively reduced. In events such as fires happening during non-opening hours or at night, electrical fires or arson attacks, the fire could be effectively controlled to substantially reduce the possibility of damage to the historic building.

The results of this study are added to those of the related research, and are summarized in Table 5, serving as the reference for subsequent studies.
Table 5. Heat release rate of chairs according to the related literature.

| NO. | Object                                                                 | Maximum Heat Release Rate (kW) |
|-----|------------------------------------------------------------------------|--------------------------------|
| 1   | Chair, one-piece wood-reinforced urethane foam (Kim and David, 2000)   | 422.50                         |
| 2   | Chair, polypropylene foam frame, urethane foam, polyolefin fabric      | 1960.00                        |
|     | (Kim and David, 2000)                                                 |                                |
| 3   | Chair, thin wood frame, California foam, polyolefin fabric (Kim and     | 765.63                         |
|     | David, 2000)                                                          |                                |
| 4   | Chair, F23, wood frame, fr cotton batting, olefin (Kim and David, 2000)| 699.64                         |
|     |                                                                        |                                |
| 5   | Sofa, wood frame, California foam, polyolefin fabric (Kim and David, 2000) | 2890.00                        |
| 6   | A chair made mainly of wood (Ahonen et al., 1984)                      | 160.00                         |
| 7   | A wood-framed armchair manufactured by Shelby-Williams Inc. with       | 1114.00                        |
|     | polyurethane foam covered with 100% olefin fabric (Cleary et al., 1994)|                                |
| 8   | A wood-framed armchair with auditorium polyurethane foam covered with  | 718.00                         |
|     | 100% wool fabric (Denize, 2000)                                         |                                |
| 9   | A wood-framed armchair with generic polyurethane foam covered with     | 1306.00                        |
|     | 100% polypropylene fabric. Interliner present. (Enright, 1999)         |                                |
| 10  | A wood-framed, straight-back, open-leg designed chair with standard     | 1194.00                        |
|     | polyurethane foam covered with a 100% polypropylene fabric (Hill, 2003)|                                |
| 11  | A wood-framed armchair with TB117 polyurethane foam covered by 100%    | 1150.00                        |
|     | wool fabric (Ohlemiller and Villa, 1990)                               |                                |
| 12  | The chair is wood-framed with polyether foam covered with 100% FR      | 596.00                         |
|     | cotton fabric (Sundstrom, 1993)                                         |                                |
| 13  | Constructed with a wooden frame and a seat cushion of solid polyurethane foam. Shredded polyurethane foam was used in the back cushion. The fabric cover was made from cotton. (Lawson et al., 1984) | 210.00                         |
| 14  | A wood-framed upholstered chair composed primarily of polyester fiber and polyurethane foam. Included in the test were two (2) pillows composed of polyester fiber and covered by a cotton/polyester blend fabric. (Stroup et al., 2001) | 2600.00                        |
| 15  | A wood-framed three-seated sofa with polyether foam covered with 100%  | 2331.80                        |
|     | polyester fabric (SP, 2004)                                            |                                |
| 16  | Individual bench (YELLOW PINE) (Results of this research)              | 1159.78                        |

3.4. Suggestions for Space Improvement

This study is aimed at facilitating the sustainable use and permanent preservation of historic buildings. The onsite survey data showed that the ceiling of the target building of this study was made of wood with a height of 6 m. The seats/benches inside the building were all made of wood as well, and the left/right distances between benches were relatively small (about 65 cm). There were only fire extinguishers in the building, and no other active firefighting facilities or other fire protection equipment, which manifested the concern about the current usage of the building. In order to ensure that this historic building can
be continuously used under safe conditions, the suggestions for space improvement are as follows:

(1) Suggestions for short-term goals—the wooden benches can be replaced by benches made of fire-retardant or non-flammable materials to reduce the incidence of fires, and the distances between benches can be appropriately increased.

(2) Suggestions for medium-term goals—With the aim of effectively detecting fires and carrying out early-stage firefighting, it is necessary to install smoke detection devices and water mist systems. Water mist systems can be as effective as traditional sprinkler systems, but use only 10–50% of the water volume of the traditional systems (Ko et al., 2020) [22], which is especially suitable for such spaces.

(3) Suggestions for long-term goals—change the material of the ceiling into non-flammable material to avoid the complete burning of the ceiling and the destruction of the building.

