Case Studies in Fire Safety 2 (2014) 9–15

Contents lists available at ScienceDirect

Case Studies in Fire Safety

journal homepage: www.elsevier.com/locate/csfs

Assessment of fire protection systems in proscenium theaters

Jaewook Kwon *

Ove Arup & Partners PC, New York, United States

ARTICLE INFO

Article history:
Received 29 October 2013
Received in revised form 30 June 2014
Accepted 1 July 2014
Available online 22 July 2014

Keywords:
Fire safety
Theater
CFD
Active fire protection systems

ABSTRACT

Stage fire protection measures, details differing from one region to another, have been established, codified and enforced throughout the world and have changed little over the past 100 years. Technological advancements in both stagecraft and fire protection systems have led to a need in the theater community to study the current state of theater fire protection requirements. The objective of the study was to assess the level of protection afforded by stage active fire protection measures, as prescribed by the International Building Code (IBC) (2009), NFPA 80 Standard for Fire Doors and Other Opening Protectives (2007) and as implemented in current design practice, in the event of a fire in the stagehouse of a proscenium theater. The study presented herein assesses the effectiveness of each of the fire protection systems required by building codes for proscenium type theaters. The egress study is not part of this study and thus not specifically carried out.

Computational fluid dynamics (CFD) has been utilized to examine fire conditions and to assess the effectiveness of the fire protection systems provided within a stage. The input data including representative theater dimensions, fuel loads, and fire scenarios have been determined by a survey of theater design professionals.

Introduction

Stage fire protection measures, details differing from one region to another, have been established, codified and enforced throughout the world and have changed little over the past 100 years. Technological advancements in both stagecraft and fire protection systems have led to a need in the theater community to study the current state of theater fire protection requirements. The objective of the study was to assess the level of protection afforded by stage active fire protection measures, as prescribed by the International Building Code (IBC) [1], NFPA 80 *Standard for Fire Doors and Other Opening Protectives* [2] and as implemented in current design practice, in the event of a fire in the stagehouse of a proscenium theater. This study consists of two parts. Part I identified (1) the magnitude of fire necessary to activate the automatic fire protection systems including rate-of-rise heat detectors, sprinklers, fire curtain, and roof vents and (2) the activation order of the fire protection systems, which was published through the Fire Protection Research Foundation (FPRF) [3]. Part II presented herein assesses the effectiveness of each of the fire protection systems required by building codes for proscenium type theaters. It is noted that although an egress analysis is not part of this study, it could be part of a fire engineering analysis for any new theater design in order to compare Available Safety Egress Time (ASET) to Required Safety Egress Time (RSET).

Computational fluid dynamics (CFD) has been utilized to examine fire conditions and to assess the effectiveness of the fire protection systems provided within a stage. The input data including representative theater dimensions, fuel loads, and fire scenarios have been determined by a survey of theater design professionals.

* Address: 77 Water St., NY 10005, United States. Tel.: +1 212 896 3263.
E-mail address: jaewook.kwon@arup.com

http://dx.doi.org/10.1016/j.csfs.2014.07.001
2214-398X/© 2014 The Author. Published by Elsevier Ltd.

The Fire Research Division at the National Institute of Standards and Technology (NIST) has been developing the CFD model, Fire Dynamic Simulator (FDS) [4] that has been optimized for use in simulating the effects of fire. FDS solves numerically a form of the Navier–Stokes equations for low speed, thermally driven flows. FDS V5.2.4 was utilized for this study.

Prescriptive code requirements

The following highlights the requirements in the International Building Code with regard to stage protection and stage ventilation as it is of primary concern to this study. The IBC is the most frequently referenced source for local municipality building codes in the U.S.

Proscenium wall opening protection

The requirements with regard to proscenium wall openings for stages with a height greater than 15.24 m are as follows:

- A fire curtain or water curtain is to be provided to contain smoke/fire within the stage. The fire curtain is required to be designed and installed to prevent a glow from a fire being visible to the audience.
- The curtain is required to be activated by rate-of-rise heat detectors operating at a temperature rise of 9–11 °C per minute and by manual operation.
- The curtain is to close the proscenium opening completely within 30 s from the operation of the release mechanism.
- Smoke developed rating for a fire curtain is to be 25 or less in accordance with ASTM E84 [5].
- No smoke and fire is to be spread through the curtain for 30 min tested in accordance with ASTM E119 [6].

