Effects of Cathedral and Beamed Ceiling Construction on Residential Sprinkler Performance

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ABSTRACT

Thirty-two flaming-started fire tests were conducted in a test room to determine the effect of cathedral (sloped) and/or beamed ceiling construction on fast-response residential sprinkler performance. The fire tests were conducted with the ceiling being either horizontal or pitched to a 14° slope. Beams of two different depths were employed. Test results indicate that sloped and/or beamed ceilings represent a serious challenge to the fire protection afforded by fast-response residential sprinklers. However, with reasonable modifications to the installation standards and the water supply, fire control equivalent to that observed under smooth horizontal ceilings may be obtained.

KEY WORDS: Fast-Response Sprinkler; Residential Sprinkler Installation Standards; Fire Control

INTRODUCTION

Substantial progress in residential fire protection has been achieved in the United States since the United States Fire Administration began its program of research on life safety sprinkler technology in 1976. In particular, full scale tests conducted by Kung et al using prototype fast-response sprinklers provided the data for a complete revision in 1980 of the installation standards for sprinkler systems in one— and two-family dwellings and mobile homes, NFPA $13\text{-D}^{(2)}$. The purpose of the standard is "to provide a sprinkler system that will aid in the detection and control of residential fires and thus provide improved protection against injury, life loss and property damage" $^{(2)}$. Approval standards for fast-response residential sprinklers $^{(3)}$ were also developed from data obtained in the full-scale tests along with room tests conducted by Kung et al $^{(5,0)}$. To date, approximately five hundred thousand residential fast response sprinklers have been sold in the United States.

The present study seeks to determine the effect of cathedral (sloped) and beamed ceilings on installation standards. In addition the results of our tests provide qualitative indications of the effects of sloped and beamed ceiling construction on sprinkler response times, fire product movement and water application densities. Prior to this research program, no data existed for guidance in the installation of residential sprinklers in such architectural situations. A series of thirty-two flaming-started fire tests were conducted in a test room similar to that used in References 3

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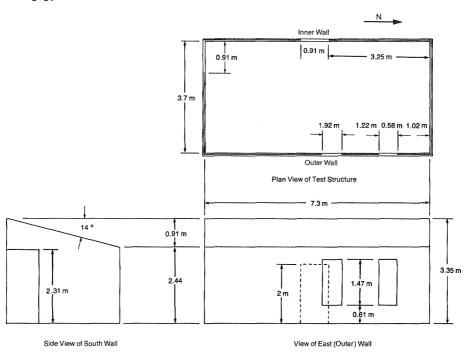
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and 4. Two of the tests were conducted with the ceiling horizontal and two sprinklers installed with the minimum water supply required by NFPA 13-D (98.4 ℓ /min). These two tests provided a baseline for determining the effect of sloped and/or beamed ceilings on sprinkler performance. In subsequent tests sprinklers were installed on smooth or beamed ceilings which were pitched to a 14° slope. In this paper the results of fifteen of the tests will be reported to identify effects of sloped and/or beamed ceilings on sprinkler performance. Full details of all tests are given in Reference 7.

EXPERIMENTAL FACILITIES

Test Facility

All fire tests in this program were conducted in a 3.7 m x 7.3 m test room constructed within a 18.3 x 18.3 x 4.7 m test facility at Factory Mutual Research in Norwood, MA. In all tests, the fire products were vented to the larger volume surrounding the test room, hence the ventilation in a house is not realistically simulated. Figure 1 shows the dimensions of the test room. The ceiling of the test room was constructed so that one side (the west or inner wall) could be raised or lowered hydraulically. In this study the ceiling was either horizontal or pitched to a 14° slope; i.e. the elevation of the ceiling at the west wall was 2.44 m or 3.35 m.



DRAWING NOT TO SCALE

Figure 1. Three views of test room.

Furnishings

Furnishings for the test series were similar to those used in References 1, 3 and 4. The furnishings consisted of a vinyl upholstered reclining chair (polyurethane foam stuffing), double-layer panels of curtains (cotton and polyester), a simulated wood end table (particle board), carpeting (nylon), and, in corner tests, a simulated end of a sofa (polyurethane foam).

