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Fire performance of sandwich panels in a modified ISO room test

Abstract. Four sandwich panel rooms were constructed as prescribed in the ISO 13784-1 test. However, the construction followed normal industry practice, and the panels were then subjected to damage typically found in commercial premises. The fire load was increased to simulate fires actually occurring in commercial premises, by stepping-up the propane burner from 300 kW to 600 kW, and placing substantial wooden cribs in two of the rooms. The results showed significant differences in fire growth rate and burning behaviour between those panels filled with polyisocyanurate (PIR) and those filled with stone wool in both the experiments without and with the wood crib. Most significantly, the PIR pyrolysis products caused ignition (by radiation from above) of the wood crib 1 minute after the burner was stepped up to 300 kW (11 minutes into the test) rather than 2 minutes after the burner had been stepped up to 600 kW (22 minutes into the test) for the stone wool panels. This interaction between building and contents is frequently ignored in assessments of fire safety. After a few minutes, the PIR pyrolysis products that escaped outside the room, from between the panels, ignited. The extra thermal attack from PIR fuelled flames distorted the panels, exposing more PIR and resulting in large flames on both the inside and outside of the enclosure. From a fire safety perspective this is most important as it shows that with larger fire loads typical of those found in commercial premises, steel-faced PIR filled panels are not capable of acting as fire barriers, and support flame spread through compartment walls and ceilings. In addition, the PIR panelled rooms produced very large quantities of dense smoke and toxic effluents, where the stone wool panelled rooms produced small amounts of light smoke of lower toxicity.

Keywords: sandwich panel, fire performance, room test.

This work results from large fires where sandwich panels have been involved, each entailing losses of several hundred million Euros. Since the construction method has been shown to influence the escape of pyrolysis gases from expanded polystyrene foam sandwich panels in fire tests, which can reduce fire spread and prevent flashover [1], an intention of the study was to establish whether non-structural damage to the panel faces affects fire performance of walls and roofs constructed from certain sandwich panels. As the most common insulation materials for sandwich panels are polymeric foam and mineral wool, these material types were chosen for the current study. Furthermore, polyisocyanurate (PIR) foam was chosen as the most fire safe of the widely used foams, and stone wool as the most fire safe form of mineral wool.

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The need for a modified test

Four potential reasons for the poorer performance of sandwich panels in fires in commercial buildings were investigated in the current study. The first was the observed failure to effectively fire-stop through-panel installations, such as cable trays and ventilation ducts, or to fill voids where such installations were not actually in place. The second derives from reports of breaches in the integrity of the metal skin of the panel through accidental damage, such as that from a forklift truck, or holes for pipework. The third was fire loadings that were much higher than the 300 kW maximum burner output specified in the test standard for sandwich panels, ISO 13784-1, for example from stored pallets in actual commercial premises. The fourth was the different requirements placed on the installers of sandwich panels when constructing large buildings, compared to fire test laboratory technicians building small fire test rooms. To test the sensitivity of these factors, the „small room" was subjected to carefully prescribed, simulated damage including pipe holes, installation of a cable tray and a ventilation duct and piercing by a fork-lift truck. The propane burner commenced at 100 kW and was stepped up to 300 kW after 10 minutes (as described in ISO 13784-1), and then additionally to 600 kW. In the 3rd and 4th experiments, a large wooden crib was placed in the test room to represent a more realistic fire load. The fire load densities of the wood cribs in the current experiments were 700 MJ m^{-2} and 400 MJ m^{-2} in the stone wool room and PIR room, respectively. These values were selected, as they are in line with both inspection data from If P&C Insurance and survey values in the literature.

Experimental Set-up and Procedure

Materials. The test rooms were constructed from two commercially available metal faced sandwich panels:

■ sandwich panels with a core of closed cell polyisocyanurate (PIR) foam. The thickness of the panel was 100 mm. According to the manufacturer's description, the panels are suitable for internal and external wall and roof applications. They are FM Approved to FMRC 4880 Class 1 Fire Classification with unlimited height, and Conformité Européenne (CE) marked with a reaction-to-fire class of B, s2, d0;

■ sandwich panels with a core of stone wool. The thickness of the panel was 100 mm. According to the manufacturer's description, the panels can be laid horizontally or vertically and are suitable for external wall applications. The panel is LPCB certified to LPS 1181 and LPS 1208 as EXT-A60, FM Approved to FMRC 4880 class 1 with non-combustible core and unlimited height.

