INTERMEDIATE-SCALE FIRE TEST – STEPPING STONE FOR PREDICTION OF MATERIAL FLAMABILITY IN REAL-SCALE FIRE THROUGH BENCH-SCALE FIRE TEST DATA

S. Nam
FM Global, 1151 Boston-Providence Turnpike, Norwood, Massachusetts, USA

ABSTRACT

Intermediate-scale fire tests were conducted in this study to predict flammability of wall panels in full-scale fire, which might be misinterpreted in bench-scale fire tests. The scale of the tests was large enough for the testing materials reveal their true behavior in full-scale fire but still small enough to provide substantial savings in the costs of testing.

The 4.9 m high parallel panel configuration, in which two vertically erected panels facing each other so that they can continuously feed heat fluxes each other while they are burning, was adopted as the intermediate-scale tests simulating the 25 and the 50 ft corner tests. The corner tests have been used to evaluate fire hazards of wall/ceiling panels and other similar building materials for decades using fire in large corner settings. In order for the parallel panel tests to provide proper interpretation of corner test results, the view factors for the radiative heat transfer and the heat flux to the testing wall panels in the parallel panel tests were kept the same as those in the corner tests. The heat release rates from the burning panels in the parallel panel tests were used to predict the outcome of the corner tests. It seemed that the heat release rate measurements can be adopted as more reliable criteria for the pass/fail of the corner tests than the current visual observations in highly smoky environment.

The predictions by the intermediate-scale tests resulted in an excellent match with the outcome of the 25 and the 50 ft corner tests. In the process of developing a physical model that would describe material behaviors in fires by utilizing bench-scale test data, reliable intermediate-scale tests will be instrumental by providing an affordable validation tool; thus they serve as a stepping stone in a journey to reach a goal of predicting outcome of full-scale fire tests by analyzing bench-scale test data.

INTRODUCTION

It is not uncommon for fire research engineers to conduct full-scale fire tests under preset conditions to gain physical insights of fire and its relations with the environment including flammability of materials involved in fire. The full-scale tests can provide quick resolutions to the imposing problems that could have been too complex to be resolved by a simplified analysis or too critical to be relied on any other means. Full-scale tests also provide the physical insights that otherwise would not have been available. However, results of the full-scale tests, which in general require high costs and large amounts of labor and materials, are usually difficult to generalize. Since no one can rely on the full-scale tests for every problem, other means of finding a solution have to be devised.

In lieu of full-scale tests, small-scale or bench-scale tests are used often because they cost less and easy to carry out. Fig. 1a shows ASTM E2058 Fire Propagation Apparatus (FPA), one of the well known bench-scale test apparatus [1] being used to acquire properties of material flammability such as heat of gasification, heat of combustion, smoke yield, critical heat flux, etc. Fig. 1b shows a burning sample to which the four electric heaters provide radiative heat flux at the combustion section of the FPA, which corresponds to the bright orange section at the lower part in Fig. 1a. Combustion tests are usually conducted with a fixed heat flux to the sample and sometimes at elevated oxygen concentrations. Pyrolysis tests are in general conduced with 100% nitrogen flowing through the test section with various heat fluxes to attain the heat of gasification of the testing material.

FIGURE 1a. Fire propagation apparatus (FPA)

FIGURE 1b. Combustion of sample at FPA

Fundamental material properties, such as the *critical heat flux* (CHF) or the *thermal response parameter* (TRP) can be found through the tests at FPA. The *critical heat flux* is the heat flux below which a material cannot generate a combustible mixture [2]. The *thermal response parameter* is an index showing the resistance of a material to generate a combustible mixture [2]. The higher the *critical heat flux* or the *thermal response parameter* values, the lower the fire propagation rate [2]. The thermal response parameter of a material can be found as [2] :

$$TRP = \Delta T_{ig} \sqrt{k \rho c_p \left(\frac{\pi}{4} \right)} \qquad [1]$$

where ΔT_{ig} is the ignition temperature above ambient, and $k \rho c_p$ are, respectively, the thermal conductivity, the density, and the specific heat of the material. For thermally thick materials, which cover many commonly used materials, the inverse of the square root of time to ignition is expected to be a linear function of the external heat flux minus the CHF value [2], as shown in Eq. [2]:

$$\sqrt{\frac{1}{t_{ig}}} = \frac{\left(\dot{q}_e'' - CHF \right)}{TRP} \qquad [2]$$

where t_{ig} is the time to ignition and $\dot{q}_e''$ is the external heat flux. Thus, by measuring the ignition time of a material, one can find CHF and TRP. Fig. 2 shows the relationship between $\sqrt{1/t_{ig}}$ and the external heat flux applied to a PMMA sample. The point where the graph meets the x-axis would correspond to the value of CHF. These examples show how a bench-scale test can be utilized in finding material flammability. There are ongoing efforts to develop a scientific model that can predict full-scale test results by utilizing the properties measured through bench-scale tests.

The bench-scale tests, however, have their own pitfalls, too. Although the main objective of the bench-scale tests is obtaining fundamental characteristics of test materials, it is practically very challenging to define the "fundamental characteristics" of a material. This is true even for homogeneous materials, and the problems are only compounded for inhomogeneous ones.

Furthermore, the dominant heat transfer mode in fires also varies from convective to radiative in general as the size of burning materials increases. In addition, some material behaviors that seem to be persistent in the bench-scale tests reveal completely opposite trends in real-scale fire tests, which makes fire scientists feel lost in interpreting bench-scale data for the prediction of full-scale fire test outcomes.