The furnishings listed above were located in four different positions in the test series. Two of the fire test scenarios were along the middle of the east and west walls; the other two were in the northeast and northwest corners. A simulated sofa end was placed opposite the chair and table in the corner tests. When the fire source was along the west wall, the access way to the kitchen was blocked.

The ignition source for the flaming-started tests following Reference 4 consisted of two 30.5 cm (12 in.) long cotton wicks soaked in a total of 25 ml of ethanol and then placed on the carpet parallel to the side of the chair. The curtains were held taut using steel rods.

Test Sprinkler and Water Supply System

The test sprinkler employed throughout the program was an Underwriters' Laboratores listed, residential sprinkler. The frame arms and deflector were similar to the prototypes used in References 1, 3 and 4, and the temperature rating was $72.8^{\circ}C^{(8)}$.

Water was supplied during a single test to as many as three sprinklers. The flow rates for each sprinkler were independently monitored by rotameters with 95 l/min capacity. Water was supplied through standard piping. Before each test, the system was pressurized and the flow rate for single-sprinkler operation was independently established. During a test, when the first sprinkler actuated, the flow rate were manually checked for any errors. At the time of the second or third sprinkler actuation, the desired flow rates were set manually.

Water Distribution Tests

In order to investigate the effect of water distribution on sprinkler performance, the application rates at a 76 cm level (midway up the back of the reclining chair) were obtained for each fire source – sprinkler configuration. (Distribution measurements were not made for a single sprinkler if another sprinkler actuated soon after the first sprinkler actuated.) Water was collected in a 1.2 m x 1.2 m area covering the fire source. The water was collected in sixteen .3 m x .3 m pans with 10.2 cm sides. Results are discussed below.

Instrumentation

The focus of this paper is the effect of sloped and beamed ceiling construction on gas and ceiling surface temperatures in sprinklered residences. Due perhaps to ventilation conditions for our tests, carbon monoxide gas concentration did not exceed 1000 ppm, even in the most severe fire tests. However, comparisons of gas temperatures between tests

with smooth horizontal ceilings and tests with sloped and/or beamed ceilings indicated significant effects due to ceiling geometry.

Gas and ceiling surface temperature were measured using thermocouples fabricated from Inconel sheathed 30 gage, chromel-alumel wire. Thermocouples mounted on the side walls were located 15.2 cm down from the ceiling and 5.1 cm (2 in.) out from the wall. These thermocouples were located at distances of 1.83 m, 3.66 m and 5.40 m from the north wall. When the ceiling was adjusted to be pitched to 14° slope, additional thermocouples were placed on the west wall at an elevation of 229 cm from the floor and 5.1 cm out from the wall at the same longitudinal locations. Along the longitudinal centerline of the test room. thermocouples were located 7.6 cm from the ceiling and at the same longitudinal position as the wall thermocouples. In each test one thermocouple was embedded in the ceiling over ignition 41 cm from the wall to provide a ceiling surface temperature. In the center of the room thermocouples were placed at elevations of 0.91 and 1.5 m from the floor. The gas temperatures reported below and in Figures 2, 3 and 4 are, except where noted, from the thermocouples at an elevation of 229 cm. mounted 5.1 cm out from the middle of either the east or west wall.

RESULTS

Smooth Horizontal Ceilings

Two of the thirty-two tests were conducted with a smooth horizontal ceiling to provide a baseline for judging the effect of sloped and/or beamed ceilings on sprinkler performance. One test was conducted with the fire source at the northwest corner while the other test was conducted with the fire source along the west wall. Since the fire challenge appeared to be less severe for corner tests in this study, we will focus on tests with the fire source along either the east or west wall.

For the baseline tests, two sprinklers were installed 1.83 m and 3.66 m from the north wall along the longitudinal axis of the test room. Water was supplied to the sprinklers at the minimum flow rate required by NFPA 13-D; i.e. 68.1~l/min for one actuated sprinkler and 49.2~l/min for each of two actuated sprinklers. Since the furnishings in the fire tests were similar to those used in References 1, 5 and 6, the results from the baseline tests are considered to be representative of the sprinkler performance envisioned by NFPA 13-D.

