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Simulating real compartment fire conditions in a furnace

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Summary

In the United States, wood has been traditionally used in residential construction. However, the combustibility of wood still limits its use as a building material in prescriptive building codes, and to overcome the limitations, performance-based codes can be used. In order to properly analyze performance-based designs, more information on the fire performance of materials is required, including fire performance under different fire exposures. The char rate when timber elements are exposed to the standard time-temperature curve have been well characterized and can be used to determine the fire-resistance rating. However, much less is known about the rate of char formation under other fire exposures and time-temperature curves. In this study, we used time-temperature data from full-scale compartment fire tests and applied that data in an intermediate-scale horizontal furnace. By measuring the furnace temperature, fuel consumption, and heat flux during the various tests, we identified that the furnace could closely replicate the shape of a real time-temperature fire curve from a ventilation controlled compartment. However, the furnace fell short in terms of meeting the peak temperatures at flashover and heat fluxes expected in a real compartment fire.

KEYWORDS

design fire scenario, fire exposure, fire performance, full-scale fire test, timber construction

1 | INTRODUCTION

In the United States, wood has traditionally been used in residential construction. However, there are currently efforts to increase the use of wood in nonresidential and mid-to-high rise construction by employing mass timber elements. The increased market for wood structures can be attributed to increased efforts toward sustainable construction, offsite prefabrication resulting in reduced construction time and costs, and increased architectural options.[1] However, the combustibility of wood still limits its use as a building material via restrictions found in the prescriptive building codes for building characteristics like height, area, and interior and exterior finishes.[2,3] To overcome the confines of prescriptive codes, performance-based codes can be used and allow for more design flexibility and innovation. Performance-based codes require proposed designs to demonstrate compliance by meeting specified fire safety goals using engineering analysis.[4] However, in order to properly analyze performance-based designs, more information on the fire performance of mass timber materials is required, including the fire performance under varying fire exposures.

Fire resistance is a measure of the ability of a building element to resist collapse or other failure during exposure to a fire.[5] Traditionally, prescriptive codes specify the required fire-resistance rating for building components somewhere between 0.5 and 4 hours. The fire-resistance ratings of all structural members and assemblies have traditionally been tested in accordance with ASTM International (ASTM) E119[6] and similar standards.[7-9] Among other things, ASTM E119 specifies a time-temperature curve known as the "standard fire." For structural wood components, char rates under the standard fire exposure are well documented and, for practical purposes, a commonly assumed nominal char rate of 0.6 mm/min is used for all exposed wood members in the absence of other data.[10] The char rate can then be used to conduct an engineering analysis of the fire-resistance rating.[11]

A typical compartment fire undergoes four distinct phases: incipient, growth, fully developed, and decay, while the standard fire curve simply continues to increase over time.[12] While the char rates have been well characterized for the standard fire, less is known about the rate of char formation under other time-temperature curves. Schaffer measured char rates under constant temperature conditions at 538°C, 815°C, and 927°C.[13] Others have found that the charring rate is proportional to the ratio of external heat flux divided by density.[14-16] However, it is known that the char rate is significantly affected by the severity of the fire exposure, and data on charring rates for nonstandard fire exposures have been limited to more recent studies related to the recent increase in interest in mass-timber buildings.[17-20] The lack of information on char rates under these conditions makes it difficult to perform fire resistance calculations under non-standard fires. Recently, several full-scale fire tests on mass timber compartments have been conducted.[21-24] From these full-scale tests, a vast amount of data was collected, including real compartment time-temperature curves. In addition to the full-scale research tests, a full-size test compartment (2.7 × 5.7 m) is required to evaluate the adhesives intended for use in a cross-laminated timber (CLT) during a fully developed fire in ANSI/APA PRG 320-2018.[25] While important, full-scale tests are expensive and unrealistic to run when determining fire performance of building materials, components or assemblies. In an effort to simulate the real compartment fire curves, design fire furnace curves were developed and run on an intermediate-scale furnace. Here we present the experimental considerations and initial results of developing and running these design fire furnace curves.

