SCALE REDUCTION: HOW TO PLAY WITH FIRE?

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INTRODUCTION

Fire testing for evaluating the reaction and resistance to fire of materials is generally time-consuming and expensive. Nevertheless, those tests are required to evaluate materials in many sectors such as building or transportation. Due to the complexity of fire phenomenon, full-scale tests are still the main and the most credible tool for investigating fire-related issues. However, the cost of those tests significantly increases with scale. The purpose of this paper is to examine the scale reduction of different tests and to mimic fire scenarios at the small scale.

In this paper, the scaling reduction of some fire tests of interest is presented. It deals with the Steiner tunnel (ASTM E-84), furnace test (UL 1709), single burning item (SBI) and the burner test (ISO 2685). It covers different types of materials (composites and steel) and several applications (composite and steel for building and carbon fiber reinforced composite (CFRP) for aviation). In all cases, the fire protection is provided with an intumescent coating.

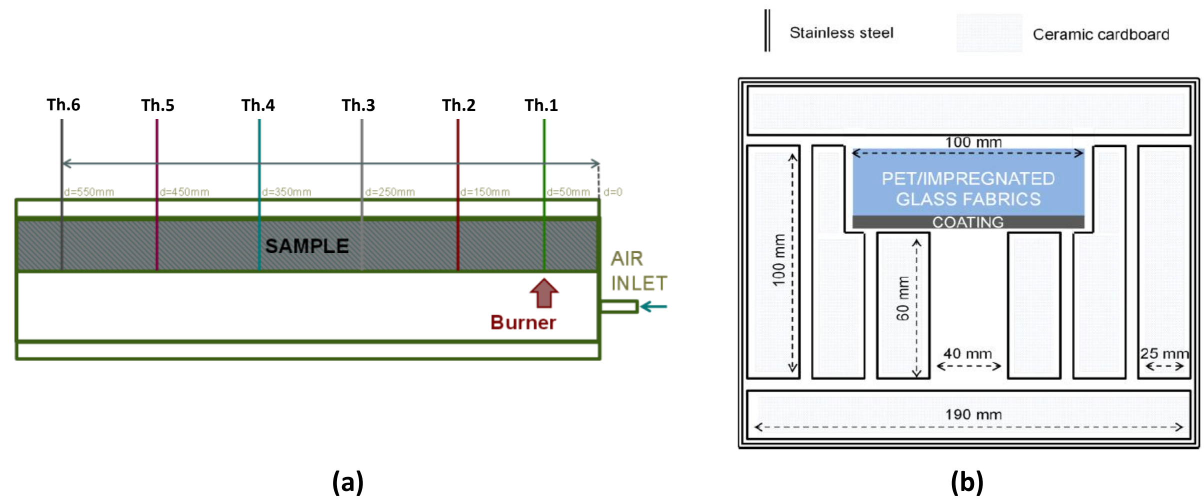
The fire protection of materials like CRP or steel can be achieved with reactive insulation coatings which react when exposed to fire increasing their thermal insulation properties, thereby protecting the underlying substrate. It happens with intumescent coatings which expand and form an insulative layer at the surface of the substrate upon heating. The intumescence process results from a combination of charring and foaming at the surface of the substrate[1,2]. The result of this process is the formation of a multicellular (alveolar) barrier, thick and non-flammable, which protects the substrate or residual material from heat or flame action. The charred layer acts as a physical barrier which slows down heat and mass transfer between gas and condensed phase. The formation of an intumescent char is a complicated process involving several critical aspects: rheology (expansion phase, viscoelasticity of char), chemistry (charring) and thermophysics (limitation of heat and mass transfer)[3]. Hence, the formation of the intumescent barrier must be adapted to the fire scenario. It is considered in the different fire tests presented in this following.

STEINER TUNNEL (ASTM E-84)

The use of composites in civil engineering structural components is increasing thanks to their light weight, high specific strength, and stiffness properties[4]. In this section, we consider polyethylene terephthalate (PET) foam sandwich structured composites used for making the ceiling of railway stations. We investigated the potential benefit of using intumescent coatings for improving the resistance to fire of PET foam-based composite. The goal is to show if better performance in terms of fire retardancy and smoke emission can be obtained using an appropriate commercial intumescent coating for protecting the composite against fire. The composite to be tested is a PET foam block (ARMAform, Armacell Benelux SA) covered with glass woven fabrics (Gurit) impregnated by an epoxy resin (Ampreg 21FR, Gurit). Different commercial intumescent coatings have been selected, including epoxy-based [Chartek8 of International Paint, Firetex M93 of Sherwin Williams (formely Leigh's paint) and XE 2458/1 of Axson], polyester-based [Polycor 2330 BR, Cray Valley] and latex-based [Avicoat FS/DS of Arabian vermiculite, Firefree 88 of Firefree coatings, Intuflam of Lurie and Pyroplast ST200 of Rutgers Organics] resins. A mass of 1kg of wet paint per square meter has been applied.