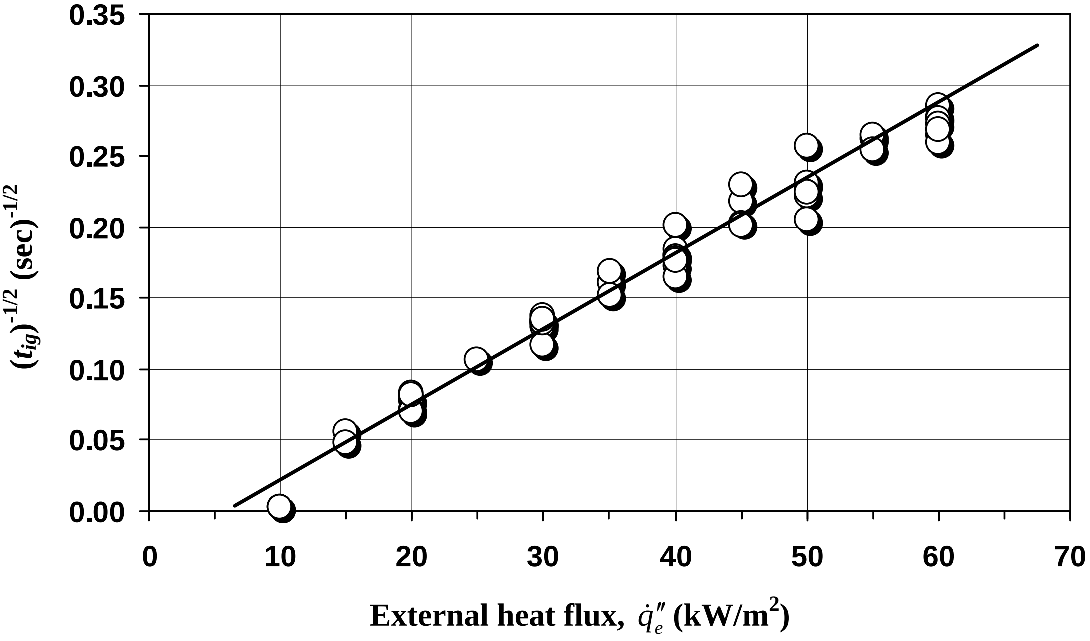

FIGURE 2. Square root of the inverse of the ignition time vs. external heat flux for a PMMA sample of 0.1 x 0.1 x 0.01 m. The CHF value lies at the intersection of the graph with the x-axis.

Lessons learned through reduced-scale tests tell that the size of testing materials matters. Then, the next question is "what is the smallest scale test that will adequately represent the behaviors of the material in full-scale tests?" That brings intermediate-scale tests, which are in between the full- and the bench-scale tests. Determination of the size of the testing material will eventually define the size of the intermediate-scale test. The size of the testing materials obviously cannot be as big as that in the full-scale tests; however, it still should be large enough to include all the critical aspects of the material characteristics so that the test can reveal the true full-scale behaviors, particularly with inhomogeneous or charring materials. In another words, the testing material size should be just large enough to embrace all the different aspects of properties that would be reflected in full-scale fire tests.

If a reduced-scale test is based on a dynamic similitude with a corresponding full-scale test, the well-established dimensionless parameters, such as Re, Fr, We, etc., can be a guide in determining the scale of the reduced test. However, that kind of a guideline cannot be helpful in determining the fire propagation of a material because one cannot scale the material flammability. There is no established way of defining the proper scale at this point to reflect the behaviors of material in full-scale fire. Most of methodologies developed so far largely depend on experiences, trials and errors.

However, there are a few principles that should be kept in developing a reduced-scale test. First, it should be very clear from the beginning that what full-scale test that the reduced-scale test is trying to emulate. The correspondence between the results of the full-scale test and those from the reduced-scale test should be precisely established. Second, what common parameters that the full-scale tests and the corresponding reduced-scale tests should share in order for the reduced-scale test data be properly interpreted for full-scale test behavior need to be established. Third, the reduced-scale test should be easy to implement. It should not require elaborate, time consuming preparation of the test material. It should be able to take a testing panel as it is. Fourth, the test method should be inclusive. It should not discriminate based on test material's properties, thickness, presence of facers, etc. One should be able to run the test without an extensive modification of test equipment regardless of the testing material.

The full-scale test example taken in this study as a target for an intermediate-scale test is the FM Approvals' 25 ft and 50 ft high corner test [3]. The fire hazard of insulated wall, wall and roof/ceiling panels, plastic interior finish materials, plastic exterior building panels, and interior or exterior finish systems have been traditionally evaluated at FM Global through FM Approvals' 25 ft High Corner Tests or 50 ft High Corner Test [1]. In this study, however, only wall panels with no contribution from ceiling material were addressed. In the 25 ft high corner tests, test samples are attached to steel frames. The east wall (long) frame is 15.2 m (50 ft) long, and the south wall frame is 11.6 m (38 ft) long. The distance between the concrete floor and the bottom of the ceiling furring strips is 7.6 m (25 ft). The test fire load consists of conditioned oak pallets, which are stacked 1.5 m (5 ft) high at the intersection of the assembly walls, 0.3 m (1 ft) apart from each wall. The stack of pallets is ignited and the test continues for 15 min. During the test period, the flames from the burning material should not reach any of the limits of the corner test structure in order for the material to pass the test. A wall panel passing the 25 ft corner test is approved for use up to 9.1 m (30 ft) high [2].

For the Class 1 Approval for wall panels to the maximum height of 15.2 m (50 ft) or with no height restriction, the material must pass the 50 ft corner test. In the 50 ft high corner tests, the east wall and south wall frames are both 6.1 m (20 ft) long. The distance between the concrete floor and the bottom of the ceiling furring strips is 15.2 m (50 ft). The test fire load is the same as that of the 25 ft corner tests described above. During the test period, the flames from the burning material should not reach any of the limits of the corner test structure in order for the material to pass the test. If ignition of the ceiling of the assembly does not occur during the test period, in addition to meeting the conditions mentioned above, the material passes with the "unlimited height" approval; otherwise, the approval is limited to a 15.2 m (50 ft) high wall. Fig. 3 and Fig. 4 shows fire-propagating and non-fire-propagating test panels, respectively, in the 25 ft corner test. Figs. 5 and 6 show, respectively, fire propagating and non-propagating panels in the 50 ft corner tests.