Sprinklers

Sprinklers are required to be provided under a roof and a gridiron. If catwalks and galleries over the stage are more than 1.2 m in width, the sprinklers must be provided under all catwalks and galleries over the stage. It is noted that these requirements are not required for the stages in which the stage area is 93 m^2 or less, the stage height is 15.24 m or less, and curtains, scenery, or other combustible hangings are not retractable vertically.

Stage ventilation

The requirements with regard to stage ventilation for stages greater than 15.24 m in height or larger in area than 93 m^2 are as follows:

Natural means of exhaust

- Two or more roof vents are required to be provided;
- Aggregate clear area of the openings is to be no less than 5% of the stage area;
- Vents are required to be located near the center and above the highest part of the stage area;
- The vents are to be activated by heat-activated devices and by manual means.

Or,

Mechanical means of exhaust

- A mechanical exhaust system is to be activated by the operation of sprinkler system protecting the stage and manual means that are readily accessible to the fire department.
- A smoke layer must be maintained at greater than 1.83 m above the highest level of the seating or maintained above the top of the proscenium opening.

Fire modeling input

Geometry

It was decided that the models would need to be representative of theaters being built today, with currently mandated code requirements as the goal was to look at the performance of modern, current fire protection systems. For quality and relevant data, the assistance was provided from both American Society of Theater Consultants (ESTA) members and the theater consulting community through an online survey which gathered dimensional criteria for three theater models – small, medium and large – which is summarized in the table below. Thirty five responses were returned, the results compiled and averaged, and the data turned into plans and sections. Based on these, the geometry of the CFD models was built.

Dimension	Small	Medium	Large
Proscenium height [m]	5.56	6.25	11.27
Proscenium width [m]	10.66	12.34	15.24
Stage width [m]	19.35	20.75	34.52
Stage depth [m]	8.68	11.88	14.70
Rigging height [m]	12.65	18.05	29.26
Grid height [m]	n/a	15.92	27.12
Flytower height [m]	13.03	19.27	30.48
Auditorium width [m]	18.67	21.49	30.17
Auditorium depth [m]	20.11	29.41	38.17
Seat count [seats]	420	780	1950

And then the survey asked respondents to rank the most likely location for the fire and materials involved in the conflagration, based on each individual's experience or knowledge. Several Technical Directors around the U.S. offered material lists from recent shows in their proscenium theaters. Rationalizing the responses, three locations for the fire were proposed: (1) center stage at floor level, (2) center stage approximately 7.6 m above the stage involving flown scenery, and (3) in the stage wings at stage level. Based on the survey results, it was determined that of the common materials on stage including muslin, wood, plywood, vinyl, medium-density-fiberboard (MDF), masonite, (cardboard) sonotubes, velour and wool draperies etc., a 75% to 25% mass weighted mixture of natural and synthetic materials respectively, was appropriate and representative of sensible "scenery stuff", which was used for the fuel properties in the CFD models. These average values are as follows:

- Heat of Combustion (ΔHc): 15,630 [kJ/kg]
- Soot yield: 0.0356 [kg/kg]
- Carbon monoxide yield: 0.021 [kg/kg]
- Radiative fraction: 0.35 []

Grid resolution

Prior to modeling, a calibration study was done to determine the optimal cell size and approximate calculation accuracy. A series of models were set up to recreate the results from set of fire tests that were conducted previously by Underwriters Laboratories on the interaction of sprinklers, smoke vents and draft curtains [6]. From the grid resolution study, a 0.2 m grid size was selected, and its percentage error in predicting first sprinkler activation time was approximately 5%. According to available information, the fire safety curtain will not block airflow between the auditorium and the stage completely. To resolve the flows around the fire safety curtain at the top and the sides within the smoke pocket, 0.025 m $\times$ 0.05 m grid cells

