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RESEARCH BRIEF 2002/009

Evaluation of the Performance of Fire Doors – An Integrated Approach

INTRODUCTION

Fire resistance of doors is strictly a conferred performance by the prototypical design of the doors, the alteration of which would nullify the fire resistance performance. This research leveraged on a double-barrelled product development and fire hazard assessment plan to enhance fire safety. An improved prototypical design plan for FD 30 door prototype was developed, encoding broad and descriptive limitations and variations into specific constructional forms and quantitative dimensions, in relation to the fire resistance performance in the standard tests. This design plan mainly covered single-latched, single-swing FD 30 flat-edge timber doors with and without lippings. A bench-scale fire resistance testing protocol using the Cone Calorimeter was further fine-tuned and modelled in tandem with the design guide. It aimed to provide a cost and time efficient fire resistance evaluation technique of timber doors, in lieu of the full-scale furnace testing.

The two main objectives of this study were to: -

- validate the proposed limitations and variations in the door prototypical plan via the developed char rates specific for finite timber door structures, and
- examine the bench-scale fire burning characteristics to validate the correlation of fire resistance performance.

METHODOLOGY

Determination of nominal charring rates

The charring rate, as characterised by *the rate of advance of char front*[1] *(mm/min)*, was determined from the temperature profiles. The increased charring rate encountered in the exposed members, such as the door frame structure, was provided by the rounding-of-arrises design approach.

The charring rates in the scaled furnace were modelled from the mock-up timber door assemblies (Fig. 1). The cube specimens were tested in both

Figure 1: Scaled furnace testing – "Cube Test".

overpressure (max 20Pa) and atmospheric pressure conditions. Insulation and integrity failures were assessed in accordance with BS 476: Part 20: 1987 [1].

In the Cone Calorimeter fire resistance evaluation, 100 mm x 100 mm x 42 mm thick hardwood specimens were tested to a linear heat flux of 50 kW/m^2 in the open atmospheric condition (Fig. 2). Important burning characteristics such as the char contraction factors, char yield and char density were also determined from both the furnace and Cone Calorimeter.

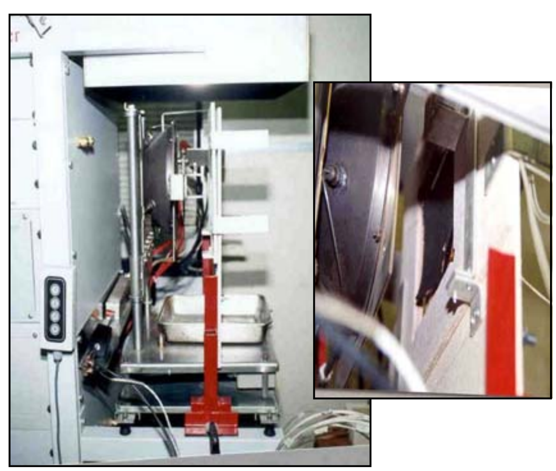

Figure 2: Cone calorimeter set up. Inset: Close-up view of the charring test in the cone calorimeter.

[1] The interface where the temperature in wood has attained 288°C in the perpendicular axis normal to the vertical surface of the timber structures.

Cone Calorimeter measurements

For calorific studies, 100 mm x 100 mm timber specimens of 42 mm thickness were tested in accordance with the standard procedures listed in BS 476: Part 15:1993 [2], or the equivalent in ISO 5660-1: 1993 [3]. Heat release rate (HRR), heat of combustion (HOC) and mass loss rate (MLR) were collected from each wood sample to compute charring rate as well as to examine char oxidation.

RESULTS

Burning behaviour of finite timber

The finite thickness of timber construction could not achieve pseudo-steady-state heat transfer in both the atmospheric and overpressure Cube Tests[2]. It was therefore incorrect to use the nominal charring rates proposed by BS 5268: Part 4: 1978 [4] for fire resistance design of timber door structures since it assumed a steady-state heat transfer. Burning behaviour in finite timber was modelled to obtain the correct average charring rates for fire resistance design of timber doors.

The time-location models for charring behaviour showed that in both the scaled furnaces and Cone Calorimeter, there was a non-linear relation between time and the location of the char front for all the finite timber slabs. The charring rates in the furnace increased with time. The ever-increasing temperature time-curve in the furnace sustained heat penetration through the built-up char layer, thus raising the charring rates. The charring rates are summarised in Table 1.

