SAFETY EVALUATION OF VERTICAL DROP FIRE SHUTTER OF BUILDINGS IN FIRES

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ABSTRACT

The paper summarizes the results of a series of experiments, including eight standard tests (each covering a test area of 3m×3m), two standard tests (each covering a test area of 1m×1m), and one full-scale fire test. The insulation performance of fire shutters was measured by radiometers and thermocouples. It was found in this research that fire shutters that did not provide fire insulation had to be used with a certain safety clearance distance in a fire compartment in order to effectively prevent the fire from spreading. Shutter slats, if coated with intumescent paints, could provide insulation and thus greatly reduce thermal radiant heat and prevent flames spreading when the heated paints expand. For this sake, such painted shutters can be used in escape routes to facilitate a safe escape in an emergency.

Key words: fire shutter, intumescent paints, radiation
1. INTRODUCTION

To prevent fires from spreading, buildings must have fire compartments. Firewalls, fire-rated glass, and fire-rated windows are used in non-opening areas of the fire compartment while fire doors can be installed in smaller openings. However, fire shutters are often installed as fire compartments in buildings that have larger openings, such as department stores, mega malls, hospitals, courtyards, and underground parking lots. Fire shutters, used as plane fire compartments, can be classified into two types according to the directions of the openings: vertical drop fire shutters and side operation fire shutters. Since the shutter case of the vertical drop fire shutter is installed below the floor and thus takes up less space, the vertical drop fire shutter is installed in many places.

Presently, most countries in the world use standard temperature-time curve to measure the fire resistance period of building elements, such as: fire-rate roofs, floors, fire doors, firewalls, fire windows, etc. Current technologies have made it possible to provide at least 3-hour long fire insulation and 3-hour long fire integrity. But conventional fire shutters can only provide three hours (or longer) of fire integrity. In a standard furnace test, generally speaking, it only takes about three minutes for the unexposed surface to reach the standard temperature criteria of fire insulation. (The maximum unexposed surface temperature should not be higher than $210^\circ C$ and the average unexposed surface temperature should be kept below $170^\circ C$). After the first ten minutes, the thermal radiant heat at the spot one meter away from the unexposed surface of the fire shutter can exceed the ignition criteria of common wood $1w/cm^2$ [1-4], which suggests that although the fire shutter has passed the fire integrity rating, it still fails to prevent fire from spreading in the event of a fire, if it falls short of fire insulation requirements. Hence, in addition to re-locating fire shutters and regulating the danger zones, improvements should be made to conventional fire shutters so that
the thermal radiant heat can be effectively reduced.

Relevant researches on fire shutters have been conducted. Wong et al., [5-7] measured the unexposed surface temperature in his reduced scale experiments and used formulas to predict how thermal radiant heat could damage human skin [8]. Yuen et al., [9] used CFD to simulate the fire insulation of double-sided fire shutters and the requirements of shutter safety distance in relevant construction regulations [10]. However, such computerized simulations lack detailed, tested data and thus cannot explain to what extent galvanized and stainless steel fire shutters can be damaged in the event of a fire. Therefore, it is important to analyze the heating behavior of fire shutters. This research used the standard furnace tests to measure the real thermal radiant heat of a 3m×3m area on the fire shutter to analyze the behavior of shutters in a fire. In addition, the exposed surface of the fire shutter was painted with a 0.3mm-thick layer of intumescent paint. A full-scale natural fire test and two standard tests (1m×1m) were conducted to analyze how intumescent paint could help unexposed surface reduce thermal radiant heat. The rolling of the shutter was also tested to make sure that intumescent paint could be used on the shutter and would not come off the surface after rolling up and down. This was to ensure the feasibility of theoretical analysis to a real life setting.

This research, by presenting an analysis of heated fire shutters, aims to help the general public better understand the fire integrity and fire insulation performance of fire shutters as well as to provide construction professionals and relevant governmental agencies with accurate information in order to effectively contain fire and reduce the loss of life while keeping property damage to a minimum.