FIGURE 3. Fire propagating panels in the 25 ft corner test

FIGURE 4. Non-fire-propagating panels in the 25 ft corner test

FIGURE 5. Fire propagating panels in the 50 ft corner test

FIGURE 6. Non-fire-propagating panels in the 50 ft corner test

INTRODUCTION TO PARALLEL PANEL TEST (PPT)

The objective of this study is to develop an intermediate-scale fire test which is well suited for modeling fire growth in the 25 or the 50 ft corner tests. The parallel panel test, where two vertically erected burning panels face each other, was adopted as the corresponding reduced-scale test because it incorporates many important features of large-scale fire growth. In addition, FM Global has considerable experience with these corner tests and the parallel panel tests as well. Fortunately, the case in this study meets the first condition described in the previous section well. The full-scale test that the reduced-scale test is simulating is the 25 ft and the 50 ft corner tests. Thus, we have a clear objective, which is not necessarily a common practice in many reduced scale-test developments related to material flammability.

The parallel panel tests have a long history of applications in either small-scale or intermediate-scale tests in FM Global. A small parallel panel configuration had been used in the early 1980s as a demonstration tool to educate field engineers on flame propagation along a vertical wall. Tewarson and Khan[4] were the first to have utilized the configuration into an industrial application to the evaluation of fire propagation behavior of electric cables in 1988. The length of the panel in the tests was 4.9 m (16 ft) as shown in Fig. 7. Then the configuration was extended in screening materials for clean room applications in 1997 with 2.4 m long (8 ft) panels [5]. Meantime, a large quantity of test data has been accumulated in terms of heat flux along the walls, and correlations with material flammability [6-9]. Fig. 8 shows the parallel panel test with 2.4 m high panels used by Alpert [8] to investigate material flammability. All the knowledge, data, findings and experiences developed through the long history mentioned above have been utilized in this study.

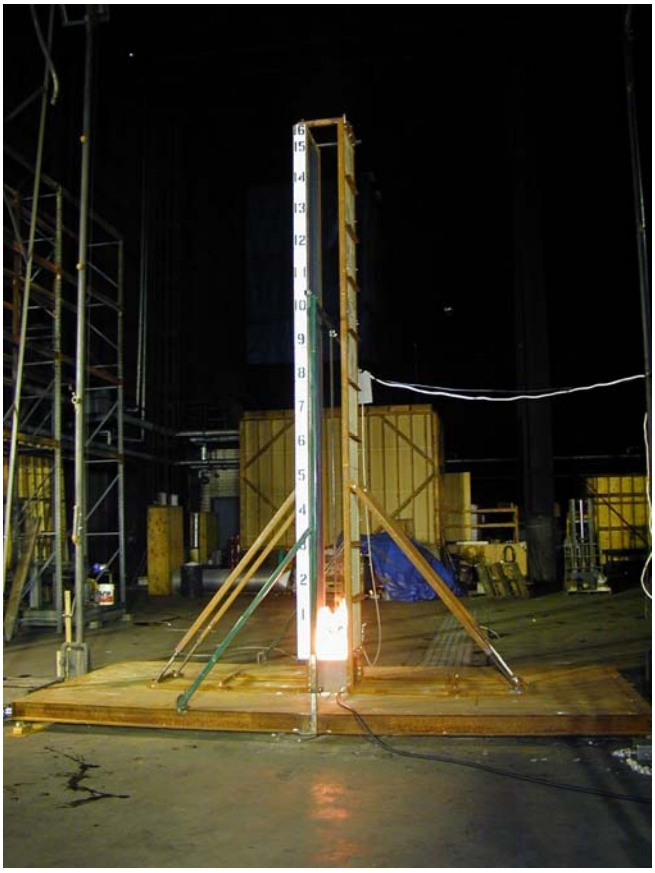

FIGURE 7. The 4.9 m high parallel panel configuration to evaluate flame propagation on the cables

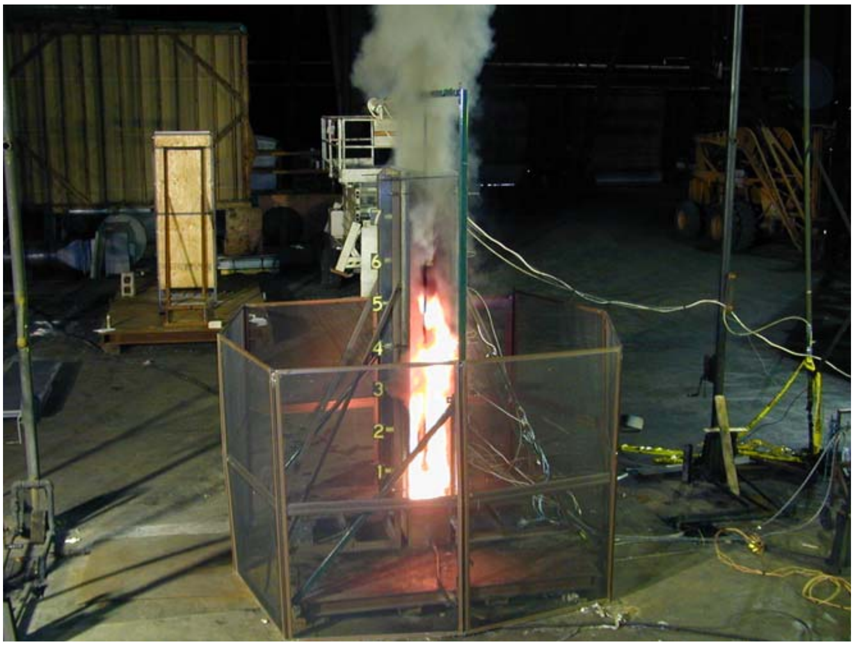

FIGURE 8. The 2.4 m long parallel panel test used to evaluate material flammability by Alpert [8]

The parallel panel test apparatus used in this study consists of two parallel panels, each 4.9 m high by 1.1 m wide, maintaining a 0.5 m clearance in between. A sand burner, 1.1 m by 0.5 m by 0.3 m high, is located at the bottom of the panels. The maximum heat release rate from the propane burning sand-burner was measured as 810 kW. The total heat release rate from the burning panels during the test was measured by the 5 MW capacity fire-products collector (FPC) located above the panel apparatus. Fig. 9 and Fig. 10, respectively, show a photo and a schematic of the apparatus. Fig. 11 shows fire-propagating panels and Fig. 12 shows non-fire-propagating panels in parallel panel tests.