2 | MATERIALS AND METHODOLOGY

2.1 | Materials

Six wood species were chosen for the study based on their use in the construction industry, varying densities and use in previous work conducted by White.[26,27] The softwoods tested included Douglas fir (*Pseudotsuga menziesii*), southern yellow pine (*Pinus spp.*), redwood (*Sequoia sempervirens*), and black spruce (*Picea mariana*). The hardwoods tested included red oak (*Quercus spp.*) and maple (*Acer spp.*). Table 1 provides the measured densities for the species. Prior to construction of the specimens, the lumber was conditioned in a 21°C/50% relative humidity room until equilibrium. All specimens, except black spruce, were constructed from lumber with a cross-section of approximately 83 × 83 mm. The black spruce specimens were constructed from lumber with a cross-section of approximately 32 × 83 mm. After installation of thermocouples, described in Section 2.4, the lumber was glued with a phenol-resorcinol-formaldehyde (PRF) adhesive (Hexion Cascophen LT-75 with Cascoset FM-282). PRF adhesive was used as Schaffer observed that char progresses through PRF in the same manner as in solid wood.[28] Figure 1 shows six completed specimens, with a final exposed surface dimension of 412 × 412 mm, wrapped in ceramic fiber batting.

TABLE 1 Measured densities for each species

Species	Density (kg/m^3)
Douglas fir	485
Southern yellow pine	407
Redwood	361
Black spruce	532
Red oak	672
Maple	724

2.2 | Furnace

The intermediate-scale horizontal furnace located at the Forest Products Laboratory (FPL) is a metal box lined with high temperature-resistant insulation and heated by eight diffusion-flame natural gas burners on the floor of the furnace. The interior dimensions of the furnace are 1.83 m long, 1.09 m wide, and 1.27 m high. All air for combustion was provided by natural draft through static vents at the bottom of the furnace. Six capped furnace thermocouples were located 305 mm from the top of the furnace interior. The gas was controlled so the average temperature of the six capped thermocouples followed the desired time-temperature curves. The lid of the furnace varied and was either inert ceramic material or contained six wood specimens. No loading was applied to the specimens for this test series. Figure 2 shows the furnace without the lid in place.

Although the furnace was controlled via internal temperatures, a gas flow meter (Fox Flow Meter, FT2A-06 IE-SS-ST-E2-B0-G3) was

FIGURE 1 Six wood specimens wrapped in ceramic fiber batting [Colour figure can be viewed at wileyonlinelibrary.com]

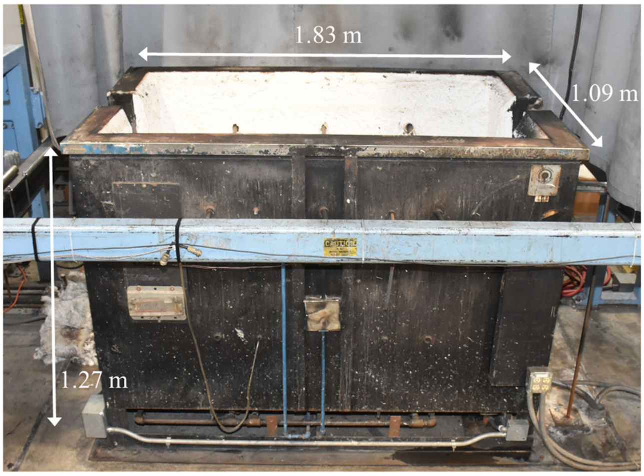

FIGURE 2 Intermediate-scale furnace located at Forest Products Laboratory (FPL) shown without lid [Colour figure can be viewed at wileyonlinelibrary.com]

installed on the natural gas line feeding the furnace to monitor fuel consumption.

2.3 | Fire curves

In addition to the standard fire defined in ASTM E119, three real, ventilation-controlled compartment fire curves obtained from full-scale fire tests of CLT structures were used to develop two design fire curves achievable in the furnace. Figure 3 shows the three real compartment fire curves versus the standard fire curve.

The first design fire curve was based on Test 3 of the Tall Wood Building (TWB) Fire Tests conducted at the ATF Fire Research Laboratory.[23] This compartment test was conducted on a full-scale apartment with one exposed CLT wall in each room. Data from a thermocouple located 2.74 m above the finished floor in the living room was used as a basis to define the furnace time-temperature curve. The second design fire curve was based on Tests 3 and 7 from full-scale fire tests conducted by Li et al on a single-room compartment.[21] The growth and fully developed phases of Test 3 were combined with the decay phase from Test 7 to develop the desirable time-temperature profile for the second design fire curve to be run in the furnace. Test 3 was a fully exposed CLT room, and Test 7 was a room with one exposed CLT wall.[21] Figure 6 shows the combination of Test 3 and Test 7 data, referred to here as LI, as well as the second design fire curve. The real fire curve data from TWB and LI were then applied in the furnace and the corresponding design fire curves are referred to as furnace curves F1 and F2, respectively.