The associated test for evaluating our materials is the Steiner Tunnel (ASTM E-84). Steiner tunnel is a large scale test which is referenced as a method to assess flame spread and smoke density. It is the primary test method for evaluating resistance to fire of interior finish materials. The apparatus consists of a tunnel-like enclosure measuring 8.7 × 0.45 × 0.31 m (25 × 1½ × 1 ft). The test specimen is 7.6 m (24 ft) long and 0.46 m (18 in.) wide and is mounted in the ceiling position. It is exposed at one end, designated as the burner end, to an 88-kW (5000-Btu/min) gas burner. There is a forced draft through the tunnel from the burner end with an average initial air velocity of 1.2 m/s (240 ft/min). The measurements consist in flame spread over the surface and smoke obscuration in the exhaust duct of the tunnel. The test duration is 10 minutes, flame spread is determined visually through windows built into the tunnel and an optical cell mounted at the tunnel exhaust measures the smoke density. A flame spread index (FSI) is calculated on the basis of the area under the curve of flame tip location versus time. The FSI is 0 for an inert board, and is normalized to approximately 100 for red oak flooring. A smoke developed index (SDI) is calculated on the basis of the area under the light obscuration vs. time curve, and is equal to 100 for red oak flooring. To make fast evaluation of our materials, we developed a ‘mini’ Steiner tunnel (reduction of the Steiner tunnel at 1/8 scale) which is fully described in Figure 1. The burner is fed with methane and the flow rate is 0.74 l/min (gas velocity = 1.9 m/s). It gives a temperature at the surface of the evaluated sample of about 980°C. Temperatures as a function of time (it is not required in the ASTM E84 but it gives information about the efficiency of the intumescent coating as heat barrier) are measured during the test using 6 thermocouples (hereafter called Th.x with $1 \leq x \leq 6$), small windows permit to follow flame spread and smoke is collected in the chimney to measure its opacity with a smoke density analyzer including a halogen light.

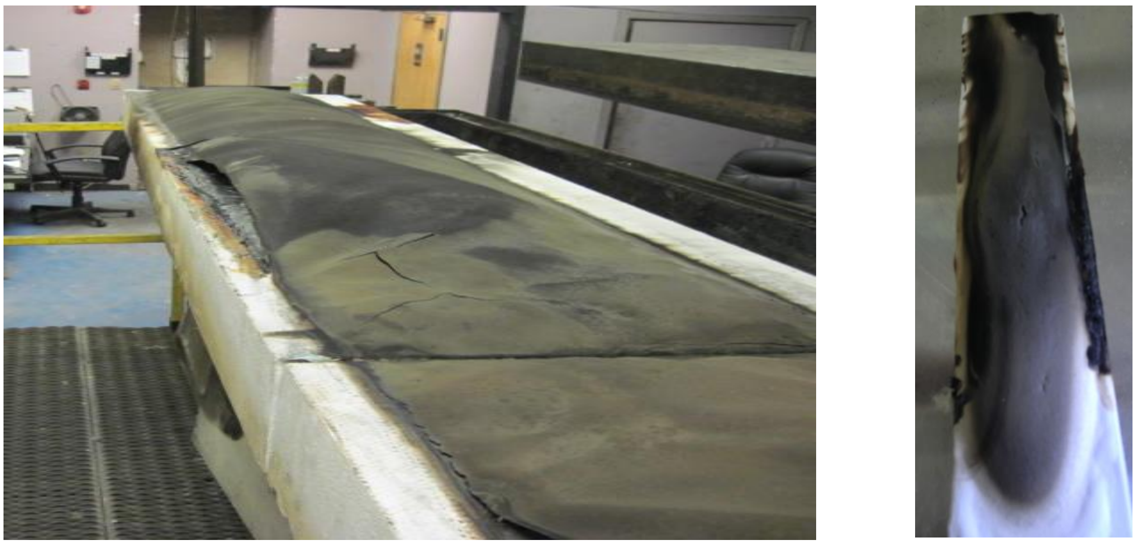
Figure 1. (a) Schematic view of the lab-scale Steiner tunnel and (b) its internal construction (side view)



The temperature/time curves (curves not shown)) are very promising and allow us to discriminate the different coatings. Avicoat, Pyroplast ST200 and Intuflam give the best barrier properties. Visual observation of the residues indicates that not all the coatings have developed an intumescent structure. Avicoat and Intuflam do not swell but they provide the best performance forming a non-expanded char at the surface. In our conditions, thermal constraint is not high enough to make the expansion of the material. At the end of the test, we can observe that the PET foam is intact when protected with Avicoat which indicates that the efficiency of this coating is really high.