Table 1: Charring Behaviour and Time-location Model in Overpressure Furnace

Generic Hard-wood	Char Depth (mm)	Charring Rate (mm/min)	Time-location Model	Charring Rate (mm/min)	Time-location Model
Balau	16	0.382	$Y=6.775x^{0.71}$	0.417	$Y=1.105x^{1.29}$
	24	0.326		0.320	
	32	0.397 ↑		0.346 ↑	
Kapur	16	0.529	$Y=10.952x^{0.52}$	0.442	$Y=2.213x^{1.01}$
	24	0.258		0.402	
	32	0.496 ↑		0.441 ↑	
Meranti	16	0.495	$Y=22.505x^{0.27}$	0.320	$Y=12.718x^{0.50}$
	24	0.308		0.368	
	32	0.543 ↑		0.456 ↑	
Nyatoh	16	0.354	$Y=26.861x^{0.26}$	0.396	$Y=1.119x^{1.32}$
	24	0.284		0.248	
	32	0.523 ↑		0.328 ↑	
Durian	16	0.463	$Y=9.142x^{0.63}$	0.611	$Y=0.326x^{1.58}$
	24	0.221		0.514	
	32	0.401 ↑		0.408 ↑	

In the Cone Calorimeter, the opposite was observed. The experimental results showed that the test parameters affected charring behaviour in the timber specimens of the same finite thickness. The constant linear 50-kW/m^2-heat flux in the Cone Calorimeter could not counterbalance the insulative effect of the progressively thicker char base. The charring rates decreased with time, as shown in Table 2.

Table 2: Charring Behaviour and Time-location Model in the Cone Calorimeter

Generic Hardwood	Char Depth (mm)	Charring Rate (mm/min)	Time-location Model
Balau	16	0.506	$Y=0.516x^{1.45}$
	24	0.313	
	32	0.312 ↓	
Kapur	16	0.553	$Y=1.508x^{1.05}$
	24	0.503	
	32	0.368 ↓	
Meranti	16	0.562	$Y=1.314x^{1.09}$
	24	0.519	
	32	0.388 ↓	
Durian	16	0.672	$Y=0.323x^{1.58}$
	24	0.624	
	32	0.595 ↓	

These findings questioned the validity of the correlation of fire resistance performance based on the experimental char rates at this stage without further examining the underlying physico-mechanical mechanisms and reactions. The study examined char oxidation and the burning characteristics in relation to the oxygen and ventilation levels, to develop correlation between the two test environments.

Char oxidation

Studies have suggested that char oxidation occurring at the later part of the test where the furnace temperature was higher, might cause an additional surface recession of the char layer and increase the charring rate [5]. However, the char contraction factors obtained from the furnace (Table 3) agreed well with the contraction factors derived from the nitrogen environments [6-10]. The results therefore suggested that char oxidation was not a significant cause in these charring tests.

Table 3: Timber Properties for Door Core Construction

Hardwood species	Density (kg/m^3)	BS 476: Part 22: 1987		ASTM E 119	
		Notional Charring Rate (mm/min)	Notional Char Contraction Factor (dimension-less)	Notional Charring Rate (mm/min)	Notional Char Contraction Factor (dimension-less)
Heavy Hardwood; Durability > 10 years					
Balau	900 - 925	**0.361**	0.809	**0.368**	0.834
Medium Hardwood; Durability 2-5 years					
Kapur	740 - 850	**0.428**	0.862	**0.428**	0.905
Light Hardwood; Durability 2-5 years					
Meranti	740 -	**0.381**	0.834	**0.449**	0.961
Nyatoh	875 -	**0.324**	0.716	**0.387**	0.729
Light Hardwood; Durability 0-2 years					
Durian	550 - 570	**0.510**	0.645	**0.362**	0.650

In the Cone Calorimeter, the heat release results showed that in all the wood samples, the *EHC* fell below the *Burning Rate* curves of timbers (Figs. 3 to 6), which indicated that char oxidation did not occur

[2] The heat transfer profiles showing the transient temperature gradient in finite timber specimens tested in Cube Tests as well as in the Cone Calorimeter were shown in the final report of the same research, "Evaluation of the Performance of Fire Doors – An Integrated Approach", R-296-000-028-107/112/592, April 2002, Department of Building, School of Design and Environment, National University of Singapore.

Rate of Heat Release* and Effective Heat of Combustion Graphs of Hardwood for 30 Minutes' Exposure to 50 kW/m^2 Vertical Orientation in the Cone Calorimeter.

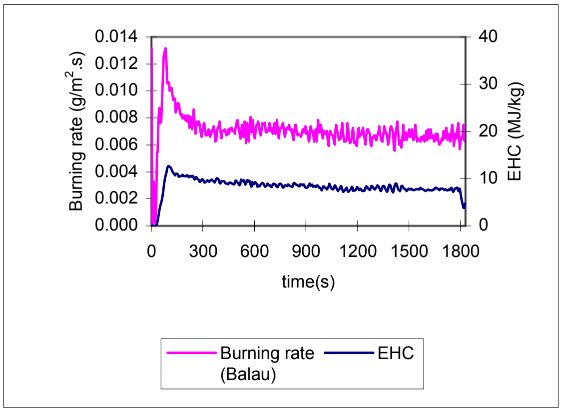

Figure 3: HRR and EHC of Balau sample.