The important aspects of applicability of parallel panel tests as a reduced-scale test for the corner tests are: (1) maintaining the same view factor in radiative heat transfer from the burning walls in the corner tests, and (2) providing the same heat flux to the test panels as in the corner test. These are the two common parameters mentioned above that the full-scale (corner tests) and the reduced scale tests (PPT) must share in order for the reduced-scale test data can be interpreted for the full-scale test outcomes.

In order to meet the conditions at Item (1), the aspect ratio of the parallel panel width to the clearance between the panels was kept equal to 2 to 1, which provides the view factors for the PPT approximately the same as that in the corner test. To meet the conditions at Item (2), the heat exposure from the sand burner was kept at 360 kW. The fire source in the corner test is a 1.5 m (5 ft) high stack of moisture conditioned wood pallets. The peak heat release rate of the wood pallets recently measured was estimated as 6 MW. The peak heat flux to the wall panels measured at the top of the burning pallets was approximately 100 kWm^{-2}. Thus, the PPT apparatus needed to provide a maximum heat flux close to 100 kWm^{-2}. When the sand burner at PPT provided a 360 kW exposure, the measured heat flux to the panels was close to 100 kWm^{-2}. The required size of the sand burner to provide the adequate heat exposure influenced the dimension of the panel width and, consequently, the clearance between the panels.

The panel height, 4.9 m, was determined based on an earlier experience. The parallel panel test apparatus was supposed to be fabricated to achieve a strong correlation between the results of the corner tests and those of the parallel panel tests. Earlier parallel panel tests with the 2.4 m long panels[8,9] indicated that the 2.4 m long panel may not bring a strong correlation with the full-scale tests. A test showed that flames on a fire-retarded plywood specimen, which was one of the charring materials tested in the project, propagated to all the way up to 2.4 m (8 ft). That would have put the plywood in the category of “fire-propagating” material. However, a further test using 4.9 m (16 ft) high panels showed that the fire stopped propagating at 3.7 m (12 ft). So the panels were increased to 4.9 m long to properly reflect the characteristics of charring materials.

In order to address the correlation between the parallel panel tests and the 25 and the 50 ft corner tests, two steps were taken. The first step was to determine a way of relating the outcomes of the 50 ft corner tests with the results of the 25 ft corner tests so that the correlation between the parallel panel tests and the 25 ft corner tests can be extended to the cases involving the 50 ft corner tests. The second step was to correlate the results of the parallel panel tests with those of the 25 ft corner tests. (The correlation with the 50 ft corner tests will be made by a way of extending the correlation with the 25 ft corner tests.)

FIGURE 9. Photo showing the 4.9 m high parallel panel test apparatus under the 5 MW fire products collector

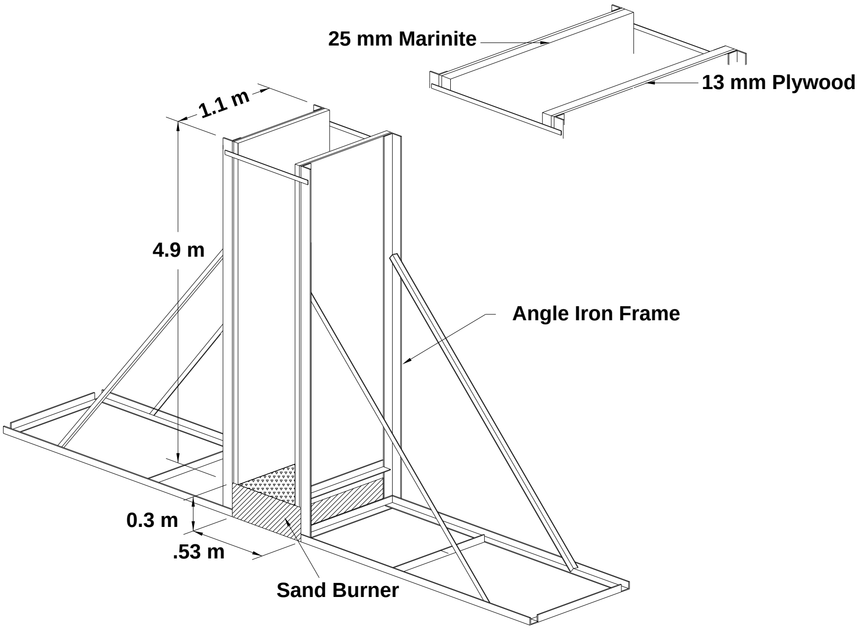

FIGURE 10. Schematic of the 4.9 m high parallel panel test apparatus

FIGURE 11. Fire-propagating panels in the parallel panel test

FIGURE 12. Non-fire-propagating panels in the parallel panel test

RELATIONSHIP OF THE 25 FT CORNER TEST RESULTS TO THE 50 FT CORNER TEST RESULTS FOR WALL PANELS

As a test for assessing material flammability, it is reasonable to assume that the 25 ft corner test should be capable of providing a means to relate the results of the 50 ft corner test. A limited review of the test record so far shows that no material that passed the 25 ft corner test failed to pass the 50 ft corner test, which allows us for the purpose of this study to assume that a way of relating outcomes of the 50 ft corner tests may lie in results of the 25 ft corner tests. This also means that the only additional outcome that needs to be specified is whether a material that has passed the 25 ft corner test should be approved with "unlimited height" or "limited to 15.2 m (50 ft) high". If the 50 ft corner test results can be predicted from the results of the 25 ft corner test, then a parallel panel test that can reliably predict the outcome of the 25 ft corner test, could also be expected to provide a prediction on flammability of the wall materials in the 50 ft corner test as well.