Test 2 in the series (tests numbers are consistent with the numbers used in Reference 7) was conducted as a baseline test with the fire source along the west wall. Two sprinklers actuated in the test; the north sprinkler at 92 sec and the south sprinkler at 93 sec. A peak gas temperature of 721°C occurred at 83 sec at the thermocouple location on the west wall nearest the fire source. The ceiling surface temperature reached its maximum of 120°C at 100 sec. After sprinkler actuation, gas temperatures decreased sharply; however, fire growth was reestablished and a second peak of 332°C occurred at 184 sec at the same west wall location. The maximum carbon monoxide concentration measured was 756 ppm while the oxygen concentration was never below 19.8%. The maximum temperature at the 150 cm level in the center of the room was 49°C. Water distribution measurements (without fire) indicate that the water application density on the fire source was 2.36 mm/min.

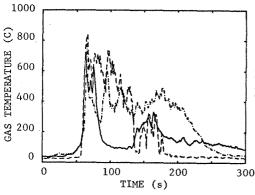


Figure. 2. Baseline Test (Test 2) __; Smooth Sloped Ceiling Tests: Test 8, __._; Test 9 ___.

In Figure 2, gas temperatures at the 229 cm location near the fire source are shown for Test 2 along with results from two smooth sloped ceiling tests (Test 8 and Test 9, see below for discussion). The time axes relative to the different tests have been shifted in order that the initial rapid temperature rises coincide. This corrects for differences in incipient burning periods. The peak temperature in Test 2 of 721°C is clearly observable but of short duration. The fire begins to reestablish itself at approximately 160 s (140 s, relative time in Figure 2); however, the maximum gas temperature of 332°C is sufficiently low to prevent rapid pyrolysis of cellulosic and plastic materials. We note that in the other baseline test in the northwest corner, fire regrowth also occurred after sprinkler actuation and the maximum gas temperature associated with fire regrowth was 316°C.

Smooth Sloped Ceiling Tests

It may be anticipated that the introduction of a sloped ceiling may significantly affect both the response times and the water distribution patterns of sprinklers. As a result of simply raising the elevation of the sprinkler, fire products must travel a greater distance to the sprinkler. In the case of a fire source on the low ceiling side (east in this study), the effect may be slightly mitigated by the favorable impact of buoyancy on the flow of the fire products up the ceiling slope. contrast, when the fire source is on the high ceiling side, the distance to the sprinkler is greatly increased and the effect of buoyancy is to trap the hot products in the apex of the ceiling and to impede flow down the slope of the ceiling. For a growing fire, the effect of increased response time is significant, since the water application density needed for fire control will depend on the response ${\sf time}^{(9)}$. Due to the inherent variability of fire growth in realistic fires, it is difficult to determine the effect of ceiling geometry on sprinkler response time. We assume that in tests in which water application densities at the fire source are equal to or greater than those of the baseline tests, and sprinkler performance is less effective than the baseline test, that response times have been increased. Regarding the effects of sloped ceilings on application densities, our water distribution tests indicate that installing sprinklers on sloped ceiling may significantly reduce water application densities. This effect appears to be the result of the increased elevation of the sprinkler, impingement of the water spray on the ceiling, and perhaps changing patterns of air entrainment around the sprinkler.

Results from fifteen tests are summarized in Table 1. Information in the table includes ceiling slope, fire location, number of beams, average water density, maximum ceiling surface temperature, $T_{\rm ceiling}$, maximum gas temperature at the 150 cm level in the center of the room, T_{150} , maximum gas temperature $T_{\rm gas1}$ and response times. In most tests, as described above, the fire began to redevelop after sprinkler actuation and a second peak in gas temperature occurred. This is designated in Table 1 as $T_{\rm gas2}$. A dash indicates that a second peak associated with fire regrowth did not occur. The water application densities in two columns refer to density measured at the fire source area. The first column gives the average water density for a single actuated sprinkler; the second column gives results when two sprinklers actuate. Note when three sprinklers actuated as in Tests 13 and 15, the second column refers to the results with three sprinklers. Dashes in column two indicate that only one sprinkler actuated.

In Test 8 (see Table 1), the ceiling was pitched to a 14° slope and the fire source was located along the east wall. Two sprinklers were installed at the same longitudinal locations used in Test 2; however, pitching the roof raised the elevation of the sprinklers by .46 m. The deflectors were parallel to the floor of the enclosure as in Test 2 and the water supply for one and two actuated sprinklers was the same as in Test 2.