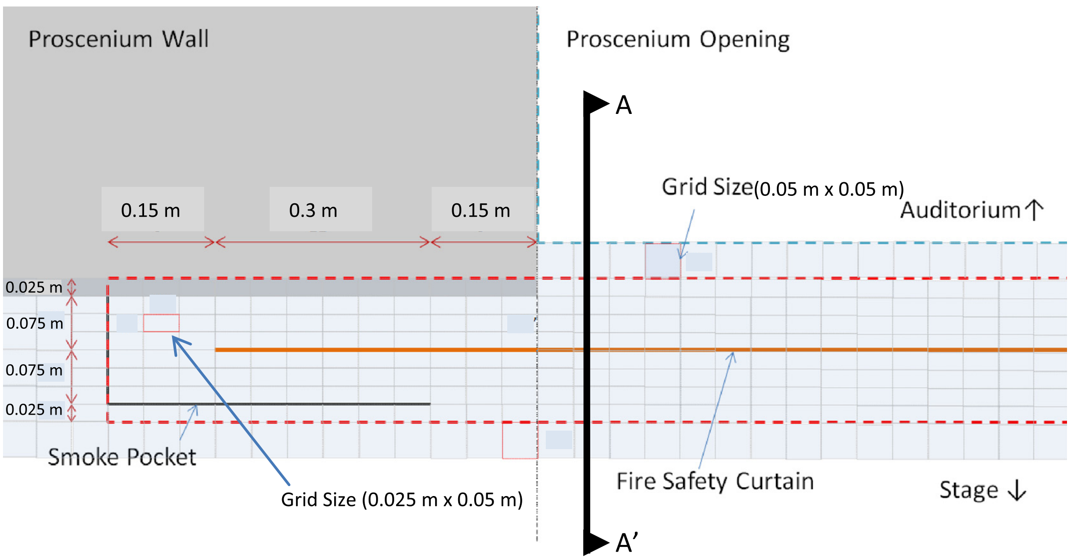

Fig. 1. Illustration of the implementation of a fire safety curtain in the model (plan view).

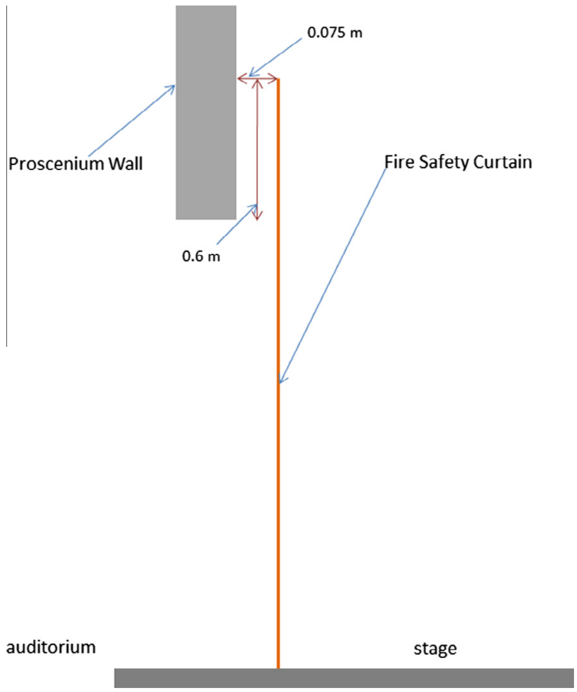

Fig. 2. Cross sectional view of a fire safety curtain (A–A′ shown in Fig. 1) after a completion of deployment.

have been utilized for the areas of the curtain assembly. A 0.075 m gap along the top of the fire safety curtain was assumed (see Figs. 1 and 2).

Fire scenarios

Two fire locations have been determined to examine the sensitivity of the fire safety measures effectiveness to variations in fire size and/or location: (1) a fire occurring in the center of the stage, and (2) a rigging fire originating in the flown scenery above the stage. Two fire locations was selected based on information gathered in the survey of theater industry professionals and the results from the Part I study [3]. From a risk perspective, the two scenarios could be considered to be the higher magnitude or impact event (center stage fire) and the most probable or frequent type of event (rigging fire).