In view of the irreplaceability of historic buildings, no fire accidents should be allowed to happen in such buildings. Thus, the above-mentioned improvement suggestions can serve as a reference basis to gradually upgrade the material or equipment year by year, without being impeded by the costs. However, before the improvement projects are implemented, the management should be strengthened, regular safety inspections for power system pipelines should be carried out, the locations and expiration dates of fire extinguishers should be confirmed, and regular disaster prevention and rescue drills should be conducted.

4. Conclusions

Tangible cultural heritage is a crystallization of human wisdom. In the context of its use and preservation, avoiding fire hazards to maintain the buildings’ historical significance and value has always been the focus of all countries’ efforts. Based on the protection of cultural heritage and the importance of sustainability, this study takes the historic building “Tamsui Church” as an example to analyze the magnitude through an FDS model, wherein fires began with the ignition of wooden benches in the church, leading to the proposal of improvement strategies to ensure that the cultural heritage can be continuously used under safe conditions. The conclusions are as follows below.

4.1. Results of Fire Simulation

By setting burnout states in the FDS fire simulations, we acquired the following information on heat release rate, temperature, judgement of fire spreading, etc.:

(1) The maximum heat release rate of the individual wooden bench was 1159.78 kW. Its burnout started at 3025 s (50.4 min), and then its heat release rate gradually dropped to 787.15 kW;

(2) The temperature measured on the ceiling reached 260°C, required for the ignition of wood, when the individual bench had been on fire for 372.87 s (6.21 min);

(3) The temperature measured on the ceiling reached 260°C when the multiple benches had been on fire for 402.88 s (6.71 min);

(4) The fire started spreading towards the benches 45 cm ahead of the igniting bench(es) 328.20 s (5.47 min) after the ignition started. The fire started spreading towards the benches 45 cm behind the igniting bench(es) at 369.6 s (6.16 min). The fire started spreading towards the benches 60 cm away on the right at 499.80 s (8.33 min), and it started spreading towards the benches 90 cm away on the left at 513.3 s (8.56 min);

(5) The heat release rate grew with the increasing number of burning benches, and it reached its peak of 2609.88 kW at 2965 s (49.4 min).

The size of the fire is an important topic of this study. Only by accurately estimating the size of the fire source can we propose appropriate and feasible improvement plans. Applying theories to reality can better demonstrate the value of this study. In particular, historical buildings are often limited by space and structure. The addition of any kind of equipment is not an easy task. Previous studies on fire simulation have mainly focused on
the investigation of newly constructed buildings, and no studies on historical buildings have been carried out, which further demonstrates the importance of this study and its results.

4.2. Follow-Up Management and Improvement Strategies

Based on the data concerning the magnitude of fire and the possibility of the fire spreading, as obtained from the fire simulations, the required improvement measures are explained as follows:

(1) It is necessary to conduct regular pipelines safety inspections, confirm the locations and expiration dates of fire extinguishers, and carry out disaster prevention/rescue drills on a regular basis before the improvement measures are implemented;

(2) Currently, the distance between rows of benches is only 45 cm, which would contribute to the spread of fire at 328.2 s (5.47 min). In order to prevent the fire from rapidly expanding, it is suggested that the distance between rows of benches be appropriately increased;

(3) In terms of short-term goals, it is suggested that the wooden benches could be replaced by benches made of fire-retardant materials or non-flammable materials, so as to reduce the incidence of fires;

(4) As regards medium-term goals, it is suggested that smoke detectors and water mist systems be installed;

(5) With respect to long-term goals, it is suggested that the material of the ceiling be changed to a non-flammable material, so as to avoid the complete burning of the ceiling.

Being limited by their structural and spatial characteristics, historic buildings often fail to comply with regulations put in place to comprehensively improve their fire protection equipment and features. However, the usage of these buildings should still be maintained, so that their historical significance is protected and the sustainability of tangible cultural heritage can be ensured. With the advancement of fire dynamics, the magnitudes of possible fires can be explored through simulation models, and appropriate improvement measures can be implemented without destroying the original spatial characteristics, which thus achieves the goals of continuous usage and safety, by which the architecture and its culture can be sustainably preserved.

Historical buildings go through processes such as preservation, restoration, reuse, etc., after years of use. Each building has its own usage characteristics, and the environment around each building is also different. Based on the results of this study, two directions are proposed for subsequent studies. (1) It is feasible to investigate the scale of a real fire through simulation, and each case can be simulated depending on the actual condition. (2) In addition to adding a water mist system to the fire protection plan for the initial stage of a fire, other strategies worthy of in-depth discussion should also be considered in future studies.

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