2. DESCRIPTIONS OF THE EXPERIMENTS
2.1 SPECIMENS
2.1.1 TYPICAL VERTICAL DROP FIRE SHUTTERS
Fire shutters, when used as fire compartments, can be divided into two types: stainless steel shutters and galvanized shutters. Most stainless steel shutters are not coated, but in order to analyze how shutter material and coating influenced the spread of fire, four different kinds of fire shutters were used: stainless steel shutter, galvanized shutter, galvanized + resin shutter, and galvanized + painted shutter, in the two hour long experiment of fire resistance period (the area of the test specimen: 3m×3m). ISO 834 standard temperature-time curve was used for the test temperature of the standard fire test furnace (furnace for short hereinafter), as is shown in Eq. (1) [11]. Both sides of the fire shutters were tested, so there were a total of eight tests. The slats were 1.5mm thick (see Fig. 1) and the types of shutter are shown in Fig. 2.

\[
T = 20 + 345 \times \log_{10}(8t + 1) \quad \text{Eq.(1)}
\]

where

- \(T\): average standard furnace temperature (°C)
- \(T\): time (min)

### 2.1.2 FIRE SHUTTERS SPRAYED WITH INTUMESCENT PAINTS

Intumescent paint, generally speaking, is sprayed onto the surface of the steel structure of buildings [12, 13]. When heated, the paint layer will expand and become carbonized, preventing the direct exposure of the steel structure to heat so that the building would not collapse right away. There are two kinds of intumescent paints: water-based paint and solvent-based paint. In this experiment, the surface of shutter slats was sprayed with solvent-based paint. No epoxy zinc phosphate primer and epoxy topcoat were used. The paint was sprayed at once onto the shutter slat surface, creating a 0.3mm-thick layer. Then, the shutter slats were air-dried for seven days before tests were conducted. Two one-hour standard tests were carried out to a 1m×1m area of the test specimens. One full-scale natural fire test was also conducted. All of the three tests were done to the galvanized slats sprayed with intumescent paint.
Other parts of the shutter, such as the shutter case and the motor, were not tested. The test numbers and test specimens are shown in Fig. 3.

2.2 STANDARD FURNACE HEATING CONDITION AND MEASUREMENTS

Liquefied Petroleum Gas (LPG) was used in the standard furnace test for the 3m×3m test specimens. Fig. 4 shows the fire shutter installed in the frame. A radiometer was placed one meter away from the center of the test specimen (see Fig. 5). Diesel fuel was used in the standard test for 1m×1m test specimens. Fig. 6 shows the unexposed surface temperature and the thermal radiant heat of the test specimens. The pressure inside the furnace was set at 0(±2)Pa at the height of 0.5 m above the ground.

2.3 FULL SCALE FIRE TESTING CONDITIONS AND MEASUREMENTS

The density of the fire load of the full-scale fire test was 50kg/m². The interior height was 3m; walls and floors were made of 12cm-thick reinforced concrete. The wood was elevated with 15-cm high white bricks placed below. A 1m×1m square pot was placed under the wood, filled with 200ml of kerosene to ignite the wood [14]. Inside the room, a thermocouple was placed 10cm under the ceiling, and another thermocouple was placed 10cm away from the exposed surface of the fire shutter to measure the temperature of the fire room. The thermal radiant heat of the unexposed surface of the test specimen was also measured. Fig. 7 shows the installation of the fire shutter and measuring instrumentations, the layout of the fire load, and the size of the fire room.

2.4 MEASURING INSTRUMENTATION

Type-K thermocouple used to measure the temperatures of the fire, the furnace, and the unexposed surface of the test specimens, conformed to ISO 834 requirements. The radiometer was made by Medtherm corporation (model: 64 series water cooled) and was used together with a cooling water circulation device. All of the
thermocouples and radiometers were connected to a computer. Records were made at intervals of two seconds. The experiment was filmed and photographed.