It is proposed below for the purpose of this study that the extent of lateral flame spread in the 25 ft corner test can be translated into the extent of fire spread in the 50 ft corner test despite the much greater vertical flame height in the 50 ft test. A rationale for this method is provided by appealing to the results of Heskestad and Hamada[10] for a case which differs from the corner test configuration. Thus the ultimate validity of the method depends on the empirical results from comparisons of the 25 ft and 50 ft corner test. In another words, the evaluation of the 50 ft corner test in terms of the 25 ft corner results is only an intermediate step in developing a parallel panel test that would correlate with the 50 ft corner test results.

Heskestad and Hamada[10] showed that the relationship between the flame radius, L_r , after impingement upon a ceiling, and the vertical flame height, L_v , in the absence of ceiling can be expressed as:

$$L_v = H + 1.05L_r \qquad [3]$$

where H is the ceiling height. It is assumed that this relationship remains valid in the corner configuration. It was confirmed by free burn data obtained in a corner constructed with inert walls. As the geometric center of the flame in the 25 ft corner test is 0.84 m (33 in.) off the corner following the test standard (see Fig. 13) the flame radius in Eq. [3] and the length of horizontal flame extension along the eave in either direction, L_h, will have the following relation.

$$L_h = 0.84 + L_r \qquad [4]$$

where L_h and L_r are in m. Thus, the vertical flame height in the absence of ceiling can be given in meters as

$$L_v = H + 1.05L_h - 0.88 \qquad [5]$$

The 25 ft corner test with inert walls and ceiling conducted recently showed that the burn-mark was approximately 3.0 m (10 ft) long along both eaves. The extent of *intermittent flames* shown in the video as well as the measured heat fluxes indicate that the flames reached 3.7 m (12 ft) along both eaves. Thus, it is likely that the extent of flames estimated by burn mark in the test could be slightly lower than the extent of real flames.

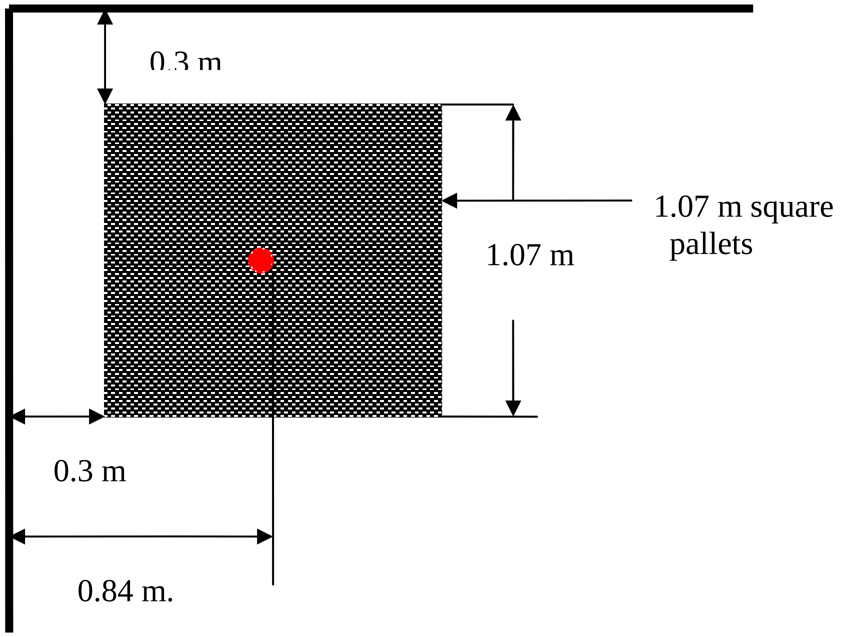

FIGURE 13. The geometric flame center in the corner test configuration

Eq. [5] indicates that the vertical flame height in this case would be just under 10.7 m with L_h = 3.7 m if there was no ceiling. Thus, the maximum height of the flames at the 50 ft corner test where there is absolutely no contribution from any burning material is expected to be close to 10.7 m. Alpert and Davis[11] ran a 50-ft corner test using gypsum[*] boards as inert walls. The video shows that the maximum height of the continuous flames was 9.8 m and that of intermittent flames was about 10.7 m. These values match well with the estimated values based on the 25 ft corner test results and support the concepts associated with the Eq. [3] through [5].

If the vertical flame length in a 50 ft corner test is lower than 15.2 m, then the flames will not touch the ceiling at 15.2 m high and the material will pass the test with an “unlimited height” approval. Following that logic, one can find a condition for the material with the unlimited height approval from the 25 ft corner test as follows:

Taking 0.6 m (2 ft) as a safety margin, one can define the maximum acceptable vertical flame height in the 50 ft corner test as 14.6 m (48 ft) for the material to be qualified for “unlimited height” approval in the 50 ft corner test. Then from Eq. [5], the vertical flame height 14.6 m (48 ft) corresponds to the horizontal flame length of 7.6 m (25 ft) along either eave in the 25 ft corner test. Since the length of flame extension along the eaves can be asymmetric, the total combined length of the flame extensions along both eaves would be convenient in practical applications. Thus, if the total length of the flame extension along both eaves in the 25 ft corner test is shorter than 15.2 m, then it is hypothesized that the material meets the performance required for approval with “unlimited height.” If a material shows the total flame extension along both eaves longer than 15.2 m (50 ft) in the 25 ft corner test, but still passes the test, then it is hypothesized that the material meets the performance required for approval with the “limited to 15.2 m (50 ft) high” condition.