The modified test. ISO 13784-1 [2] describes the construction of a „small room", of internal dimensions 2,4 x 3,6 x 2,4 m (W x L x H), with a single open doorway 0,8 m wide and 2,0 m high, from sandwich panels, supported by a rigid steel frame. It uses the same methodology as the ISO 9705 room corner test [3], with a sandbox propane burner situated near the rear corner of the room, with an output of 100 kW for 10 minutes followed by an output of 300 kW for 10 minutes. In ISO 13784-1, the walls and ceiling are made from sandwich panels, and form the room enclosure, whereas in ISO 9705 the material under test is the wall lining, mounted on non-combustible walls. The sandwich panel test rooms were based on the rooms in ISO 13784-1 [2] with respect to shape and dimensions. Each room consisted of four walls at right angles and a ceiling, and was located on a rigid, non-combustible surface. The tests were conducted outside over two days in mild (15 – 20 °C) conditions with light wind and no rain.

The room was built to the specification in ISO 13784-1, with internal dimensions of length: 3,60 ± 0,05 m, width: 2,40 ± 0,05 m, and height: 2,40 ± 0,05 m. The sandwich panels were fixed to the outside of a pre-constructed steel frame. The construction of the test rooms was carried out by a local construction firm who regularly erect sandwich panel buildings. They were asked to fit the panels as they would in a typical installation, in order to be more representative of the end use scenario.

A total of four experiments were conducted, as summarised in Table. Measurements of temperature, heat flux, inlet and effluent gas velocities, effluent toxicity and video data were collected. The first set of experiments, 1 and 2, were carried out with a propane sandbox burner, as the only fire load. In the second set of experiments, 3 and 4, a wooden crib was placed in the room as an additional fire load.

Results

The two experiments with the propane burner alone are described first, followed by the two experiments in which a large wooden crib was placed in the room. For each pair of experiments, the applied heat release rate and the calculated total heat release are presented, followed by visual and photographic observations of the burning rooms, temperature profiles recorded in the centre of the room, and gas concentrations measured near the top of the doorway to the room.

Experiments with Burner Only. *Total heat release rate in the compartment.* Heat release rate data are reported for both the input heat release rate and the calculated heat output. The input heat release rate was calculated directly from the mass flow of propane to the burner. The output heat release rate is calculated by a species evolution approach using oxygen consumption calorimetry (OC). Figure 1 shows the input heat release rate (HRR input) and the output heat release rate (OC – Upper and Lower limits), calculated from the oxygen depletion and gas flows, measured in the doorway during the first two experiments. The uncorrected data is shown as the upper limit (assuming the measured flows to be precise, and the oxygen concentration to be uniform across the plume). In addition, an estimation of the uncertainty is shown as the lower limit, the probable heat release being within the „calculated HRR region". The supply of propane in the PIR test was shut off earlier (around 21 minutes after ignition), after having been stepped up to 600 kW for around 3 minutes. At this point the metal protection of the PIR panels had distorted so much in the vicinity of the burner that it was not considered safe to maintain the supply of propane.

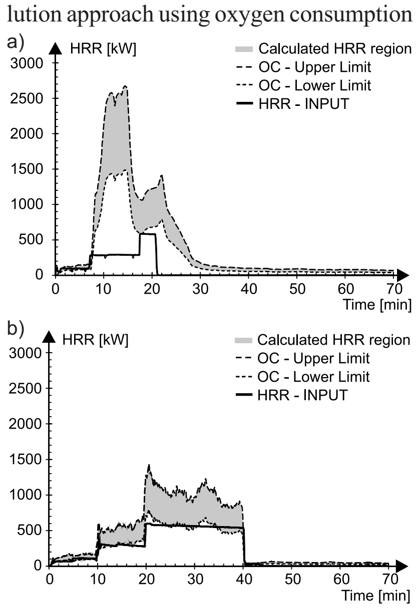

Fig. 1. Heat input and output from tests with burner only. OC refers to measurements based on oxygen consumption calorimetry: a) – PIR panels; b) – stone wool panels

Temperature Profiles and Gas Concentrations. Figure 2 shows the volume-weighted average temperature from the highest six thermocouples in the centre of the enclosure over the duration of the tests, and the CO and CO_2 concentrations measured 15 ± 5 cm below the top of the doorway in each enclosure. Both CO_2 profiles are qualitatively similar to the total heat release profile, suggesting that the CO_2 in the smoke is approximately proportional to the oxygen depletion.