Both sprinklers actuated at approximately the same time in Test 8; however, the water application density was only 1.83 mm/min (Table 1), a reduction of 22% compared to Test 2. The maximum gas temperature before sprinkler actuation was 792°C. Gas temperatures fell rapidly after sprinkler actuation; but fire growth was reestablished and a second peak of 605°C occurred. Gas temperature at the 229 cm level near the fire source remains near 400°C until the chair padding was consumed. These results may be seen in Figure 2 and contrasted with the results from the baseline test, Test 2. Furthermore, the ceiling surface temperature in Test 8 reaches 230°C compared to the 120°C of Test 2. Clearly sprinkler performance is degraded in this sloped ceiling installation. Both the lower water application densities and increased distance of the sprinkler from the fire source would appear to be contributing factors.

Table 1. Test Results

Test	Slope	Fire Location	No. of Sprinklers	No. of Beams	ater Density mm/min 1 Sprinkler	Water Density mm/min 2 Sprinklers	T _{ceiline}	T 159	{5€} [™]	See L	Sprinkler Response Time(s)
2	0*	¥	2ª	0		2.36	120	49	721	332	92,93
8	14-	Ε	2ª 2b	0		1.83	230	50	792	605	68,70
9	140	¥	2 ^b	0		2.81	89	39	839	736	81.86
10	140	Ε	2 ^b	0	2.20	2.57	124	33	739	332	88,227
13	140	¥	3 ^c	0	3.71	4.52	67	43	896	310	101, 172, 179
15	0°	W	3 ^c	0		5.09	77	44	811		105, 111, 115
16	0.	W	2ª 2d	2 (24 cm)		1.51	289	59	834	856	85,86
17	0°	¥	2 ^d 2	2 (24 cm)		1.55	300	81	786	711	178, 185
18	0.	¥	2 ^a 2 ^b	2 (14 cm)		1.87	247	53	772	715	125,130
19	14*	N₩	2 ^b 2	2 (24 cm)	3.3		105	31	312		99
20	140	¥	2p	2 (24 cm)		2.73	108	61	897	812	112,113
21	140	£		2 (24 cm)		4.56	135	54	791		122, 155
24	140	W		2 (24 cm)	4.48		57	52	913	407	149
26	14*	W		2 (14 cm)	4.73		53	47	875		120
27	0°	¥	3 ^e	2 (14 cm)	5.54	5.87	97	45	768	199	103,109

Sprinklers located 1.83 m from the east wall and at distances of 1.83 and 5.48 m from the north wall; deflectors parallel to the floor; 68.1 t/min for 1 sprinkler; 49.2 t/min for each of two sprinklers.

b Sprinklers located 1.52 m from the east wall at distances of 1.83 and 5.48 m from the north wall; deflectors parallel to the ceiling; 68.1 t/min for each actuated sprinkler.

^c Sprinklers located 1.83 m from the east wall at distances of 1.2, 3.66, and 6.10 m from the north wall; deflectors parallel to the ceiling; 68.1 1/min for each actuated sprinkler.

d Sprinkler as in a, but lowered to place deflector 19.1 cm from ceiling.

In Test 10 (Table 1), the sprinklers were repositioned closer to the fire source along the east wall. The sprinklers remained 1.83 and 3.66 m from the north wall, but were moved .3 m closer to the east wall. addition, the sprinklers were positioned so that the deflector was parallel to the ceiling instead of the floor. The water supply was increased so that the water application density at the fire source was comparable to that in Test 2, i.e. the water application density with two sprinklers in Test 10 was 2.57 mm/min compared to 2.36 mm/min in Test 2. This was accomplished by increasing the flow rate for each of two sprinklers to 68.1 l/min. As a result of those changes, fire control as indicated by gas and ceiling surface temperatures was quite similar to the baseline test. The maximum gas temperature was 739°C; however, as in Test 2, this peak was of short duration. After first sprinkler actuation, fire growth was reestablished with a second peak of 332°C, the same as in Test 2. Unlike Test 2, both sprinklers did not actuate at approximately the same time. In this test, the sprinkler at the south end actuated first at 88 s followed by the second at 227 s. This may be due to a lower heat release at the time of first sprinkler actuation resulting from a decreased distance of the sprinkler from the fire source. When the first sprinkler actuated, the water application density of 2.20 mm/min caused sufficient cooling to keep the second sprinkler from actuating until fire growth was reestablished.