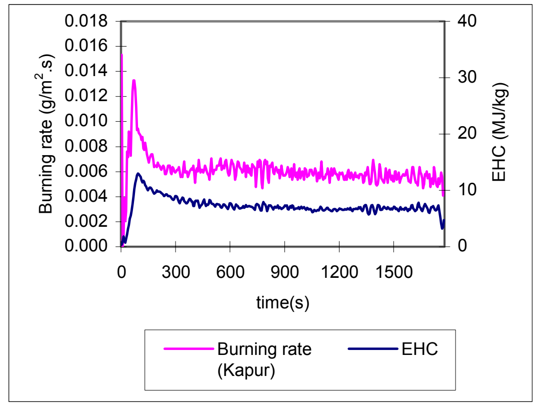

Figure 5: HRR and EHC of Kapur sample.

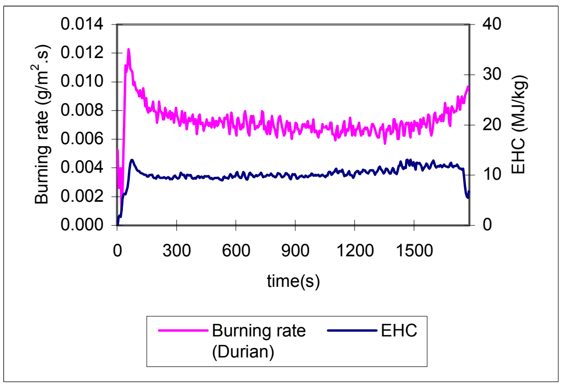

Figure 4: HRR and EHC of Durian sample.

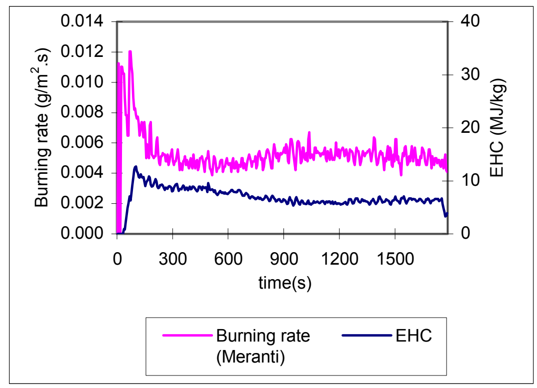

Figure 6: HRR and EHC of Meranti sample.

**HRR (kW/m^2) has been normalized to "Burning Rate" in units of $g/m^2.s$ to facilitate comparison with Effective heat of Combustion (EHC) as shown in Figures 2 to 5.*

during the 30 minutes of testing. The full flame sheet that covered the timber specimens with horizontal fissures excluded the oxygen from oxidising the char, despite a high oxygen level. The results of heat release data strongly purported the numerical correlation of char depths between the two test protocols.

Fire resistance and analytical design

The study found that the average charring rates in furnaces ranged between *0.324 mm/min* to *0.428 mm/min*[3] when tested according to BS 476: Part 20: 1987; and varied between *0.362 mm/min* to *0.449 mm/min*, when burnt according to ASTM E152: 1981, as shown in Table 3. These actual average charring rates for the door leaf core were in fact lower than 0.5 mm/min proposed for analytical design of hardwood with density greater than 650 kg/m^3 and 18% moisture content[4].

This study also found that the standard furnace and Cone Calorimeter produced similar char contraction factors, which showed that both techniques could in fact yield similar extents of char depth, despite the different test configuration and ventilation level.

CONCLUSION

A constructional guide was developed for FD 30 timber fire door construction. Some important quantitative findings indicated that for FD 30 timber door, the required door core thickness was established between 42 mm to 45 mm, using hardwoods with density greater than 650 kg/m^3. No thicker door core was required to achieve FD 30 for BS 476: Part 20: 1987 or ASTM E152: 1981. Analytical design using the char depth and charring rates obtained from the Cone Calorimeter was developed to evaluate the fire resistance of timber fire doors.

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[3] Except the average charring rate for Durian: 0.510 mm/min as the density tested was below the minimum 650 kg/m^3 as set out in BS 5268: Part 4.

[4] **BS 5268: Part 4: Section 4.2: 1978**. **Fire Resistance of Timber Structures. Section 4.1 Recommendations for Calculating Fire Resistance of Timber Members**. British Standards Institute, London.

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