For the PIR panels, the CO_2 concentration reaches a peak of 17 % 11 minutes after ignition. The CO concentration reaches

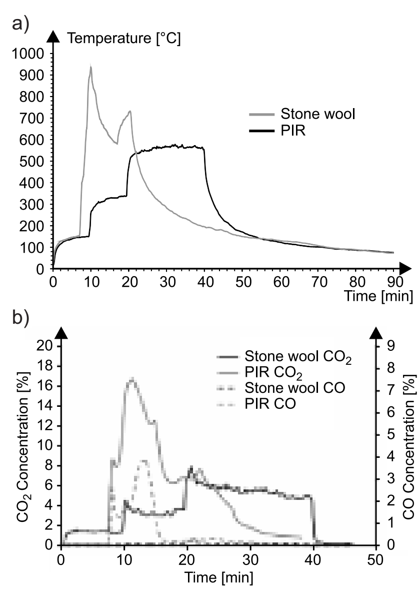

Fig. 2. Volume-weighted average temperature of upper layer – burner only experiments (a); CO_2 and CO concentrations at doorway – burner only experiments (b)

Experimental configurations for the four room experiments

Experiment number	Panel type	Propane burner duration [min] 100 kW	300 kW	600 kW	Number of 10 cm diameter holes through rear wall	Distance of cable tray from rear wall [cm]	Fork-lift damage, screw holes and vent	Wooden crib [mass/kg]
1	PIR	7	10	3	3	50	Yes	–
2	Stone wool	10	10	20	3	50	Yes	–
3	PIR	10	2	–	0	100	Yes	169
4	Stone wool	10	10	5	0	100	Yes	297

a peak of 3,75 % slightly later, after around 13 minutes. This increase in CO concentration implies that the fire is becoming more under-ventilated. The CO concentration peak occurring 2 minutes after the CO_2 concentration peak, and the oxygen concentration falling to 0% from 11 to 15 minutes, in the PIR room, provide additional insight into the fire behaviour. As the oxygen concentration falls within the room, the temperature and CO_2 concentration fall, while the CO peak rises. Also, the main heat release step, which is the conversion of CO to CO_2, shifts from inside the room to the plume outside the door. When the oxygen concentration in the room is close to zero, the high radiant flux and free radical concentrations drive the reaction forward, despite the lack of oxygen. The location of the sampling probe at the exit to the room may give higher CO concentrations and CO/CO_2 ratios, than would be found higher up in the plume. The CO/CO_2 ratio will continue to decrease on mixing with air, until the temperature falls below 625 °C [4].

Figure 3 shows the concentrations of hydrogen cyanide (HCN) measured during these experiments. As the effluent was collected in bubblers over different time periods, the calculated gas phase concentrations are averages over the sampling period (shown as bars in Figure 3). Concentrations of up to 140 ppm were measured for the PIR panel room, while concentrations of around 20 ppm were measured for the stone wool panel room. The HCN from the PIR test is assumed to derive from under-ventilated combustion of PIR foam. The HCN from the stone wool may derive from atmospheric nitrogen (15 ppm have been observed in methane flames5) or from decomposition of the polyurethane used in the manufacture of stone wool panels, to attach the wool to the steel sheet.

Experiments with both Burner and Wooden Crib. *Total heat release rate in the compartment.* In the second pair of experiments, the input HRR from the propane burner was augmented with a wooden crib in each enclosure (297 kg in the stone wool enclosure and 169 kg in the PIR enclosure). These experiments were conducted without the three 10 cm diameter holes on the rear wall, and with the cable tray located 100 cm from the rear wall. Figure 4 shows the input heat release rate (HRR input) and the calculated heat release rate (Heat output OC) from the propane burner. The gas supply to the PIR experiment was switched off shortly after the transition to the second stage because the enclosure participated so readily in the burning that it was considered unsafe to continue supplying propane. In the stone wool enclosure experiment, propane was delivered to the burner until the crib had fully ignited.