In order to see empirical support for the proposed condition mentioned above, data that show the results of the 25 ft corner test and the 50 ft corner test together are needed. However, the number of

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[*] The actual material was 5/8 in. DensDeck™, which is glass fiber faced gypsum core material.

materials that were exposed to both the 25 ft and the 50 ft corner tests is very limited. Table 1 shows some of the few materials that were exposed to both tests. The flame extension along the eaves in the 25 ft corner test and the vertical flame height in the 50 ft corner tests are given. The lengths of flame extension along the eaves in Table 1 were determined through the post-test burn marks the flames left on the walls; thus, they are expected to be somewhat shorter than the real flame extensions during the tests. All the combined flame extensions along the horizontal eaves in Table 1 were shorter than 15.2 m and all the materials passed the 50 ft corner tests with “unlimited height.” Thus, the data support the proposition mentioned above.

TABLE 1. Description of the past 25 ft/50 ft corner tests

Material	**Flame extension along the eaves in the 25 ft corner test**	**Vertical flame height in the 50 ft corner test**
FRP Composite ($4.9\ kgm^{-2}$)	5.5 m (18 ft: south wall); 6.7 m (22 ft: east wall)	10.7 m
FRP Composite ($5.2\ kgm^{-2}$)	4.9 m (16 ft: south wall); 4.9 m (16 ft: east wall)	12.2 m
FRP Composite ($3.7\ kgm^{-2}$)	5.5 m (18 ft: south wall); 5.5 m (18 ft: east wall)	11.3 m

CORRELATION BETWEEN PARALLEL PANEL TESTS AND THE 25 FT CORNER TESTS

A series of 25 ft corner tests were conducted to provide comparisons with performance in parallel panel tests, which were proposed as reduced-scale tests for the 25 ft corner tests. Results from the corner tests conducted recently are given in Table 2. The length of the flame extension along the horizontal eaves was determined through the videotapes taken during the corner tests except for the polyurethane core insulated wall with an inert facer. No video was taken in that test and the flame extension lengths were visually determined by the post-test burn mark on the surfaces.

TABLE 2. Fire propagation in the 25 ft corner tests

Material	**Fire propagation?**	
	25 ft corner test	**Flame extension along the eaves**
¾ in. PVC	Yes in 5.3 min	15.2 m (50 ft) along the east wall
¼ in. PVC	Yes in 5 min.	15.2 m (50 ft) along the east wall
10 in. polystyrene panels with inert facer	Yes in 7 min[&]	15.2 m (50 ft) along the east wall
¾ in. FR-Plywood	No	5.5 m (18 ft) along both eaves
½ in. FR-Plywood	No	7.0 m (23 ft) along both eaves
¼ in. FR-Plywood	No	9.8 m (32 ft) along both eaves
Polyurethane core insulated wall panels with inert facer	No	6.1 m (20 ft) along both eaves
2-mm fiberglass reinforced melamine w/ inert facer	No	5.2 m (17 ft) along both eaves

An extensive series of parallel panel tests were conducted with various materials. In order for the parallel panel test results to be used as the indicator of the outcome of the corner tests, there must be a

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[&] One sprinkler with a discharge density of 8 mm/min was operating.

strong correlation between the results of the two sets of tests. A total of twenty five parallel panel tests were conducted and brief results are given in Table 3. The "$\dot{Q}_b$"and "Peak $\dot{Q}_{ch}$" in the third and the fourth column denote, respectively, the heat exposure from the gas burner and the maximum total heat release rate from the burning panels measured by the fire products collector in the test. The "Fire Propagation" in the last column says whether the flames ever had reached all the way to the top of the 4.9 m high panels during the test, and if yes then the elapsed time to reach the top is also given. The materials used in the tests include various types of wall-panel materials: homogeneous and non-homogenous, thermally thick and thermally thin, with and w/o inert facers, melting and non-melting, charring and non-charring materials. The tests were conducted with almost no modifications in the test apparatus. The tests were conducted in a very universal manner with no special treatments or modifications based on the testing materials. When the panels covered with inert facers were tested, the seams were always located at the center of the parallel panels so that the seams of the test panels coincided with the center-axes of the panels. That would have exposed possibly the weakest joints to the maximum heat exposure from the sand burner.

The PPT data showed that when the flames propagated to the top of the panels, the measured total heat release rate was greater than approximately 1130 kW regardless of the burning material of the panels, provided that the exposure was 360 kW. When flames did not propagate all the way up to the top of the panels, the maximum total heat release rate never exceeded 1130 kW. Thus, the go/no-go decision on the fire propagation in the parallel panels in the table was made based on whether and when the measured total heat release rate during the test hits the 1130 kW point.

The 25 ft corner test results in Table 2 were compared with the results of the corresponding materials in parallel panel tests in Table 3. The parallel panel test results and associated performance from the corner tests are compared in Table 4. In the table, "Fire Propagation" was defined as flames reaching 11.6 m (38 ft) along either eave in the corner test, and flames reaching the top of the panels in the parallel panel test. In the parallel panel tests, however, in addition to the visual flame propagation, the performance was also determined based on the total heat release rate, as explained earlier. When the maximum total heat release rate was greater than 1130 kW, this result was observed to be equivalent to flames propagating all the way to the top. This is a more reliable way of determining fire propagation than the visual observation that tends to be subjective under highly smoky environments.

When the maximum HRR was less than 1130 kW, then the maximum HRR and the corresponding time during the test duration are given. In the corner tests, test duration was 15 min as the standard [3] calls for. In the parallel panel test, the test duration was extended to 20 min in general. However, when the total heat release rate clearly indicated that there was no chance of fire propagation, then the test was terminated after 15 min to protect the test equipment from overheating.