In addition to the location of the fires, the models were parameterized to explore relative impact of each of the provided stage fire safety measures. The baseline performance of the required systems is established in models that assume all fire safety measures operate and/or deploy as intended by design. Subsequent models consider the omission or failure to activate or deploy of each fire safety measure independently. The approach allows positive contributions of each measure to be qualified for ranking purposes in achieving fire and life safety goals.

- **Scenario 1** assumes all automatic fire safety measures – sprinklers, fire safety curtain, and stage roof vents – are functional and operate when predicted to do so. Stage vents open upon actuation of fusible links located directly below the vents. Fire growth is halted upon sprinkler actuation and maintained constant in magnitude henceforth.
- **Scenario 2** assumes all automatic fire safety measures, except for the fire safety curtain, are functional and operate when predicted. Stage vents open upon actuation of fusible links located directly below the vent. Fire growth is halted upon sprinkler actuation and maintained constant in magnitude henceforth.
- **Scenario 3** assumes all automatic fire safety measures, except for the roof vents, are functional and operate when predicted to do so. Fire growth is halted upon sprinkler actuation and maintained constant in magnitude henceforth.
- **Scenario 4** assumes all automatic fire safety measures, except for the sprinklers, are functional and operate when predicted to do so. Stage vents open upon actuation of fusible links located directly below the vents. Fire growth continues unabated at the assumed fast growth rate throughout duration of the simulation of 600 s (approximately 16.9 MW at 600 s).
- **Scenario 5** assumes all automatic fire safety measures are functional and operate when predicted to do so. Stage vents are opened by means of rate-of-rise heat detectors in lieu of fusible links. Fire growth is halted upon sprinkler actuation and maintained constant in magnitude henceforth.

Table 1
Material thermal properties used in model.

Item	Concrete [7]	Yellow pine [8]
Specific heat (kJ/kg/K)	1.04	2.85
Conductivity (W/m/K)	1.80	0.14
Density (kg/m^3)	2280	640

A total of 27 simulations were completed as part of this study. With limited exceptions, each of the aforementioned scenarios for the two selected fire locations were simulated within each of three theater sizes; designated small, medium, and large. It was found during Part I of this study that detection times of center stage fires within the "large" theater were in excess of the total simulation time of 600 s. Accordingly, no additional center fire scenarios were simulated within the large theater during the Part II study.

Growing fire model

A stage typically contains a considerable amount of fuel, but a fuel load and fuel arrangements vary from one theater to another and/or from one production to another, which made difficult to generalize a fire curve. It was therefore assumed that the heat release rate follows a fast *t*-squared growth curve and assumed that a fire growth is halted at the time of sprinkler activation and a constant heat release rate is maintained thereafter.

The fire area is modeled to increase incrementally as the heat release rate increases in magnitude until the sprinklers activate. This technique is applied differently to each of the fire locations as the relevant geometry to each scenario is unique [3].

Thermal boundary conditions

For conductive heat transfer calculations, the material properties of concrete were assigned to the ceilings, walls, and floors and yellow pine for the scenery. The material properties for each material are shown in Table 1.

Instrumentation

A series of "sensors" measuring temperatures and velocities were placed in each model to represent sprinklers, heat detectors and fusible links that are required by the code. This allows each measurement point to be analyzed as a fusible link, a heat detector, or a sprinkler, thereby providing the following benefits:

- The response times with the various parameter values such as RTI, conductive loss factor, and activation temperature can be obtained without inserting duplicate sprinkler/heat detector devices at each location.
- Other device response times that are not incorporated in FDS (i.e., rate-of-rise heat detectors) can be estimated.

Sprinklers were located at grid level and ceiling level with an activation temperature of 74 °C in accordance with NFPA 13 [9]. Rate of rise detectors were located (1) on the proscenium wall above the proscenium opening, 0.15 m below the ceiling (usual practice in the U.S.) and (2) on the ceiling just upstage of the proscenium opening. "Fusible links" were located every 3 m along the safety curtain release line at a slightly higher resolution than that required by NFPA 80 (one every 4.5 m) and at the hatches for roof venting.