3. OBSERVATIONS AND RESULTS

3.1 FIRE BEHAVIOR OF 3M×3M FIRE SHUTTERS IN STANDARD FURNACE FIRES

Test 1~Test 6: During the two hour long experiment, no burst of flames was observed and the bended part of the bottom rail of the fire shutter was not longer than 1.91cm. All shutter slats did not derail. The unexposed surface temperature exceeded 210℃. These meant that all of the specimens passed the two-hour long fire integrity rating but did not provide fire insulation rating. In Test 7 and Test 8, after the first 40 minutes, flames began to burst out from under the shutter case. The bended part of the bottom rail was 3.5cm at maximum. These results suggested that the specimens did not pass the one-hour long fire integrity rating. For the sake of safety, the tests were stopped after one hour. In the test on the inside of the fire shutter, where the motor case was installed inside the furnace, the flames could burn out the plastic parts and the control switch of the motor. Therefore, a less unpleasant smell was produced than was the case for the other side. In Test 5 and Test 6, all of the resin on the shutter salts were burned out and fell down after the first twenty minutes. In Test 1~8, shutter salts gradually turned red right after the test began. In the tests (Tests 3-8) on galvanized shutters, the thermal radiant heat at the unexposed surface of the test specimens reached the ignition criteria of wood, 1w/cm², after the first ten minutes, while for tests on stainless steel test specimens, the thermal radiant heat at 1m away from the unexposed surface side exceeded the ignition criteria of wood, 1w/cm², after twenty minutes. The thermal radiant heat of galvanized fire shutters (Test 3~8) could, at most, reach 6.7w/cm² over a two hour long time period. The thermal radiant heat of stainless steel fire shutters (Test 1~2)
could, at most, reach 4.9\,w/cm^2 over two hours (see Fig. 8). No matter which side of the shutter was exposed to fire and no matter what the shape the shutter slats, shutters made with the same materials, either sprayed or not, or painted with resin, had almost the same thermal radiant heat. The thermal radiant heat of galvanized fire shutters was (about 1.37 times) higher than that of stainless steel shutters.

3.2 FIRE BEHAVIOR OF 1M×1M FIRE SHUTTERS IN STANDARD FURNACE FIRES

In Test 9, intumescent paint was sprayed on the exposed surface of the galvanized slats, while in Test 10 both sides were sprayed with intumescent paint. Both tests lasted for one hour. It was found that intumescent paint could greatly reduce thermal radiant heat because the heated intumescent paint could expand and form an insulation layer. During the hour, shutter slats did not turn red. In Test 9, the thermal radiant heat at 0.6\,m away from the slats could reach as high as 0.27 \,w/cm^2 (temperature: 86.6^\circ C) and the thermal radiant heat at 1\,m away from the slats could reach 0.08\,w/cm^2 (temperature: 51.8^\circ C). The maximum unexposed surface temperature of the slats was 402^\circ C. In Test 10, the thermal radiant heat was lower. The thermal radiant heat at 0.6\,m away from the slats could reach as high as 0.15 \,w/cm^2 (temperature: 79.4^\circ C) and the thermal radiant heat at 1\,m away from the slats could reach 0.04\,w/cm^2 at maximum (temperature: 43.5^\circ C). Shutters with two sides painted with intumescent paint could more effectively reduce thermal radiant heat than could one-side painted shutters. The intumescent paint on the exposed side expanded to become a 3cm-thick white carbonized layer while the paint on the unexposed side would slight foam to become a brown jelly-like layer with a maximum thickness of 0.5cm (see Fig. 9).

3.3 FIRE SHUTTERS SPRAYED WITH INTUMESCENT PAINTS UNDER CELLULOSIC FIRES
A full-scale test is totally different from a standard furnace test. For example, under ISO 834, flames from burners must not directly touch the exposed surface of the test specimen, the furnace pressure is fixed (at 50cm above the ground, the pressure is set at 0 Pa), and the temperatures at places 10 cm away from the exposed surface should be the same. All of the requirements of a full-scale test are different from those of a standard furnace test. In tests, the expanded intumescent paint is very likely to peel off or break down because of wind or smoke flows; and inside the fire room, the higher a spot is from the ground, the higher the temperature of the spot. This will cause the upper part of the intumescent paint to expand first (see Fig.10), which differs from the case in a standard furnace test, where expansion takes place at the same time. A furnace test uses fuel gas or diesel oil while a full-scale test uses wood as the fuel. In a standard furnace test, the heating temperature rises steadily. However, a real fire has periods of growth duration, develop-fire duration, decay duration, and flashover. This is why it is necessary to conduct full-scale fire tests. The focus of the full-scale test in this research is not on determining if the burning behavior should be a ventilation-controlled fire or a fuel-controlled fire [15-17]. What’s important is that this research has successfully simulated a very dangerous fire setting, with a temperature even above 1275°C, the highest point of the linear temperature range of Type-K thermocouple line [18].