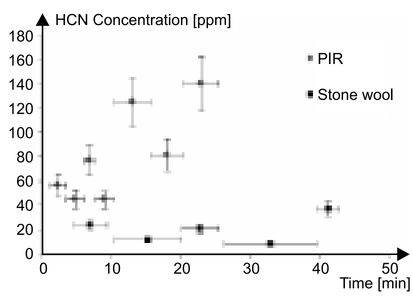

Fig. 3. HCN concentrations – propane burner experiments (the horizontal bars indicate duration of bubbler sampling)

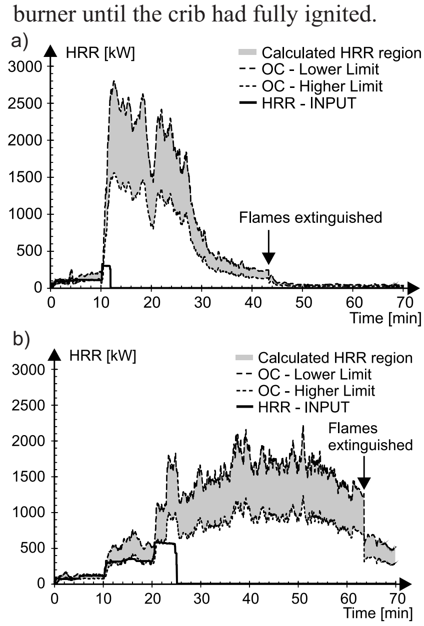

Fig. 4. Heat input and output from burner and wooden crib (note that ignition of the crib occurred after 10 minutes, so the propane was switched off after 11 minutes; a) – PIR panels; b) – stone wool panels

In both cases the initial OC lower limit follows the HRR input curve (for 10 minutes for the PIR panels, and for 22 minutes for the stone wool panels). This is to be expected, because the combustion will be almost complete at this stage, and all combustion products will leave through the doorway. Soon after, the OC lower limit diverges from the HRR input, as the wood ignites. In both cases there is a substantial contribution to the heat release from the large wooden cribs. However, the most remarkable feature of the second pair of tests is the dramatically shorter time to ignition of the wooden crib in the PIR enclosure (11 minutes with burner at 300 kW, rather than 22 minutes with burner at 600 kW). There are two major contributory factors:

- pyrolysis of products from the PIR panels added to the total heat release rate. In Figure 4 it can be seen that this effect is marginal until the burner is turned up to 300 kW;
- the increased radiant flux from soot particles from the incomplete combustion of the PIR products. The different flame colour and smoke density is evident in other photographs.

Temperature Profiles. Figure 5 shows the weighted average temperature from the 6 highest thermocouples in the upper layer near the centre of the room, and the CO and CO_2 concentrations leaving the PIR and stone wool panel enclosures for the duration of the experiments incorporating a wooden crib. There is some qualitative similarity between the temperature and the heat input from the propane burner for both tests, up to 10 minutes for the PIR panels, and up to 22 minutes for the stone wool panels, corresponding to the time to ignition of the wooden crib in each experiment. The stone wool panel temperature profile shows a distinct peak when the wood ignited, followed by a decrease when the burner was switched off. The higher temperatures in the PIR panel room show the contribution of PIR to the fire. For the stone wool room the burner output was increased to 600 kW for 3 minutes, whereas it was only increased briefly to 300 kW for the PIR enclosure.

At ten minutes the burner output was increased to 300 kW and as a result, the combustion product measurements of the two enclosures diverged. The fire grew rapidly in

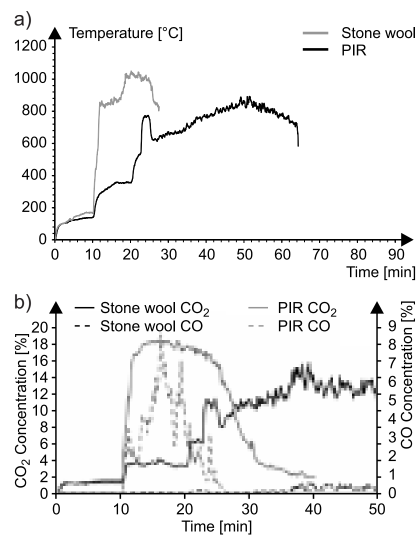

Fig. 5. Weighted average temperature of upper layer – burner and wood crib experiments (a); CO and CO_2 concentration at doorway – burner and wooden crib experiments (b)

the PIR panel enclosure; within a minute, the crib ignited, visible as the small shoulder on the CO_2 curve from 17 to 18%. This provides evidence that there was already a significant amount of non-propane gaseous fuel in the room, making the fire much bigger around the time the burner was stepped up from 100 kW to 300 kW. At the start of the 300 kW burner stage, both the CO and the CO_2 concentrations measured in the PIR enclosure were higher than those measured in the stone wool enclosure. This occurred despite the fact that the burner in the PIR enclosure was cut at 12 minutes. When the crib ignited in the stone wool enclosure, the CO_2 concentration increased to around 11%, rising to 15% at 39 minutes. This is lower and later than the CO_2 peak concentration in the PIR enclosure of 18% at 15 minutes.