Regarding the good results obtained with Avicoat in terms of fire barrier properties, a specimen coated with this reference has been tested under large scale ASTM E84 conditions in the evaluation center of Intertek in Elmendorf-USA. The Avicoat coating was about 700 µm thick and it exhibited good adhesion to the composite when carrying the ASTM D3359B test. The description of the specimen indicates that a charred aspect is observed on 85% of the total length (Figure 2-a). Then, a discoloration occurs. The picture of a section of the specimen however clearly shows that no intumescent phenomenon appeared during the test. The observation of the sample tested on the small scale tunnel also shows a charred aspect without intumescence; the coating is only distorted and cracked (Figure 2-b). These results suggest that, on the one hand, the standard conditions are reproduced: the results of the small scale test can be extrapolated for the evaluation of the thermal barrier effect (time-temperature curves). On the other hand, the thermal constraints seem to influence the behavior of the coating as follows: the flame constraint and the conditions of the tunnel test lead to no intumescence, only to the formation of a crust.

Figure 2: (a) Avicoat coating protecting PET foam after the large scale Steiner tunnel and (b) after the mini Steiner tunnel test



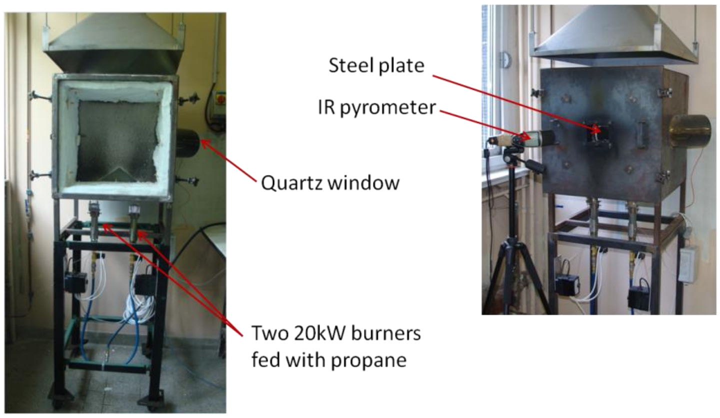
(a) **(b)**

FURNACE TEST (UL 1709)

The protection of metallic materials against fire has become a very important issue in the construction and petrochemical industries, as well as in the marine and military fields. Structural steel loses a significant part of its load-carrying ability when its temperature exceeds 500°C. Prevention of the structural collapse of a building is crucial to ensure the safe evacuation of people and it is a prime requirement of building regulations in many countries.