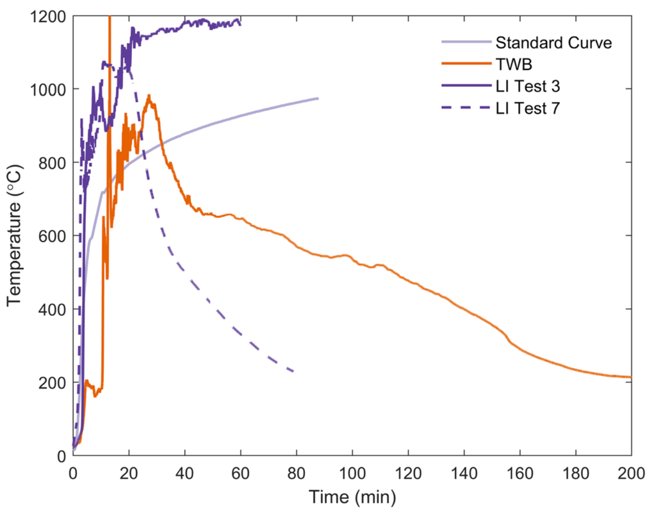

FIGURE 3 Standard fire curve compared with the real fire curves (Tall Wood Building [TWB] and Li) that were used to develop the design fire furnace curves [Colour figure can be viewed at wileyonlinelibrary.com]

2.4 | Instrumentation

In addition to the thermocouples that controlled and monitored the furnace temperatures, 18 thermocouples made in-house from 30 gauge type K wire (Omega GG-K-30-SLE) were installed in each wood specimen at various depths. There were a total of 108 embedded thermocouples for each test with wood specimens installed in the lid. These thermocouples, shown in Figure 4, were installed by drilling 2.4 mm (3/32 inch) diameter holes to the middle of the lumber (16 mm for black spruce and 41 mm for all other species), creating a channel for the thermocouple wire and inserting and stapling the thermocouples in place. The final configuration was such that the thermocouples were parallel to the isotherms and the adhesive lines were perpendicular to the isotherms. This configuration has been shown to provide more accurate measurements of temperature compared to a perpendicular thermocouple installation.[29,30] The embedded thermocouples were used to monitor the temperature profile of each wood specimen with respect to time. The depths of the thermocouples (Table 2) varied based on the furnace curve and previous data to optimize the locations and best capture the temperature profile in the specimens. Additional thermocouples were installed on the fire-exposed and nonfire-exposed surfaces of each specimen.

Two water-cooled heat flux sensors (Huskeflux, SBG01) were installed when wood specimens were used in the lid. The location of the sensors varied to determine the effect of location in the furnace on the heat flux to the specimen surface. During the standard and F2 furnace tests, the heat flux sensors could only be used until the char reached a depth of approximately 25 mm (1 inch). After that point, the sensors had to be removed to prevent damage. For the F1 furnace tests, a water-cooled holder was made for the heat flux sensors that allowed them to be used for the entire test.

3 | RESULTS

3.1 | Fire curves

When developing the furnace curves, the main features of the real fire curves that were desirable to simulate in the furnace included the