Figure 6 shows the concentrations of HCN taken from the doorway during each experiment. The concentrations of HCN in the stone wool experiment are similar to those observed in the second experiment. This correlates with the very high yields of HCN found in the under-ventilated flaming of PIR measured under more carefully controlled

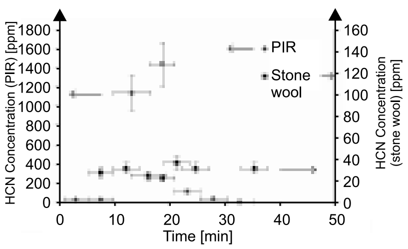

Fig. 6. HCN concentrations – propane burner and wooden crib experiments (horizontal bars indicate duration of bubbler sampling)

conditions. Again, the HCN from the PIR test is assumed to derive from under-ventilated combustion of PIR foam, while that from the stone wool may derive from atmospheric nitrogen [5] or possibly from decomposition of a polyurethane adhesive. High hydrogen cyanide yields derive from the presence of nitrogen in the fuel, particularly during incomplete combustion. Wood itself has very low nitrogen content (the three main components, cellulose, hemicellulose and lignin, contain no nitrogen at all). The N the content of dry wood has been quantified [6] as 0,11%, thus the burning wood crib would not be expected to contribute significantly to the HCN yield.

Conclusions

The aim of this work was to provide experimental results to explain why buildings constructed with sandwich panels that, despite the fact that they had been given the highest fire safety ratings by the insurance industry, contributed to large fires, involving losses of several hundred million Euros. The single room-scale experiments, built following normal construction industry practice, used larger fire loads than those used in the standard ISO 13784-1 room test. The rooms had been subjected to typical damage found in such commercial premises. The resultant fires show clear differences in behaviour both between different types of panel filling and between the standard and the modified test. Specifically, the PIR pyrolysis products made a significant contribution to the fire growth. This was most apparent in the tests with the wood crib, where the time to ignition of the crib in the PIR room occurred 1 minute after the burner was stepped-up to 300 kW (11 minutes), as compared to happening after 10 minutes at 300 kW and 2 minutes at 600 kW (22 minutes) in the experiments with stone wool. This difference is due to the contribution to the fire from the pyrolysis of the PIR. Moreover, once ignited, the flame spread from the top to the bottom of the crib in the PIR room in just 2 minutes, whereas the same flame spread took 10 minutes in the stone wool room.

The most significant modification to the ISO 13784-1 standard was the increased fire load (higher output from the propane burner and the presence of the wood crib). This extended the test protocol from a reaction-to-fire test into an assessment of the fire response to develop flaming. Because the current insurance industry classifications fail to distinguish between the two types of filling tested in the current study, and they show radically different fire behaviour in the modified tests, this type of assessment should be introduced to minimise the risk of such large losses in the future.

The amount of structurally superficial damage in the room was greater than would typically be found in a single room in commercial premises. It was primarily included to study the effects of each type of damage. It is evident that holes all the way through panels breach the fire barrier, independent of the filling material, and therefore increase the likely speed of fire development. However, if such damage results in exposure of combustible material, it will compromise the fire safety. Although only measured at the doorway, the amount of dense smoke, and its toxicity, was significantly greater from the PIR panel room, and visual observation suggests that the total volume and toxicity of the effluent from the PIR room would be much greater.

The most significant result of this work is the evidence that sandwich panels, faced with non-combustible material, but filled with combustible insulation do not provide fire protection by acting as an effective fire barrier in the current scenarios, and contribute fuel to the fire. Photographic evidence, in particular, shows how flames emerge from the gaps between panels, causing further distortion to the steel plates, exposing large areas of foam for attack by the growing fire.

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