Test 9 was conducted under the same conditions as Test 10 except that the fire source was along the west wall. The effect of the sloped ceiling and new sprinkler installation is to greatly increase the distance of the fire source to the sprinkler. Furthermore, it would be anticipated that an additional effect of the sloped ceiling would be to increase the response time due to trapping of fire products at the apex of the sloped roof. The water application density at the fire source for two sprinklers was 2.81 mm/min, 19% higher than in Test 2. The two sprinklers actuated at approximately the same time, 81 and 86 s (52 s and 57 s relative time in Figure 2). As expected, despite increased water application density, sprinkler performance was degraded. In Figure 2 gas temperature at the 229 cm level near the fire source is contrasted with results from Test 2 and Test 8. The maximum gas temperature after sprinkler actuation in Figure 2 is 736°C , 131°C greater than even the maximum achieved in Test 8. The increased gas temperature despite increased water application density would suggest that response time was increased by the sloped ceiling. The ceiling surface temperature maximum was only 89°C probably due to cooling of the fire products as they were convected to the 3.35 m ceiling height.

In order to achieve fire control at the west wall fire source location as effective as in Test 2, three sprinklers were installed in Test 13 along the longitudinal centerline of the room at a distance of 1.22 m, 3.66 m and 6.10 m from the north wall. The deflectors were parallel to and 10 cm from the sloped ceiling. Each actuated sprinkler was supplied with 68.1 ℓ /min of water. Although the water application density was 3.71 mm/min for the first actuated sprinkler, fire growth was reestablished and the other two sprinklers actuated. Test results were comparable to Test 2 (Table 1).

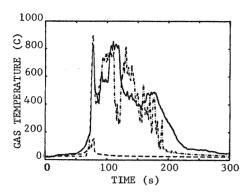
When the test conditions of Test 13 were repeated with the ceiling adjusted to horizontal, again all three sprinklers actuated but the fire was suppressed. This would seem to be due to the increased water application density and shortened path length relative to Test 13.

Beamed Ceiling Tests

Sprinkler performance in installations on beamed ceilings is also anticipated to be affected by changes in response times and water-application densities. In the beamed ceiling tests described below two beams spaced at 2.44 m intervals from the north wall were installed. In these tests, the beams were parallel to the north wall, dividing the test room ceiling into thirds. The width of the beams was 3.8 cm. Beam depths were either 24 cm or 14 cm. For two sprinkler installations such as in Tests 2 or 8, if the fire source is located along the east or west walls and two beams are installed as described above, then the flow of hot gases to the sprinklers is obstructed by the beams. Sprinkler response times will then be increased. Furthermore, water application density at the fire source is greatly reduced by water directly impinging on the beams. In contrast, when the fire source is in a corner, sprinkler performance is expected to be enhanced since the flow of gases away from the sprinkler is impeded.

The ceiling was adjusted to be horizontal in Tests 16 to 18 and the fire source was along the west wall between the beams. No data exists to provide guidelines for the installation of residential sprinklers near obstacles such as beams even in the case of horizontal ceilings. In Tests 16 and 17 two sprinklers were installed (Table 1, notes a, d) the deflectors of the sprinklers were located 10.2 and 19.1 cm, respectively, below the ceiling. Beam depth was 24.1 cm in both tests. The water supply to each actuated sprinkler was 68.1 L/min. In both tests the water application densities were reduced by more than one-third from Test 2 (see Table 1). This was somewhat surprising in the latter test since lowering the deflector to 19.1 cm below the ceiling visibly reduced the quantity of water impinging on the beams. A water distribution test conducted without beams but with the sprinkler in the same position showed that simply lowering the sprinkler from 10.2 to 19.1 cm below the ceiling reduced the average density at the fire location by 16% compared with Test 2. The low application densities combined with the obstruction of gas flow by the beams resulted in high gas and ceiling surface temperatures. Reduction of the beam depth from 24.1 to 14 cm in Test 18 improved the water application density somewhat; however, gas temperatures remained high (see