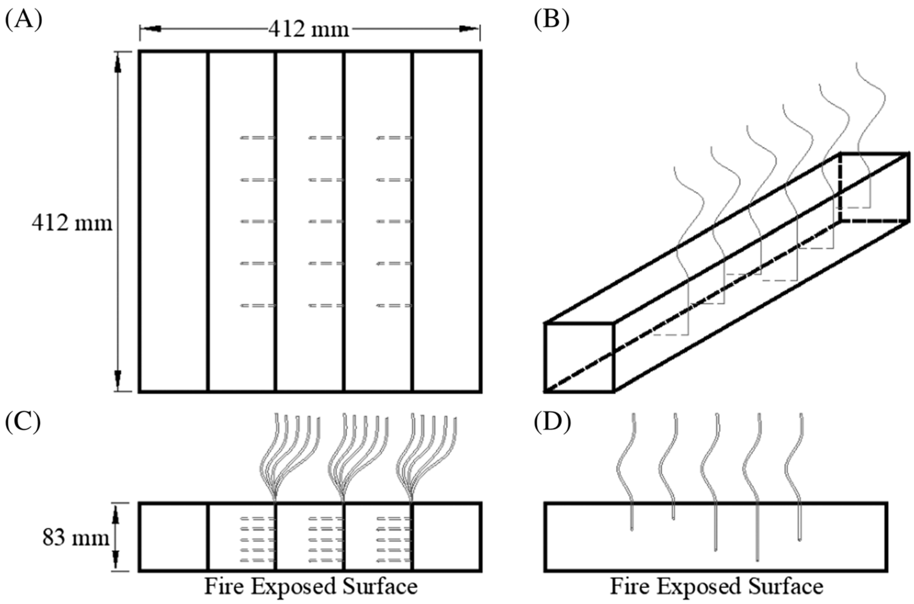

FIGURE 4 Schematic of (A) top (unexposed surface) view of wood specimens, (B) individual lumber with thermocouples installed parallel to isotherms, (C) side view of specimen. and (D) side view of individual lumber with thermocouples

TABLE 2 Thermocouples placement varied between each test to optimize the resolution of the char front

Test	Standard 1	Standard 2	Standard 3	F1 1	F1 2	F1 3	F2 1	F2 2	F2 3
Depth from fire exposed surface (mm)	12	10	10	10	7	6	16	16	16
	24	20	20	20	14	12	32	32	32
	36	30	30	30	21	18	47	40	38
	48	40	40	40	28	24	55	48	44
	60	50	50	50	35	30	63	56	50
	72	60	60	60	42	36	71	64	56

maximum temperature, average heating rate, and the cooling rates during the decay phase. To better meet the features of the TWB real fire curve, F1 was started at 8.46 minutes into the real fire curve. The maximum temperature in TWB reached 1233°C at 4.03 minutes on the shifted time scale. However, the spike was brief and unlikely to have a significant effect on char rates. The second highest temperature in the compartment was 985°C at 18.11 minutes. The F1 curve hit a maximum temperature of 969°C at 18.75 minutes, resulting in a furnace curve that is very close to the real fire curve. As can be seen in Figure 5, the heating and cooling rates between the TWB and F1 were closely matched.

Figure 6 compares the LI real fire curve with the attainable, F2 furnace curve. The maximum temperature in LI during the fully developed phase was 1192°C at 46.7 minutes, while the maximum temperature reached in the furnace was 1024°C at 61 minutes in F2. The fully developed phases for both the LI and F2 curves lasted approximately 52 minutes and 54 minutes, respectively. Due to limitations of furnace power, the heating rate and maximum temperature from LI were not able to be matched in the furnace. However, the F2 furnace curve was able to closely follow the decay phase from LI.

For each furnace test conducted, the area under the time-temperature curve above a 20°C baseline was computed for the

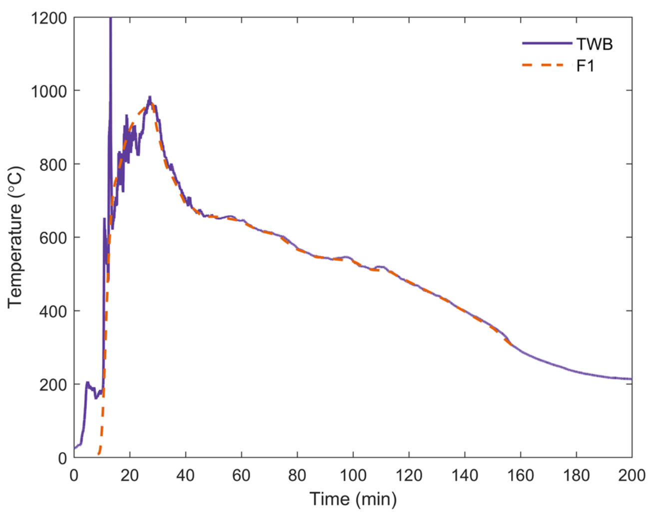

FIGURE 5 Comparison of the F1 furnace curve with the Tall Wood Building (TWB) real fire curve [Colour figure can be viewed at wileyonlinelibrary.com]

duration of the test. The average for the three replicates of each furnace curve is presented in Table 3. The area under the real fire curves (TWB and LI) was calculated for the same duration as the furnace tests

