Developing a Fire Test Strategy for Storage Protection Under Sloped Ceilings

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Abstract

Protecting storage under sloped ceilings requires special consideration. This work describes Phase 2 of a project to develop sprinkler installation guidance for storage protection under sloped ceilings. Results of numerical simulations of sprinkler activation for sloped ceilings with obstructed ceiling construction and ridges are presented, along with spray simulations for sprinklers commonly used for storage protection. The findings are used to develop a test plan for future large-scale fire suppression tests. The goal of these tests is to develop sprinkler installation guidance for storage protection.

Keywords: Sloped Ceiling, Sprinkler, Suppression

Introduction

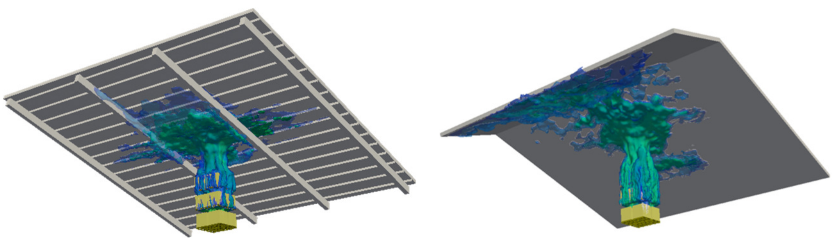
A sloped ceiling can change smoke transport dynamics from those expected under horizontal ceilings, and modify sprinkler activation time behavior. Further, sloped ceilings often have unique features such as obstructed ceiling construction (e.g. purlins, girders, etc.) and ridges that may affect sprinkler performance, particularly sprinkler activation. Currently, a knowledge gap exists in understanding the impact of these construction details on fire suppression performance. This is reflected in the limited guidance on sprinkler design under sloped ceilings included in sprinkler installation standards [1-3]. In fact, large-scale suppression tests with sloped ceilings are not readily available [4], and only a few experimental small- and intermediate-scale studies have been published [5,6]. The necessary empirical evidence needed to develop suppression system design guidance presently does not exist.

A Fire Protection Research Foundation project entitled 'Protection of Storage Under Sloped Ceilings' was initiated to address this knowledge gap in support of the development of new sprinkler installation guidance. In Phase 1 of the project, a review of storage configurations was conducted via a survey to understand design and installation details [7].

Numerical simulations of the effects of ceiling slope on suppression performance were also performed in Phase 1 using the computational fluid dynamics (CFD) code FireFOAM [8]. The modeling examined sprinkler activation times for smooth ceilings inclined up to 33.7° (a slope of 8 in 12). The spray simulations examined the effects of ceiling slope and deflector orientation on sprays from a pendent K200 $lpm/bar^{0.5}$ (K14.0 $gpm/psi^{0.5}$) sprinkler.

In Phase 1, a range of factors for storage protection were identified. Five of these factors were selected for parametric exploration in Phase 2: (1) Ceiling Slope, (2) Ceiling Construction Details, (3) Sprinkler Spray Pattern, (4) Sprinkler Orientation, and (5) Sprinkler Stand-Off Distance. A full factorial exploration of these five factors would be vast; being neither feasible for large-scale fire testing nor for numerical simulations.

Instead, the approach taken in Phase 2 [9] was to define a baseline set of parameters to serve as a basis of comparison for parametric variations using FireFOAM simulations, with the goal of identifying suitable full-scale fire test configurations. Highlights from the Phase 2 numerical simulations are presented in support of large-scale fire test recommendations. Example simulation configurations are provided in Fig. 1.



(a) (b)

Fig. 1. FireFOAM simulations of ceiling interactions for an inclined ceiling (a) with purlins and girders; and (b) with a ridge [9].

Approach

In the Phase 2 effort [9], the baseline case for FireFOAM numerical modeling used a smooth, full-slope, unobstructed ceiling construction (i.e. no ridges, purlins, or girders) with a slope of 18.4° (4 in 12). The baseline commodity configuration included a 2 x 2 x 3-tier FM Global Cartoned Unexpanded Plastic (CUP) commodity with a 3.05 m (10 ft) clearance between the top of the commodity and the ceiling. The baseline sprinkler was a pendant, K200 $lpm/bar^{0.5}$ (K14.2 $gpm/psi^{0.5}$) storage sprinkler operating at 3.5 bar (50 psi). The baseline sprinkler sensitivity was a quick-response, ordinary temperature (74 °C (165 °F)) sprinkler providing a lower bound for sprinkler activation time.

The sprinkler deflector was in the parallel-to-floor orientation in the baseline case, at a distance of 0.3 m (13 in.) from the ceiling.