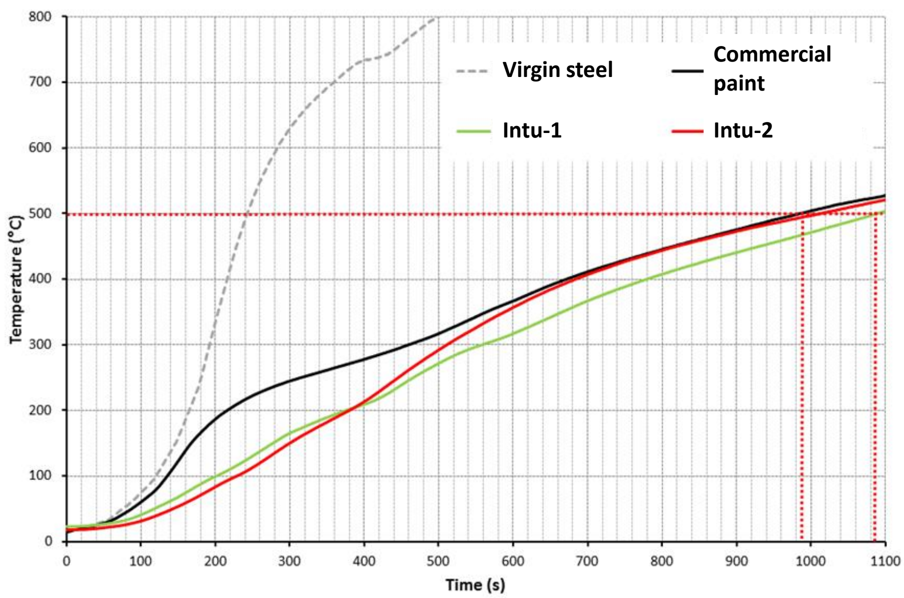
We have developed a small scale furnace test to evaluate the fire performance of intumescent coatings in cellulosic and hydrocarbon fires. This test was designed to mimic the ISO834 (or ASTME119) and the UL1709 normalized temperature/time curves, respectively related to cellulosic fire and to hydrocarbon fire. The lab-scale furnace exhibits an internal volume of 40 dm^3 (Figure 3). Refractory fibers (stable up to 1300°C) cover the different faces of the furnace. The furnace was equipped with two gas burners (20 kW propane burners). The gas pressure was fixed at 1.8 bars and the flow was regulated in order to mimic the UL1709 curve (in this work). A temperature probe inside the furnace regulates the temperature and a K-type thermocouple allows the furnace temperature profile to be registered. The temperature at the back side of the plate is measured as a function of time using a pyrometer (temperature measured in the center of the plate). The backside of the plate is coated with black paint (Jeltz) having a constant emissivity (0.92) and thermally resistant up to 800°C in order to get reliable temperature measurements with the pyrometer.

Figure 3. Furnace set up to mimic cellulosic and hydrocarbon fire scenario



Novel intumescent paints based on silicone as polymeric matrix (hereafter called Intu-1 and Intu-2)[5] were developed in the lab and were evaluated with the small furnace on steel plates according to UL-1709 temperature curve (Figure 4). The failure temperature has been taken at 500°C. Uncoated steel plate reaches 500°C at 240s while the coated steel with intumescent coatings (thickness on steel plate = 1 mm) reaches the failure temperature at times higher than 980s. It shows that intumescence is an efficient way to protect steel since the time to failure temperature is 5 times longer than that with virgin steel. Our intumescent paints have been compared to a commercial paint and it appears that they are much more efficient at shorter times (t<500s) suggesting a faster development of the intumescence at the beginning of the test.

Figure 4. Temperature measured on the backside of steel plates coated with intumescent paints as a function of time in the conditions of UL 1709 in a small furnace

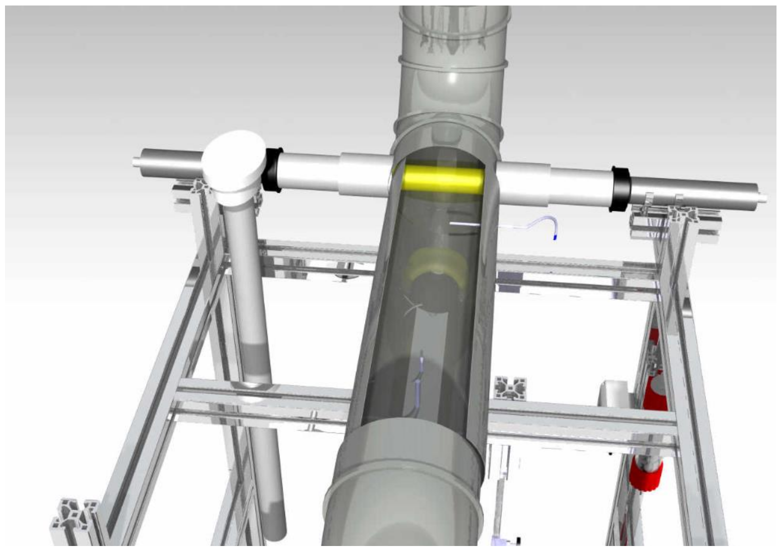


SINGLE BURNING ITEM (SBI, EUROCLASS)

The SBI test method is planned to assess the performance of building products in a (real scale) room corner scenario. In the pursuit of our efforts to make scale reduction, we have developed a SBI at 1/3 scale (Figure 5). It measures all parameters as in the large scale SBI including heat release rate (HRR), total heat release (THR), FIGRA, smoke opacity and SMOGRA. Wooden panel protected by an intumescent paint was evaluated with our bench-scale SBI. The results show that HRR is dramatically reduced when the panel is protected by the intumescent coating (Figure 6 – (a)). The intumescent charred layer develops upon burning and provide the protection (Figure 6 – (b)).