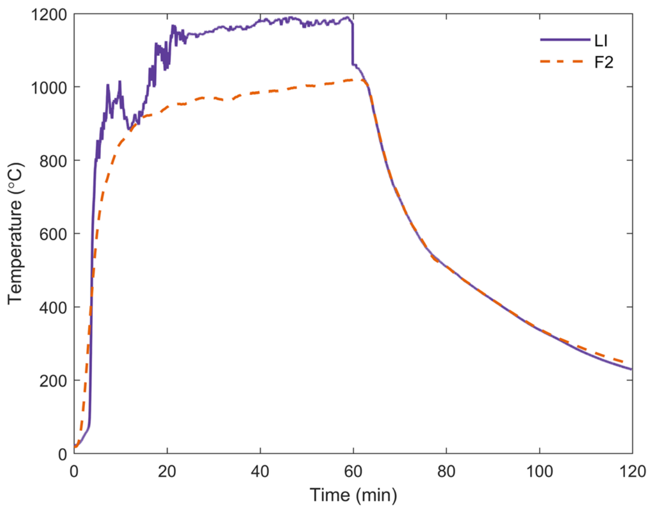

FIGURE 6 Comparison of the F2 furnace curve with the combined real fire curve, LI [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Comparison of average areas under time-temperature curves

	Standard Curves	TWB vs F1 Curves	LI vs F2 Curves
Area under furnace curve (F1 or F2) (°C-min)	71 559	82 512	79 500
Area under real curve (TWB or LI) (°C-min)	71 772	84 400	88 330
Area % difference compared to real curve (%)	−0.30 ± 0.5%	−2.24 ± 0.1%	−10 ± 0.5%
Duration (min)	87.9	150.0	118.3

and can also be found in Table 3. In the case of the standard curve, the area under the curve was interpolated for the tested duration from Table X1.1 taken from ASTM E119.[6] The percent difference between the real curves and the furnace curves was calculated as

$$\%difference = 100\left(\frac{area\ furnace\ curve - area\ real\ curve}{area\ real\ curve}\right). \quad (1)$$

The standard fire curve was within 0.3% of the theoretical curve. The areas under the furnaces curves, F1 and F2, were below the corresponding real fire curves (TWB and LI) by 2.4% and 10%, respectively.

3.2 | Fuel consumption

For each design fire furnace curve, three tests were run with wood specimens in the lid as well as one test with a noncombustible lid. Currently, there are discussions regarding the amount of fuel used when comparing combustible and noncombustible construction materials.[31,32] The fuel required will vary based on furnace configuration, so to evaluate the difference in fuel consumption between the two lid types on, the gas flow was measured for all tests. The tests run with wood specimens consumed less fuel than the noncombustible lid due to the energy contribution of the burning wood. A comparison of the energy used in the different tests can be found in Table 4. For each curve, the flow rate of gas, plotted in Figure 7 below, was integrated and converted from the volume of gas consumed to the amount of energy consumed assuming that natural gas has a gross heating value of 37.3 MJ/m^3. For the furnace tests run with wood inserts, the value in the table represents the average

TABLE 4 Comparison between energy used to run furnace with inert lid versus with wood samples

	Standard	F1	F2
Inert lid (MJ)	833	845	791
Wood inserts (MJ)	679	784	664
Difference (MJ)	154	61	127