The numerical simulations evaluated the sprinkler activation times and sprinkler spray fluxes for the following installation details: (1) ceiling slope, (2) structural characteristics such as ridges, purlins, and girders, (3) sprinkler type, and (4) deflector parallel-to-floor and parallel-to-ceiling configurations. The effect of standoff distance on the sprinkler spray was examined in a series of laboratory tests. Results from these tests will be reported separately.

Simulations of sprinkler activation were performed using ceiling jets resulting from a growing fire on a 3-tier high rack-storage array of FM Global Cartoned Unexpanded Plastic (CUP) commodity. Ceiling clearances of 3.05 m (10 ft) and 6.1 m (20 ft) were considered, with ceiling inclinations between 0° and 18.4°. Obstructed ceiling construction in the form of purlins and girders were included in the simulations, with purlin depths of 0.1-0.6 m (4-24 in.) and a girder depth of 0.6 m (24 in.). Purlins and girders were separated by distances of 1.5 m (5 ft) and 7.6 m (25 ft), respectively. An example of obstructed ceiling construction is shown in Fig. 1(a).

Sprinkler activation simulations were also conducted with a ceiling containing a symmetrical ridge. The distance between the center of the commodity and the ridge was either 6.1 or 12.2 m (20 or 40 ft), measured along the slope of the ceiling. These distances were chosen to provide different levels of remoteness between the commodity and the ridge, and were based on two to four times the linear sprinkler spacing of 3.05 m (10 ft).

Numerical simulations also examined the effect of ceiling slope and deflector orientation on water distribution above the rack-storage array for sprays originating from upright K160 $lpm/bar^{0.5}$ (K11.2 $gpm/psi^{0.5}$) and pendent K240 $lpm/bar^{0.5}$ (K16.8 $gpm/psi^{0.5}$) sprinklers. The water-flux distribution reaching the top of the rack-storage array was simulated for the ignition location under one sprinkler as well as among four sprinklers.

Results

Results from the Phase 2 numerical simulations [9] are presented to support recommendations for large-scale fire suppression tests. The modeling work was divided into two parts: (1) a sprinkler activation study, and (2) a sprinkler spray investigation.

Sprinkler Activation

Ceiling inclination causes biased flow towards the elevated side of the ceiling due to buoyancy. However, the presence of purlins, shown in Fig. 1(a), tends to provide confinement of the combustion products.

Results show that increasing purlin depth for a given ceiling inclination generally causes greater skewness of the activation pattern in the direction of the purlin channels.

For the numerical simulations of sprinkler activation, the four sprinklers immediately adjacent to the fire source were the primary focus of the analysis. The activation times of these sprinklers are expected to be a good indicator of relative fire suppression performance among the configurations considered. For quick-response, ordinary temperature (QR/OT) sprinklers with horizontal ceilings (0°) and purlin depths of up to 0.6 m (24 in.), a marginal increase (maximum 4 s) in the average activation time was observed. For ceilings inclined at 9.5° and purlin depths of up to 0.3 m (12 in.), the average activation times are similar to those for horizontal ceilings for the same purlin depths. Considerable delays in sprinkler activation time, which may adversely impact suppression performance, were observed on the non-elevated side of the 9.5° ceiling with purlin depths of 0.6 m (24 in.). The average activation time of the four sprinklers immediately adjacent to the fire source for a ceiling inclination of 18.4° and purlin depths of up to 0.1 m (4 in.) compares favorably with the smooth ceiling results. For purlin depths of 0.2 m (8 in.) and larger, considerable delays in non-elevated sprinkler activations were observed.

The presence of a ceiling ridge, as shown in Fig. 1(b), did not affect the initial ceiling jet development. However, for a ceiling with a ridge located 6.1 m (20 ft) away, the ceiling jet extended past the ridge, down the slope of the ceiling on the far side of the ridge, and combustion products accumulated at the ridge after 80 s. With the ceiling ridge located farther away, this same behavior was not observed and the ceiling jet developed similar to a smooth ceiling with no ceiling ridge.

The presence of ridges marginally affected the activation times of the four QR/OT sprinklers surrounding the ignition location. Activations near the ridge were also affected with slightly earlier activation times observed on the near side of the ridge, with the ridge located 6.1 m (20 ft) away. The effect of the ceiling ridge on the sprinkler activation patterns was more significant for standard-response/ high-temperature (SR/HT) sprinklers where significantly more SR/HT sprinklers activated near the ridge compared to a ceiling with a ridge located 6.1 m (20 ft) away.