The results

The key results of Part II are provided below. It is noted that the following results are based on the scenarios and inputs considered herein.

- The visibility contours from the vent failure model and the sprinkler failure model are shown in Figs. 3 and 4. This show the operation of the roof vents is most critical in providing a safe environment in the auditorium for egress of the theater occupants/patrons.
- Fig. 4 shows that a fire safety curtain alone is inadequate to stop smoke from spreading to the auditorium completely, although the fire curtain restricts air movement reducing the rate of smoke spread to the auditorium.
- The fire safety curtain and roof vents are fire and life safety systems that are intended to work in tandem. Alternate strategies that employ only ventilation or stage exhaust in lieu of a fire safety curtain require a thorough analysis to be completed to establish acceptable fuel loads and fire sizes. Such an approach would also likely call for a detailed fuel management program that might in turn reduce the flexibility in theatrical use of the space. As scenic elements/arrangements are changed, such spaces should require special analysis for each production as to whether the modified arrangement would produce smoke/fire exceeding the capacity of a smoke control system provided.

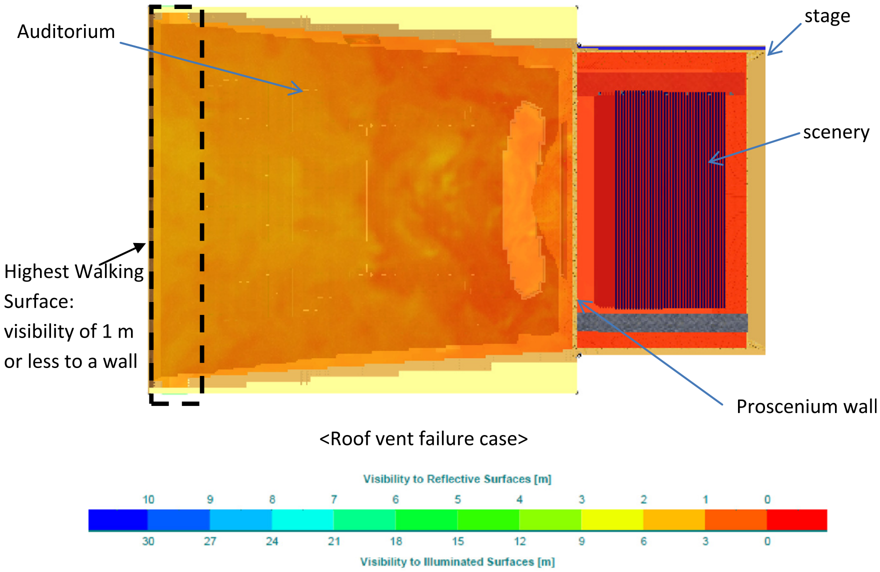

Fig. 3. Visibility contour in the case of the roof vent failure taken 1.8 m above the highest walking surface in the auditorium at 600 s (center stage fire – medium theater).