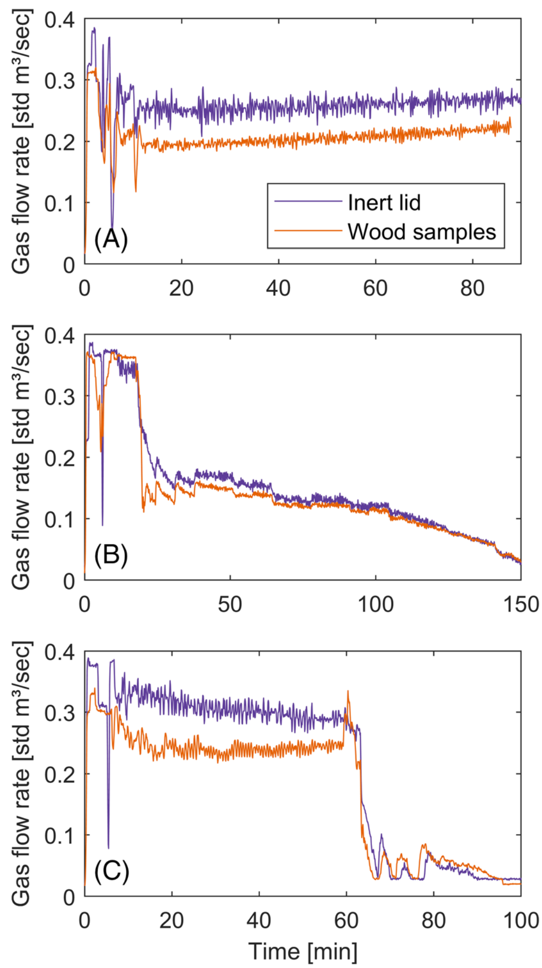

FIGURE 7 Gas flow rate during the (A) standard curve tests, (B) TWB furnace curve tests, and (C) LI furnace curve tests [Colour figure can be viewed at wileyonlinelibrary.com]

value for the energy used in three replicates. The difference was calculated simply as the average of the wood tests subtracted from the value measured using the inert lid.

3.3 | Heat flux

The heat flux in the furnace was measured in two places for each furnace curve test, for a total of six measurements for F1 and six for F2. The averages of those measurements are provided in Figure 8. For F2, the maximum measured heat flux before the sensor had to be removed was approximately 150 kW/m^2 at 28 minutes. However, it is expected that the heat flux would continue to increase after that point until the beginning of the decay phase. The heat flux for the F1 curves peaked around 145 kW/m^2 at 19 minutes, which correlates to the time of the maximum temperature for that curve. Both of the furnace curves produced heat fluxes on the surface of the specimens that were significantly higher than that of the standard fire curve during the time period measured. It is important to note that because these measurements were taken with water-cooled Gardon/Schmidt-Boelter type gauges, they represent the heat flux incident on the surface of the specimen.

4 | DISCUSSION

Harmathy and Lie once suggested, "to achieve maximum economy in fire endurance design, the fire load concept must be abandoned and the fire test must become a truer representation of the conditions that probably will be met under particular circumstances.[33]" They pointed out that to do this would mean replacement of the standard temperature-time curve by more realistic ones or by a heat-flux-time relationship. The current standard furnace time-temperature tests are practical in terms of repeatability and cost, but do not aid in the prediction of material behavior during a real fire. Conversely, full-scale

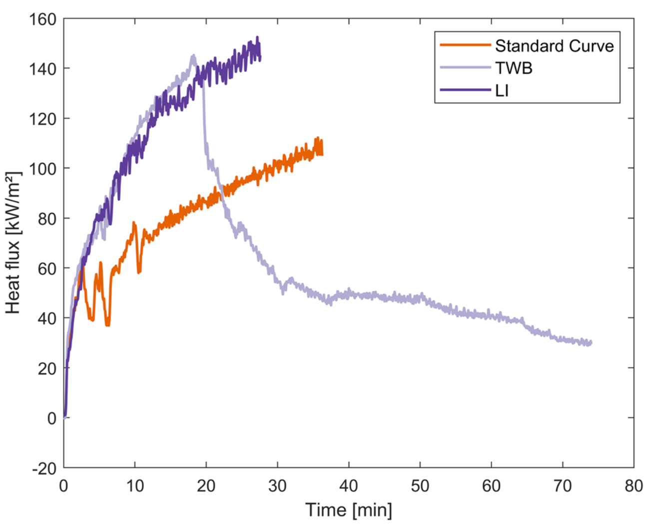

FIGURE 8 Average incident heat flux for each time-temperature curve run in the furnace [Colour figure can be viewed at wileyonlinelibrary.com]

fire tests provide important information about material performance and material effects on compartment fires, but are costly and time-consuming. Identifying the abilities and limitations of a furnace when producing more realistic fire curves will facilitate and improve on the currently available methods for determining fire resistance of building materials.