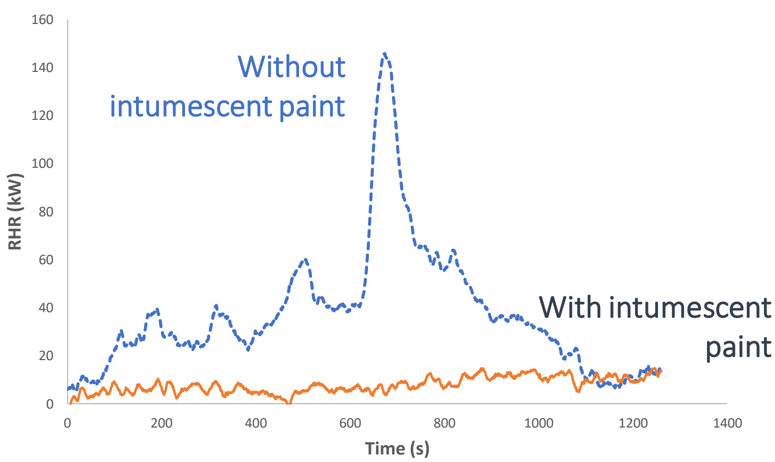
Figure 5. (a) Mini-SBI test; (b) Cross-section of parameters measurement (smoke opacity, O_2 analyser and pressure)

(a)



(b)

Figure 6. (a) HRR as a function of time of wooden panels at the bench-scale SBI; (b) wooden panel protected by an intumescent paint burning at the bench scale SBI



(a)

(b)

Our mini SBI was designed to be correlated with the values of the large scale SBI. It gives good prediction for the wooden panels as shown in Table 1.

Table 1. Comparison of the classification of wooden panels between the large scale SBI and the bench scale SBI

	Wooden panel (SBI)	**Wooden panel (mini SBI)**	**Wooden panel (intumescent)**
THR @600s [MJ]	15.7 (+/-2)	18.2 (+/-3)	3.2 (+/-1)
FIGRA [W/s]	440 (+/- 79)	524.3 (+/- 85)	164 (+/- 25)
TSP [m²]	47 (+/- 10)	66.8 (+/- 10)	0
SMOGRA [m²/s²]	3 (+/-1)	10.9 (+/-3)	0
Rating (Euroclass)	Ds2d0	Ds2d0	Cs1d0

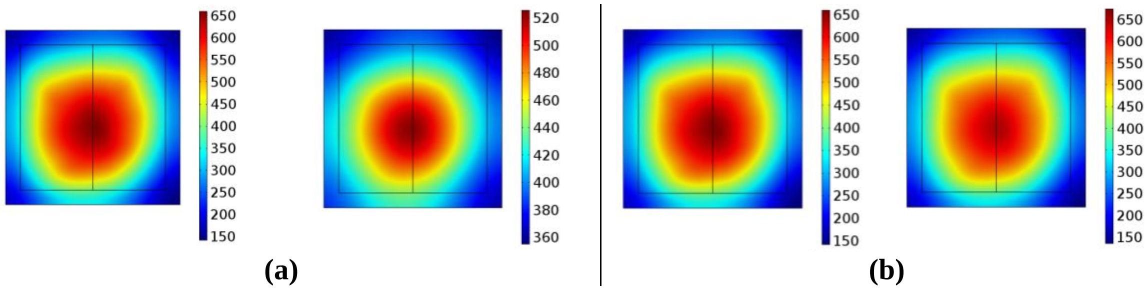
BURNER TEST (ISO 2685)

Composite materials are increasingly being used in the design of aircraft. However, the recent application of carbon fiber reinforced polymer (CFRP) in aircraft structure has introduced potential fire threats and it raises concerns regarding fire safety[6,7].

The fire resistance of components, equipment and structure located in 'fire zones' (e.g. compartments containing main engines and auxiliary power units) is conventionally evaluated according to the international standard ISO 2685. The test is established on a pass/fail basis thereby an element is considered to pass its fire test if it is capable to sustain its design function after the standard flame exposure for a specific lapse of time. In this research we are interested in the fire behavior of CRFP undergoing fire as defined in ISO 2685. Even if ISO 2685 is a medium-scale test, it is time-consuming and expensive, especially when CFRP samples must be produced for this purpose. In this paper, a small scale bench was developed to mimic ISO 2685 and to evaluate CFRPs with and without fire protection (intumescent coating).