In Test 9 and Test 10, it is found that the higher the temperature of the inside of the furnace, the greater the thermal radiant heat. Fig.11 shows the temperature of the fire room and the thermal radiant heat at the 1m spot. In Test 11, the temperature of the fire room reached 1370°C (the highest temperature was recorded on NCH1 thermocouple after 7.75 minutes; the highest temperature was recorded on NCH2 thermocouple after 12.25min). Since the fire source was ignited from a spot further away from the opening of the interior, it was not the spot 1m away from the
unexposed surface that could quickly reach a high temperature. The amounts of radiation absorbed at the centers of both shutters were 0.394 w/cm² (NCH6, time: 14.00 minutes) and 0.277 w/cm² (NCH5, time: 14.00 minutes) (see Fig. 12), respectively. In addition, it took fourteen minutes from the full-developed fire period for the temperature of the fire room to enter into the decay period. In other words, the maximum thermal radiant heat and the develop-fire duration were the same. When the temperature of the fire room stopped rising, the thermal radiant heat stopped increasing. In the duration of the test, no slats derailed from the guide rail. The bended part of the shutter bottom rail was less than 1.91 cm, and for a short time flames spurted out of the border between the guide rail and the concrete part. This was because when the shutter was installed, the cracks were intentionally not filled in with cement mortar in order to make the experiment setting more rigorous.

4. ANALYSIS AND DISCUSSION

4.1 INTEGRITY AND INSULATION OF FIRE SHUTTERS IN STANDARD FIRES

Fire shutters are basically made from iron. The melting point of iron is 1500°C [19]. In ISO 834 standard heating curve, within the first four hours, the temperature of iron will not go higher than 1152°C, so in the test, it was unlikely that shutter slats would be burned out. In addition, it was required that the pressure at a height of 50 cm above the shutter bottom rail should be 0 Pa. For every 1 m increase in height, the air pressure increases 8 Pa. Accordingly, for a shutter at a height of 300 cm, the air pressure around the shutter case was about +20 Pa, and the pressure around the shutter bottom rail was -4 Pa. So, even though the shutter bottom rail was bended, the flames in the furnace did not spurt out from below the shutter bottom rail. Most of the test failures of fire shutter flame resistance resulted from bursts of fire from shutter cases. Some failures took place when the shutter bottom rail was elevated more than 1.91 cm.
The fire out of the shutter case reduced the cracks between the shutter case and the slats. Iron plates could also be installed in the shutter case to prevent bursts of fire. The thickness of the bottom rail also could be increased to prevent the bottom rail from bending (see Fig.13), but this would not substantially reduce the radiation of the fire shutter. For example, in Test 7 and Test 8, after the first forty minutes when flames burst out from border between the shutter and the shutter case, tests were declared failures. The bursting of flames lasted for twenty minutes, the height of the flames reached to about 15cm, and the bended part of the bottom rail reached 5cm. But the thermal radiant heat did not increase as a result (see Fig.8). From the perspective of preventing fire spreading, since the emissivity of stainless steel is lower than that of galvanized materials [20], stainless steel shutters can greatly help to reduce thermal radiant heat. It will be meaningful to consider whether flames burst out and to compare the height of the bended part of the bottom rail. It was found in experiments that both galvanized fire shutters and stainless steel shutters produced high thermal radiant heat. As a result, if such shutters are to be used as fire compartments, even with fire integrity rating, fire spreading still cannot be prevented. Therefore, it’s necessary to specify the position of the installed fire shutters.

4.2 THE FIRE INSULATION OF INTUMESCENT PAINT AND RELEVANT APPLICATIONS

The standard furnace test proved that intumescent paint could greatly help to reduce thermal radiant heat. During the first hour when the temperature of the furnace reached to 925.3°C, the thermal radiant heat at 1m away from the galvanized shutter was 4.63w/cm². In the full-scale test with the galvanized shutter sprayed with intumescent paint, the thermal radiant heat at the 1m spot was about 0.18w/cm². Galvanized shutters, if sprayed with intumescent paint, can reduce thermal radiant heat by as much as 95%. According to Howell [8], the relation between thermal
radiant heat and distance can be computed (see Eqs. (2) (3)). At fire settings where temperatures reach 925.3°C and 1049°C, the safety distance for the galvanized shutters should be at least 390cm and 490cm, respectively so that the thermal radiant heat can be kept under 1.0 w/cm². In the full-scale fire test where the galvanized shutter was sprayed with intumescent paint, when the temperature of the fire room reached 925.3°C, the thermal radiant heat was 0.22w/cm²; the temperature of the fire room reached 1049°C, the thermal radiant heat released from the shutter was about 0.35w/cm² (see Fig.11~Fig.12), which was less than 1.0 w/cm², the generally accepted critical radiation for ignition of combustible materials.