In this study, we used time-temperature data from full-scale compartment fire tests and applied that data in an intermediate-scale horizontal furnace to try and replicate the real fire curves. By measuring the furnace temperature, fuel consumption, and heat flux during the various tests, we identified that the furnace could closely replicate the shape of a real time-temperature fire curve from a ventilation controlled compartment. However, the furnace fell short in terms of meeting the peak temperatures at flashover and heat fluxes expected in a real compartment fire.

4.1 | Furnace curves

Sultan, et al found that the furnace temperature measuring device response time is crucial in assessing building elements performance particularly in a short duration tests.[34] The furnace temperatures here were controlled based on measurements made by thermocouples inside protection pipes as specified in ASTM E119.[2] However, the real fire curves were measured on bare thermocouples located in different positions throughout the room. For this reason, a comparison of the real fire curves and the furnace curves reveal some differences. The protection pipes on the furnace thermocouples damp out the measurement of temperature changes in the furnace and add a short time delay between the actual temperature of the furnace and the measured temperature. This effect can be seen in Figures 5 and 6, where the furnace curves are smoother than the real fire curves and do not contain all of the short temperature peaks. While the dampening of the temperature measurements reduced the ability of the furnace to meet the initial heating rates past a temperature of 750°C, the furnace was able to match a time weighted average of the TWB real curve. This was not the case for the LI real fire curve where the temperatures during the fully developed phase were too high for the furnace to match. A furnace designed for higher ramp rates and temperatures with higher power burners, perhaps with premixed air and fuel, could help to achieve the faster ramp rates and higher temperatures of certain real compartment fires.

4.2 | Fuel consumption

Recent discussions surrounding standard fire resistance furnace tests have questioned the different thermal exposures between combustible and noncombustible products.[31] The argument being that the fuel input into a furnace differs between building materials when controlled based on temperature, and, therefore, the current fire-resistance ratings from a furnace test do not account for the contribution of a combustible structure to the intensity and duration of a real fire. Despite these concerns, Schmid et al point out that, regardless of the lid construction (noncombustible vs wood inserts), the thermal exposure is equivalent in furnaces simulating a ventilation controlled fire development for a pre-defined duration.[32]

For this test series, the overall goal was to determine if the intermediate-scale furnace located at the FPL was capable of following a realistic time-temperature curve from ventilation-controlled compartment in lieu of the standard fire curve. Because of this goal, it was important to control the furnace based on temperature although the fuel consumption was measured for each curve. Here, the difference in fuel consumption between tests with the noncombustible lid and tests with wood specimens is due in part from the energy contribution of the burning wood and thermal inertia differences between the inert material and the wood. Future work will evaluate the effect of the fuel consumption between lid materials compared with real compartment fires.

4.3 | Heat flux

The heat flux sensors remained in place longer for the F1 furnace curves when compared with the F2 and standard fire furnace tests, and it is reasonable to expect the heat flux for the F2 and standard fire curves to be higher than what was recorded. The heat flux for the F2 furnace curve would have continued to increase until approximately 60 minutes when the decay phase of the programed furnace curve began. Based on previous work, the heat flux during the standard fire curve would have continued to roughly 175 kW/m^2 at 2 hours.[34,35] While the peak heat flux occurred faster in the design fire furnace curves (F1 and F2) when compared with the standard fire curve, the maximum heat fluxes are still below what would be expected in an actual fire compartment. For the TWB test series, the incident heat flux in the compartment, as measured by a directional flame thermometer, reached almost 240 kW/m^2.[36] Future work will investigate the effect of the lower heat flux achieved in the furnace versus the higher heat flux expected in a compartment fire.

5 | CONCLUSIONS

The current standard furnace test does not provide a realistic fire exposure, and furnace fire tests must move toward a more realistic representation of the conditions expected in a compartment to determine material performance. This work shows that we were able to run nonstandard curves in our furnace and that we can see substantial, meaningful, and repeatable differences in the heat flux and fuel consumption. Future work is needed to compare the char rates measured in this experiment with those measured in full-scale compartment fires; this will ultimately determine whether or not the curves simulated in the furnace are close enough to real compartment fires to draw any useful conclusions. Additionally, future work will examine the effect of the fuel consumption and heat flux differences. While more research is needed to develop and validate more realistic time-temperature curves in a furnace, this work allows for the ability to obtain more realistic data from furnace tests.

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