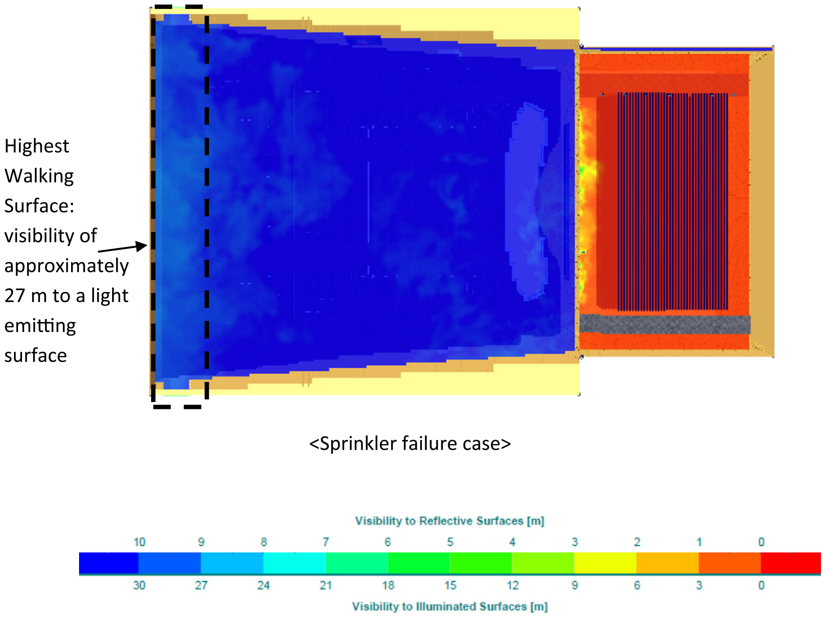

Fig. 4. Visibility contour in the case of the sprinkler failure taken 1.8 m above the highest walking surface in the auditorium at 600 s (center stage fire – medium theater).

- As can be seen in Fig. 4, delayed activation of sprinklers and even failure of sprinklers to operate can be tolerated in terms of a life safety provided the fire safety curtain and/or roof vents are designed properly and actuated rapidly to preclude smoke spread to the auditorium.
- Activation of the roof vents and the fire curtain by rate-of-rise heat detectors provides the most rapid means for system deployment (notwithstanding manual operation) thereby increasing the likelihood of maintaining a tenable environment within the auditorium regardless of the presence or successful operation of sprinklers.
- The results show that the late activation of the roof vents may result in unsafe conditions for egress in the auditorium. This indicates that the roof vents need to be activated as early as possible by the rate-of-rise heat detectors and/or by a means of manual activation.

- It was observed that opening of the stage roof vents by means of rate-of-rise heat detectors precede the activation of sprinkler, while sprinkler activation precedes roof vent activation by fusible link due to its mass of thermal element.
- While the activation of sprinklers seem less critical compared to the effective operation of the roof vents and fire safety curtain for the maintenance of a tenable environment within the auditorium, sprinklers are key to limiting the ultimate magnitude of the fire, protecting the integrity of the structure, and limiting property damage and losses.
- During the simulated time, no automatic means of fire protection systems were activated in the fire occurred in the center of a stage in the large-sized theater, indicating human intervention and manual activation of stage fire safety systems become increasingly important as the size of the theater increases. Theaters falling into the "large" classification require special consideration because of the potential delays in system activation owing to the height of the stage.
- The sprinkler activation times were not much sensitive to the scenarios modeled in this study, except for Scenario 5. The sprinkler activation in Scenario 5 was generally delayed (30–60% more in the activation time). It is deemed that the early activation of all smoke vents by rate-of-rise heat detectors played a role in this. The values in the table below are based on the results from Scenario 1 through Scenario 4.

Fire location	On the center of a stage			In flown scenery		
Theater size	Small	Medium	Large*	Small	Medium	Large
Fire size at the sprinkler activation (MW)	~2	~5.6	N/A	~0.8	~2.4	2.8

*Not activated due to a high flytower height and a plume disruption by scenery above a fire.

- Rate of rise heat detectors on ceiling activates quicker than those on proscenium wall. Based on this result, NFPA 80 2013 edition specifically states that rate of rise heat detectors are to be located at the ceiling.

Acknowledgement

This research was funded and supported by Ove Arup & Partners PC.

References

[1] International Building Code, International Code Council. USA; 2009.
[2] NFPA 80 standard for fire doors and other opening protectives. USA; 2007.
[3] Ove Arup & Partners PC. Fire safety in theatres – a new design approach. MA, USA: The Fire Protection Research Foundation; 2009.
[4] McGrattan K et al. FDS V. 5 technical reference guide, NIST special publication 1018–5. USA: National Institute Standards and Technology; 2007.
[5] ASTM E-84, Standard test method for surface burning characteristics of building materials, USA, 2007.
[6] ASTM E-119. Standard test methods for fire tests of building construction and materials. USA; 2007.
[7] Peacock RD et al. Experimental data set for the accuracy assessment of room fire models. Maryland: NBSIR 88–3752, National Bureau of Standards; 1988.
[8] Drysdale D. An introduction to fire dynamics. 2nd ed. England: John Wiley & Sons Ltd; 2002.
[9] NFPA 13 Standard for the Installation of Sprinkler Systems; 2007.