Generally, when the fire shutter is used as the fire compartment, no objects should be placed under the shutter. However, considering the most dangerous situation, if there are combustible materials placed near the shutter, no matter how close such materials are to the shutter, they would not touch the surface of the shutter because the bottom rail under the shutter is in the shape of “⊥” (see Fig. 13). The shortest distance between the combustible materials and shutter slats should be half of the width of the bottom rail (⊥/2). Besides, it was observed that when heated, the shutter slats bended toward the source of heat. Hence, in the event of a fire, the slats will not touch the combustible materials outside the fire room. The galvanized shutter sprayed with intumescent paint can provide enough insulation to prevent fire spreading.

\[
F \geq \frac{q_{crit}}{q} \tag{2}
\]

\[
F = \frac{1}{2\pi} \left[ \frac{X}{\sqrt{1+X^2}} \times \tan^{-1}\left(\frac{Y}{\sqrt{1+X^2}}\right) + \frac{Y}{\sqrt{1+Y^2}} \times \tan^{-1}\left(\frac{X}{\sqrt{1+Y^2}}\right) \right] \tag{3}
\]

F: view factor (the fraction of radiant energy leaving the fire shutter surface which falls directly upon the object surface)

\[X = \frac{a}{c}\]
\[ Y = \frac{b}{c} \]

\( q_{\text{crit}} \): the critical radiation for ignition of combustible materials, 1.0 w/cm\(^2\) for wood.

\( q \): radiant source (w/cm\(^2\))

a, b, c: as shown in Figure 14

Sometimes, fire shutters are installed on the escape route. In this case, whether or not people will get hurt from the radiation should be considered. In the experiments using manikins conducted by Wieczorek et al. [21], it was found that a long-time exposure to the thermal radiant heat lower than 0.17 w/cm\(^2\), or to temperature lower than 44°C [22], would not cause pain to human skin. But when the thermal radiant heat went up to between 0.17 and 2 w/cm\(^2\), pain increased as the exposure lasted. As shown in Eq. (4), a thermal radiant heat of between 2 and 5 w/cm\(^2\) causes second-degree skin burns. The relation between the exposure of time length and second-degree skin burns is shown in Eq. (5). As a result, in a fire setting with a shutter sprayed with intumescent paint, the victims would not have second-degree skin burns and this is why the skin pain is the only consideration. Strictly speaking, when the victims are very close to the shutter and the thermal radiant heat is assumed to be 0.22 w/cm\(^2\) and 0.35 w/cm\(^2\), it takes 27.9 sec and 11.56 sec, respectively, for the skin to feel the pain, as shown in Eq. (4). Considering the planning of building functions and the speed at which evacuation occurs, the width of the fire shutter can be determined (see Eqs. (6)(7)) If the speed of the evacuation action is 1m/s, the widths of the fire shutters, which are installed on the escape route, are 27.9m and 11.56m, respectively.

The above is an analysis on the insulation performance of shutters sprayed with intumescent paint on a single side. From a 1m×1m test, it was found that both-side sprayed shutters could deliver better insulation performance than single-side sprayed shutters. Since it is impossible to predict on which side of the shutter a fire would take
place, it will be more appropriate to spray intumescent paint onto both sides of the shutter. In addition, considering whether or not the paint would fall off the shutter after the shutter was repeatedly rolled, a test was conducted, in which the shutter was rolled up and down 300 times. No peel-off of the 0.3mm-thick layer of paint was observed. Therefore, it is concluded that intumescent paint can be sprayed to shutters used as fire compartments in real-life settings.

\[ t_b = \frac{250}{S} q_R^{-1.9} \quad \text{Eq.(4)} \]

\[ t_{b2} = 260 q_R^{-1.56} \quad \text{Eq.(5)} \]

\( t_b \): time to skin pain (s)

\( t_{b2} \): time to second-degree skin burns (s)

\( q_R \): thermal radiant heat flux (kw/m²)

S: safety factor for the time to pain of human skin, a safety factor (S) of 2 accounting for human variability is adopted.

\[ W_{1hr} = 27.9 \times V \quad \text{Eq.(6)} \]

\[ W_{2hr} = 11.56 \times V \quad \text{Eq.(7)} \]