Sprinkler Sprays

Sprinkler sprays from upright K160 and pendent K240 sprinklers were simulated in Phase 2 with and without fire plumes present using two configurations: (1) a single sprinkler located above the ignition location, (2) ignition among four sprinklers. For the single sprinkler configuration without a fire plume, a slight decrease in the water flux to the top of the rack-storage array was observed as the ceiling inclination increased from 0° to 18.4° for both the sprinklers considered, and the deflector orientation was shown to have a negligible effect on the water-flux distribution.

With a 600 kW fire directly under a single sprinkler, the water-flux distribution reduced significantly above the ignition location when the deflector was kept parallel-to-ceiling. For ignition among four sprinklers with a 2.6 MW fire plume, a different behavior was observed for the two sprinklers considered. The spray from the upright K160 sprinkler remained similar, irrespective of the deflector orientation, while there was a small decrease in mass flow rate for the pendent K240 sprinkler with the deflector in the parallel-to-ceiling orientation. Results of the Phase 2 spray simulations confirm the Phase 1 conclusions that the sprinkler deflector parallel-to-floor orientation is preferable for spray delivery.

Test Recommendations

Based on the analysis conducted in Phases 1 and 2, a series of large-scale fire suppression tests is proposed to further develop guidance on storage protection under sloped ceilings [10]. The proposed large-scale test configuration considers an 18 m x 18 m (60 ft x 60 ft) ceiling at inclination angles up to 18.4° (4 in 12), as shown in Fig. 2. Obstructed ceiling construction in the form of purlins and girders will be considered with purlin depths up to 0.6 m (24 in.), consistent with the Phase 2 simulations.

The fire source for the tests is a 2 x 6 x 4-tier high rack storage array of FM Global Cartoned Unexpanded Plastic (CUP) commodity with a ceiling clearance of 3.05 m (10 ft). The CUP commodity is consistent with the most common stored commodities identified in the Phase 1 survey. The size of the rack storage array will be increased from that simulated in Phase 1 and 2 to allow lateral flame spread within the array and to provide a challenging fire suppression scenario.

Quick-response, pendent, K240 lpm/bar$^{0.5}$ (K16.8 gpm/psi$^{0.5}$) storage sprinklers with an activation temperature of 74 °C (165 °F) will be spaced in a 3.05 m x 3.05 m (10 ft x 10 ft) array on the ceiling. The K240 sprinkler was selected as it was found to be commonly installed in storage applications throughout North America. The parallel-to-floor sprinkler deflector orientation will be used in the tests, as this orientation was demonstrated to be preferable in the Phase 1 and 2 simulations.

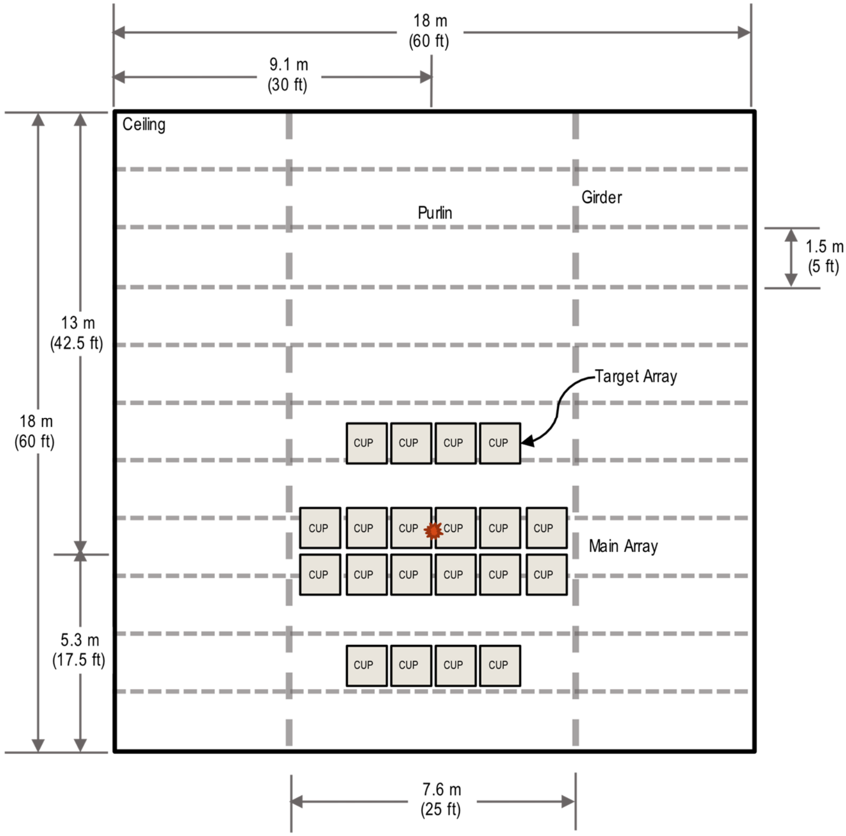


Fig. 2. Plan view of test configuration.