In Tests 19 to 21, the ceiling was pitched to a 14° slope and two sprinklers were installed and water supplied as in Test 9. Two beams were installed as in Tests 16 and 17. Note that in Test 19 (Table 1) the fire source was in the northwest corner thus the fire source and one sprinkler were within one bay formed by the beams. In that test, the fire was suppressed. In the comparable smooth horizontal test in the northwest corner (see Reference 7) the fire was only controlled even though the water application density was 4.07 mm/min. Clearly, the trapping of the fire products by the beams improved the sprinkler performance. In contrast in Tests 20 and 21 in which the fire source was located along the west and east wall respectively, fire growth was again reestablished after sprinkler actuation. Gas temperatures were quite high compared to Test 2 despite higher water application densities. In particular, in Test 21 in which the water application density was more than 1.9 times higher than in Test 2, the fire growth was only momentarily affected by first sprinkler actuation. No distinct peak in gas temperature such as in Test 2 (Figure 2) occurred. Gas temperature decreased as the padding of the chair was consumed. Such a result would be indicative of greater fire involvement at the time of first sprinkler actuation. This would result from increased sprinkler response times caused by obstruction of the gas flow to the sprinklers and channeling of the flow to the apex of the ceiling.



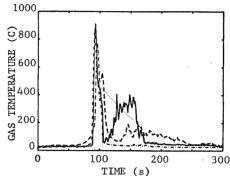


Figure 3. Beamed ceiling tests with two sprinklers; Test 16 __; Test 19 ___; Test 20 __._.

Figure 4. Beamed ceiling tests with three sprinklers; Test 24 ___; Test 26 ____; Test 27 _____.

Gas temperatures at the 229 cm location near the fire source are shown for Tests 16 and 20 in Figure 3. Gas temperatures on the west wall at an elevation of 227 cm and 1.83 m from the north wall are also shown for Test 19. The effects of flow obstruction by the beams and low water application on sprinkler performance are evident in Test 16 (horizontal ceiling) and Test 20 (sloped ceiling). Similar results were obtained in Tests 17 and 18. Test 19 clearly indicates the improved sprinkler performance resulting from the trapping of hot gases by the beams.

Because of the favorable result of Test 19 in which the fire source was located within the bay formed by the walls and a beam, three sprinklers were installed in Test 24, 26 and 27; i.e., one sprinkler was centered in each bay formed by the beams (Table 1, note c). No more than two sprinklers actuated in any test. The water supply was increased to allow 68.1~L/min of water for each actuated sprinkler.

Gas temperature at the 229 cm location near the fire source are shown in Figure 4 for Tests 24, 26, 27. In Test 24, the ceiling was sloped and beams 24 cm deep were employed. Gas temperatures in this test were only marginally higher than in the comparable smooth horizontal ceiling test. The ceiling surface temperature was relatively low (57°C) . When the depth of the beams was reduced to 14 cm in Test 26, the fire was suppressed, presumably due to a slightly higher water application density. In Test 27 in which the ceiling was adjusted to horizontal, the fire was controlled. Comparing Figures 3 and 4, it is evident that fire control is greatly improved by the installation of three sprinklers if a water supply of 136.2 ℓ /min is available.

CONCLUSIONS

The results of the extensive series of tests of this study indicate that sloped and/or beamed ceilings represent a serious challenge to the fire protection capability afforded by fast-response residential sprinklers. Sprinkler performance may be degraded by reduced water application densities resulting from the increased elevation of sprinklers and the modification of the sprinkler orientation with respect to the ceiling. Sloped ceilings also affect sprinkler performance by increasing the time

for fire products to be convected to the sprinkler. This results in part from the increased distance of the sprinkler from the fire source and the effect of buoyancy on gas movement. Beams affect sprinkler performance by both affecting water application densities and by obstructing the flow of fire products. The installation of three sprinklers in the test room, with each sprinkler being provided a water supply of 68.1 ½/min, resulted in fire control comparable to results under a smooth horizontal ceiling with two sprinklers. In the case of a ceiling with two beams, no more than two sprinklers actuated, while in the case of a smooth sloped ceiling, three sprinklers actuated.

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