The physical scaling method has been applied in this work to reduce the ISO 2685 test. Despite its simplifications, the scaling technique permits to improve the understanding of the fire dynamic involved in large scale fire and in fire testing[8]. Virtual benches were modeled (not presented here) considering a reduction by 3 (except for the sample thickness) of ISO 2685 on steel and aluminum plates. Dimensionless numbers were determined by the well-known Froude scaling technique and were used in the heat diffusion equation associated with the appropriate boundaries for making simulations. Comparisons of temperature distribution on the backside of the plates were done between the ISO bench and the virtual reduced one (Figure 7-(a)). The temperature distribution looks similar (similar shapes) but the measured and simulated temperatures are significantly different. Nevertheless, temperature distribution becomes similar (thermally thin sample) as that of the ISO bench when the duration of the test is decreased and heat transfer (convection and radiation) is increased (Figure 7-(b)).

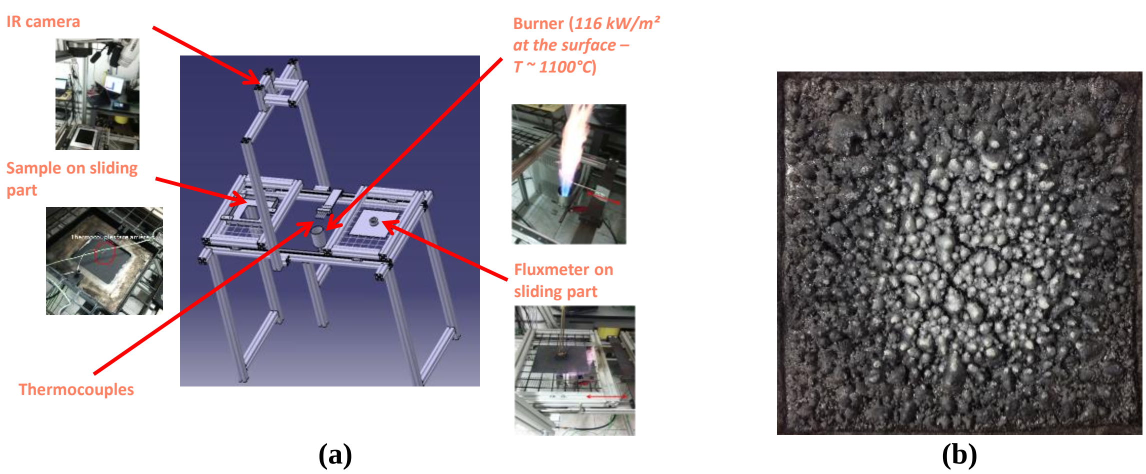
Figure 7. Comparison of the temperature distribution on the backside of steel plates measured during ISO 2685 test and by simulating ISO 2685 on reduced virtual bench with 1/3 reduction (a) and with 1/3 reduction changing the duration of the test and the boundaries (b) (Note the temperatures are in °C).



The main conclusions are temperature differences measured during the full scale ISO test compared to the virtual bench are mainly due to scaling changes. On the other hand, it was shown temperature distribution in the flame, the design of the burner and boundaries conditions had a minor influence on temperature changes.

A reduced scale bench was built up and was equipped with propane burner, insulated holder for the samples and with infrared camera and bichromatic pyrometers for measuring temperatures on the backside of the sample (Figure 8-(a)). CFRP sample prepared by Safran Company was coated with a commercial intumescent paint and the temperatures measured on the backside of the sample was significantly reduced compared to virgin CFRP. As an example, temperature measured in the center of the sample is 345°C in the stationary state with intumescent coating while it reaches 485°C without intumescent coating (Figure 8-(b)).

Figure 8. Reduced scale bench equipped with temperature rake for measuring flame temperature and with gauge for measuring heat flux impacting the sample (right); sample holder insulated from the frame (left); the two frames (right and left) are on the rail moving back and forth for calibration's purpose (a) – Intumescent coating formed after fire testing on the reduced scale ISO 2685 test (b).



CONCLUSION

Scaling reduction permitted to successfully build several bench-scale tests mimicking different fire scenarios and providing appropriate and reliable results. It was shown that prediction of fire performance at the large scale can be made. Those benches were used to examine the fire protection of several materials (steel, wooden panel and CFRP) by intumescent coatings. Intumescent coating offers highly efficient way to fire protect the substrates and the intumescence concept is therefore a method of choice in the field of fire protection.

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