The proposed test matrix includes baseline suppression performance tests under a smooth, horizontal ceiling, followed by a series of tests with obstructed ceiling construction of various depths with ceiling inclinations up to 18.4° (4 in 12). The numerical simulations showed that significant delays in sprinkler activation, which are expected to impact suppression performance, can occur on the non-elevated side of a sloped ceiling with obstructed construction, as the purlin depth is increased. A flowchart is provided in Fig. 3 to describe a proposed sequence of tests with the aim of conducting the minimum number of tests necessary to derive protection recommendations. The flow chart provides a guide to selecting conditions for subsequent tests based on the suppression performance observed in previous tests. Additional tests not shown in Fig. 3 may also be conducted depending on the test outcomes.

Time permitting, a range of supplementary tests may also be conducted to address additional test configurations such as the parallel-to-ceiling sprinkler deflector orientation, the use of standard-response sprinklers, and the effect of increasing the ceiling clearance above the commodity.

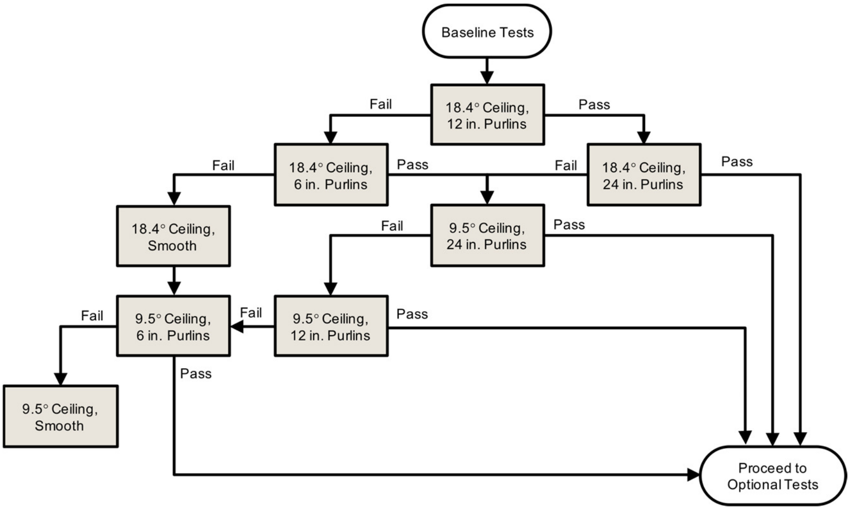


Fig. 3. Test Matrix.

Acceptable fire suppression performance during the tests will be based on the total number of sprinklers activated, the extent of fire spread, and ceiling temperatures. The maximum number of acceptable sprinkler activations in the tests will be based on the recommendations in NFPA 13 and FM Global Data Sheets. Fire spread within the main rack storage array must not reach the extents of the array during the test. Ignition of the target is permitted, as long as fire spread does not extend to the back of the target array. In addition, temperatures of simulated structural steel at the ceiling must not exceed 538 °C (1000 °F).

Summary

Numerical simulations evaluating sloped ceiling effects on sprinkler activation and sprinkler sprays revealed that:

- Increases to purlin depth for a given ceiling inclination causes greater skewness of the activation pattern in the direction of the purlin channels. The same effect is observed when inclination angle is increased for a given purlin depth.
- Presence of ridges marginally affects the activation times of the four sprinklers surrounding the ignition location. Activations near the ridge are also affected with slightly earlier activation times observed on the near side of the ridge.
- The parallel-to-floor sprinkler deflector orientation consistently provides higher water flux to commodities than the parallel-to-ceiling orientation in the presence of a fire.

Analysis of the simulation results informed the development of a test plan for upcoming large-scale fire suppression tests. The proposed test configuration considers ceiling inclinations up to 18.4°. Obstructed ceiling construction in the form of purlins and girders will be considered with purlin depths up to 0.6 m (24 in.).

A 2 x 6 x 4-tier high rack storage array of FM Global Cartoned Unexpanded Plastic (CUP) commodity will be the fire source. Pendent, storage sprinklers will be spaced in a 3.05 m x 3.05 m (10 ft x 10 ft) array on the ceiling. The parallel-to-floor sprinkler deflector orientation will be used in the tests. To minimize the number of tests, a flowchart was provided to guide the selection of test conditions. The aim of the proposed large-scale fire suppression tests is to further develop sprinkler installation guidance for storage protection under sloped ceilings.

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