In the corner test with the ¾ in. PVC panels, flames appeared above the top of the pallets at 140 s and reached the 11.6 m (38 ft) limit of the test frame at around 320 s after ignition. Thus it took about 180 s from when the first flame started to impact the panel to the complete propagation of the flames along the south eave. In the corner test with the ¼ in. PVC panels, it took about 172 s from when the first flame started to impact the panel to the complete propagation of the flames along the south eave. In the corner test with the 10 in. polystyrene sandwich panels, it took about 140 s to have flames from the wood pallets appear above the pallets and took about 280 s from the first flame starting to impact the panel to the complete propagation of the flames along the south eave. In all the three cases as shown in Table 4, where the parallel panel test results properly indicated the flame propagation in the corner tests, the times required for the flames to reach to the top of the panels in the parallel panel tests and that to reach to the horizontal end of the test frame in the corner tests were comparable indicating similar flame propagating mechanism.

TABLE 3. List of the parallel panel tests

Test #	**Material**	$\dot{Q}_b$ **(kW)**	**Peak** $\dot{Q}_{ch}$ **(kW)**	**Fire propagation**
1	¼ in. PVC	350	1115	Yes in 160 s
2	¾ in. PVC	360	1362	Yes in 178 s
3	¾ in. PVC	124	180	No in 900 s
4	¾ in. PVC	232	1226	Yes in 870 s
5	¾ in. PVC	185	1142	Yes in 1000 s
6	½ in. PVC	180	963	Yes in 790 s
7	½ in. PVC	60, 90, 120	No data	No in 3100 s
8	½ in. PVC	120, 150	313	No in 1800 s
9	½ in. PVC	160,170, 180	611	No in 1500 s
10	¼ in. PVC	160	731	No in 720 s
11	¼ in. PVC	170	593	No in 900 s
12	¼ in. PVC	180	823	No in 910 s
13	3 in. polyurethane core panels w/ steel facer	349	502	No in 900 s
15	6 in. polyisocyanuarate foam w/ steel facer	349	530	No in 900 s
16	6 in. polyisocyanuarate foam w/ steel facer	344	432	No in 900 s
17	¾ in. FR-Plywood	342	835	No in 1200 s
18	¾ in. FR-Plywood	457	955	No in 980 s
19	½ in. FR-Plywood	343	943	No in 900 s
20	½ in. FR-Plywood	461	906	No in 950 s
21	¼ in. FR-Plywood	344	1494	Yes in 164 s
22	¼ in. FR-Plywood	228	1218	Yes in 187 s
23	¼ in. FR-Plywood	180	678	No in 540 s
25	2-mm-fiberglass-reinforced melamine w/ inert facer	344	527	No in 1200 s
28	10 in. polystyrene panel w/ 26-gage steel facer	360	2100	Yes in 210 s
29	6 in. polyisocyanurate foam with 26 gage steel facer	360	610	No in 20 min

The fire propagation correlation between the corner tests and corresponding parallel panel tests shown in Table 4 is excellent except for the case of ¼ in. FR-Plywood. While the corner test showed that the flames did not propagate all the way to the end of the 11.6 m long wall; thus, qualifying the material to be the Class 1 Approval, the parallel panel test indicated otherwise. Considering that the flames extended to 9.8 m (32 ft) along the horizontal eaves in the 25 ft corner test, just 1.8 m (6 ft) shy of the 11.6 m (38 ft) fail criterion, the prediction based on the parallel panel test is only slightly more conservative. Thus, the overall comparison in Table 4 supports the positive correlation between the 25 ft corner tests and the parallel panel tests.

TABLE 4. Fire propagation correlation between the 25 ft corner test and parallel panel test

Material	**Fire propagation?**		
	25 ft corner test	**Parallel panel test ($\dot{Q}_b$ = 360 kW)**	
	Flames reached 11.6 m (38 ft) eave	**Reached $\dot{Q}_{ch}$ = 1130 kW?**	**Max vertical visual flame propagation**
¾ in. PVC	Yes in 5.3 min	Yes in 3 min	4.9 m (16 ft)
¼ in. PVC	Yes in 5 min.	Yes in 2.7 min	4.9 m (16 ft)
10 in. polystyrene panels with inert facer	Yes in 7 min	Yes in 4 min	4.9 m (16 ft)
¾ in. FR-Plywood	No	No in 20 min $(HRR)_{max}$ = 853 kW at t = 109 s	2.4 m (8 ft)
½ in. FR-Plywood	No	No in 15 min $(HRR)_{max}$ = 960 kW at t = 390 s	3.4 m (11 ft)
¼ in. FR-Plywood	No	Yes in 2.7 min	4.9 m (16 ft)
3 in. polyurethane core panels w/ steel facer	No	No in 15 min $(HRR)_{max}$ = 513 kW at t = 88 s	1.8 m (6 ft)
2-mm fiberglass reinforced melamine w/ inert facer	No	No in 20 min $(HRR)_{max}$ = 543 kW at t = 91 s	3.7 m (12 ft)

It was shown that the 25 ft corner test can be used to provide a reasonable estimate of whether a material can be accepted for 50 ft high maximum or unlimited height once the material passes the test. Based on the correlation between the corner tests and the parallel panel tests, if a material generates more than 1130 kW at any time during the parallel panel test with the exposure of 360 kW, the material is expected to fail the corner tests. Thus, all the material that are expected to pass the corner tests will generate less than or equal to 1130 kW in the parallel panel tests with $\dot{Q}_b$ = 360 kW. It is also clear that a less flammable material will generate a lower $\dot{Q}_{ch}$ in the parallel panel test and would pass the corner test with a higher height limit approval than a more flammable material will do. Thus, it is likely that the $\dot{Q}_{ch}$ in the parallel panel test can be used as a good index for determining whether a material should be approved with “up to 15.2 m (50 ft) high only” or “unlimited height” without conducting the full-scale corner tests.