\( W_{1hr} \): width of fire shutter of 1-hr fire integrity (m)

\( W_{2hr} \): width of fire shutter of 2-hr fire integrity (m)

V: escaped velocity (m/s)

5. CONCLUSIONS

(1) To prevent flames bursting out from the shutter case and to prevent the shutter bottom rail from rising above 1.91cm, iron plates can be added to the shutter case and the thickness of the shutter bottom rail can be increased. However, whether or not flames burst out from the shutter case or the height of shutter bottom rail increases to more than 1.91cm, does not substantially help to reduce the thermal radiant heat of the fire shutter. If a fire integrity fire shutter is installed in
a fire compartment, a safety clearance distance is needed to effectively prevent fire spreading.

(2) The thermal radiant heat of fire shutters has more to do with the material of the shutter than with the side where a fire takes place, or the shape of the slats. Galvanized fire shutters deliver a less satisfactory insulation performance than do stainless steel shutters. The thermal radiant heat of a galvanized fire shutter is 1.37 times higher than that of a stainless steel fire shutter.

(3) Galvanized fire shutters, sprayed with intumescent paint single-sided, can reduce 95% of the thermal radiant heat to less than 1.0 w/cm², the ignition criteria of common woods. Fire spreading can be effectively avoided under regulations of building functions and combustible materials should not directly touch the fire shutter. Fire shutters can also be installed on escape routes to help prevent second-degree skin burns.

(4) Since it is impossible to predict on which side of the fire shutter a fire would take place, it is suggested to spray intumescent paint onto both sides of the fire shutter. The improvement methods proposed in this research can provide reference for the design of fire compartments.
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NOMENCLATURE

T: average standard furnace temperature (°C)

T: time (min)

F: view factor (the fraction of radiant energy leaving the fire shutter surface which falls directly upon the object surface)

X= a/c

Y= b/c

$q_{cr}$: the critical radiation for ignition of combustible materials, 1.0 w/cm² for wood.

$q$: radiant source (w/cm²)

a,b,c: as shown in Figure 14

$t_b$: time to skin pain (s)

$t_{b2}$: time to second-degree skin burns (s)

$q_r$: thermal radiant heat flux (kw/m²)

S: safety factor for the time to pain of human skin, a safety factor (S) of 2 accounting for human variability is adopted.

$W_{1hr}$: width of fire shutter of 1-hr fire integrity (m)

$W_{2hr}$: width of fire shutter of 2-hr fire integrity (m)

V: escaped velocity (m/s)
REFERENCES


Figure 1. Sorts of the fire shutter slat (the concave side is the inside of the room)

Figure 2. Specification of the vertical drop fire shutter
Test 9: heating inside surface
Test 10: heating inside surface
Test 11: heating inside surface

0.3mm intumescent paint

Material:
Galvanized slat
Slat thickness: 1.5mm
Test area: 1m x 1m
Unit: mm

Material:
Galvanized slat
Slat thickness: 1.5mm
Test area: 1m x 1m
Unit: mm

Material:
Galvanized slat
Slat thickness: 1.5mm
Test area: 2.82m x 7.3m
Unit: mm

Figure 3. Specimens of galvanized fire shutter slat sprayed with intumescent paints

Figure 4. Fire shutter installed in the test specimen frame
Figure 5. 3m×3m furnace fire test situation and measuring position of radiometer

Figure 6. Measuring positions of thermocouples and radiometers (1m×1m fire test)

CH2, CH15, CH14: unexposed shutter slat surface thermocouple
Figure 7. Typical fire room plan, 3D perspective of the fire room and measuring positions (Test 11)

Figure 8. Thermal radiant heat fluxes recorded at 1 m from the rolling shutters (3m×3m)
Intumescent paints of the exposed surface

Figure 9. 1m×1m standard furnace fire test (After test)

The intumescent paint on the upper part of the shutter first caught fire.

Figure 10. Expansion process of the intumescent paint in the full-scale fire test

Intumescent paints of the unexposed surface

All of the intumescent paint expanded.
Figure 11. Compartment temperature-time curves in Test 11

Figure 12. Thermal radiant heat flux recorded at 1m from the unexposed fire shutter in Test 11
The arrow shows the place where flame gushed out.

Figure 13. Methods to improve the shutter and the condition of the flame gushing out between the shutter case and the slats.

Figure 14. Geometry for the view factor