Applying the conditions specified so far regarding the combined flame extension along the horizontal eaves in the 25 ft corner test to the data in Table 2 shows that the ¾ in. FR-Plywood, the ½ in. FR-Plywood, the 3 in. polyurethane core panels w/ steel facer, the 2 mm fiberglass reinforced melamine w/ inert facer, and the 6 in. polyisocyanurate foam with 26 gage steel facer can reasonably be assumed to behave as a material approved all be approved with “unlimited height” without going through the 50 ft corner tests.

Table 5 shows that the materials that can be expected to behave as a material approved for the “unlimited height,” such as the 3 in. polyurethane core panels w/ steel facer or the 2 mm fiberglass reinforced melamine w/ inert facer, generated a maximum total $\dot{Q}_{ch}$ of less than 543 kW in the parallel panel tests. In addition, the 6-in. polyisocyanurate foam with 26-gage steel facer, which is the last item in Table 5, was not just “predicted to pass” but actually “passed” the 50 ft corner test recently with the unlimited height approval.

TABLE 5. Materials that are expected to pass the 50ft corner tests with the unlimited height approval

Material	**Flame spread along the eaves in 25 ft corner Test**	$\dot{Q}_{ch}$ **in parallel panel test with** $\dot{Q}_b$ **= 360 kW**
¾ in. FR-Plywood	5.5 m (18 ft) along both eaves	853 kW
½ in. FR-Plywood	7.0 m (23 ft) along both eaves	960 kW
3 in. polyurethane core panels w/ steel facer	6.1 m (20 ft) along both eaves	513 kW
2-mm fiberglass reinforced melamine w/ inert facer	5.2 m (17 ft) along both eaves	543kW
6 in. polyisocyanurate foam with 26-gage steel facer	Passed the 50 ft corner test[**] with unlimited height approval	601 kW

The ¾ in. thick FR-Plywood, which meets the proposed approval criterion of the "unlimited height," generated about 853 kW maximum in the parallel panel test with the 360 kW exposure. Although the condition specified earlier indicates that the ½ in. thick FR-Plywood also would be accepted for the "unlimited height," the flame propagation along either horizontal eave was 7.0 m (23 ft) long, which was too close to the 7.6 m (25 ft) criterion established above. Thus, while staying on a conservative side, $\dot{Q}_{ch} < 853$ kW in the parallel panel test with the 360 kW exposure can be accepted as the criterion for approval of a material with the "unlimited height" without conducting full-scale corner tests. After conducting an uncertainty analysis associated with the HRR measurements using the fire-products collector, the two critical values mentioned above, 1130 kW and 853 kW, were further adjusted to 1100 kW and 830 kW, respectively. Thus, in conclusion: (1) if a wall panel passes the parallel panel test with the maximum total heat release rate less than or equal to 830 kW, it is expected to behave as a wall panel approved to passing the 50 ft corner test with the "unlimited height" approval, (2) if it passes the parallel panel test with the maximum heat release rate greater than 830 kW but less than 1100 kW, then it is expected to pass the 50 ft corner test with the "up to 15.2 m (50 ft)" limit, and (3) if it generates greater than 1100 kW in PPT, then the panel will not pass the corner test, with the 360 kW heat exposure.

SUMMARY

This study showed preliminary results demonstrating an example of how an intermediate-scale test can be developed to reliably predict results of a full-scale test evaluating material flammability. Although the full-scale tests provide direct answers to specific problems, the results can be hardly generalized. Due to the limitations associated with full-scale tests, mainly in terms of cost, labor, time, and environmental concerns, other means of predicting test results have to be devised. Bench-scale tests are ideal because of a low cost and a fast turn-around time, but the data are difficult to interpret for the prediction of the full-scale test outcomes without proper physical models, which are by no means easy to come by. In addition, the bench-scale test data always force us to make a second guess on whether the data reflect the true behaviors of a material in a full-scale test. These shortfalls call for an intermediate-scale test, in which the scale of the test is large enough so that the test reveals the true behaviors of testing materials as if they are in the full-scale test but still small enough so that there can be a substantial savings compared with the full-scale test.

A few principles to keep while developing an intermediate-scale test are as follows:

1. It should be clear that what full-scale test is being simulated by the intermediate-scale test.

[**] The 25-ft corner test was not conducted for this material.

2. The correspondence between the expected outcomes in the full-scale test and those in the intermediate-scale test should be precisely established.
3. The common parameters that the full-scale test and the intermediate-scale test should share in order for the results of the intermediate-scale test to be properly interpreted for the outcomes of the full-scale test have to be clearly established

The full-scale test and the corresponding intermediate-scale test adopted as an example in this study are the 25 ft (and the 50 ft) corner test and a 4.9 m high parallel panel test, respectively. The common parameters kept the same for the full- and the intermediate-scale tests were: the view factor for the radiative heat transfer from the burning panels and the heat flux upon the test panels from the source fires. The pass/fail criteria in the corner test, which were based on visual flame propagation along the panels, were replaced by the total heat release rate from the burning panels in the parallel panel test, which would provide a less ambiguity in making the pass/fail decision. The correlation between the corner tests (full-scale) and the corresponding parallel panel tests (reduced-scale) were excellent, implying that the intermediate-scale tests can reliably predict the outcomes of the full-scale tests.

Another application of having a reliable intermediate-scale test is that the tests can serve as a tool to validate a physical model that would utilize the bench-scale test data. Developing a physical model requires many validation tests at each developing stage. If the tests have to be conducted in full-scale, the costs would be prohibitively high. Employing intermediate-scale tests would be instrumental in the successful development of a physical model. Once the model is proven reliable, it will eventually be able to replace the full-scale tests with the bench-scale tests. This method would be the most advanced form of assessing material flammability and the final goal of developing reduced-scale fire tests. The current study shows a way of developing an intermediate-scale test that will serve as a stepping stone to reach the final destination -- an engineering model that can predict the outcomes of full-scale tests by using the material properties measured through the bench-scale tests.

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