




Large-Scale Fire Tests on Sliding Doors for Building Applications

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Abstract. The performance of fire doors is essential for the fire safety in buildings. In the present study, a series of large-scale fire tests on sliding doors is performed in the facilities of the Danish Institute of Fire and Security Technology. The test specimens comprise typical and commercially available door solutions for building applications. Similar doors of approximate dimensions 3 m × 3 m and 5 m × 3 m (width × height) are examined, while separate tests are conducted for each side of door exposed to fire. In all cases, the test specimens are mounted on appropriate wall frames of aeriated concrete as used in practice. The test results are compared in terms of transient temperature and deflection measurements. Findings reveal that the examined sliding doors exhibit satisfactory fire performance meeting the classification requirements. The overall fire performance is not affected by the width opening of door, while the fire resistance rating is significantly influenced by the side of exposure to fire. Finally, the failure characteristics are discussed, and the fire behavior of sliding doors is evaluated.

Keywords: Fire doors, Sliding doors, Fire tests, Fire resistance, Fire safety, Oversized doors, Building industry

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1. Introduction

Fire safety is associated with the performance of fire doors in terms of preventing the spread of fire in other compartments. Such performance is evaluated by means of the fire resistance rating that corresponds to the time of door failing to comply one of the two following criteria during a fire test:

- The insulation (I) criterion refers to the ability of maintaining the temperature rise at the unexposed side below predefined temperature limits (average and maximum temperature measurements).
- The integrity (E) criterion refers to the ability of withstanding the spread of fire by preventing the passage of flames and hot gasses (visual sustained flaming, ignition of cotton wool pad, limitation of gap openings).

1.1. State of the Practice

General guidelines for the execution of fire-resistance tests on doors are provided in EN 1634-1 [1]. The purpose of such tests is to measure the fire resistance of representative specimens according to the performance-based criteria. The experimental procedure consists of exposing the door specimen to a standard fire test in large-scale furnaces, while the test set-up may vary depending on the type and size of fire door as well as the side of exposure to fire.

Several types of doors are available in the building industry, including hinged, sliding, or rolling doors, as shown indicatively in Fig. 1. The size of fire doors is variable ranging from one to several meters in width and height. In particular, the size of hinged doors is usually limited by the self-weight of the door leaf, while sliding and rolling doors can typically reach larger dimensions. Rolling doors exhibit the advantage of not requiring space in open configuration, and they are mostly preferred in cases of large openings within compartments of limited free space. However, they typically possess lower fire resistance than sliding doors, due to thickness limits imposed by the flexibility of door and the effect of restrained thermal expansion that becomes critical with increase of the door width. Therefore, sliding doors are more preferable in cases of compartments exhibiting large openings in which a high fire-resistant rating is required.

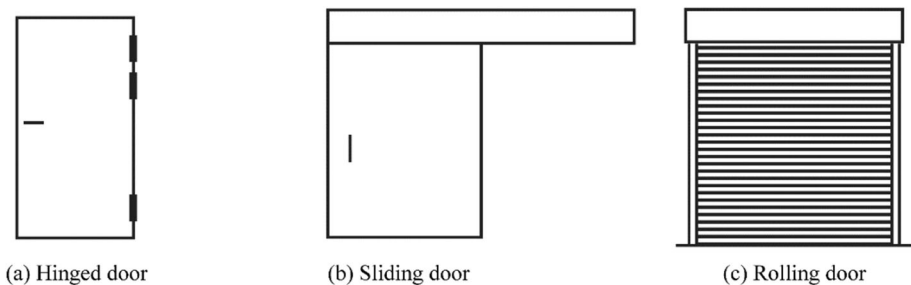


Figure 1. Type of fire doors.

For the classification of a fire door, the test specimen typically incorporates the maximum size of door for which approval is to be sought. However, the size of fire doors is continually growing due to the increasing industrial demands, while a limited number of fire testing laboratories are globally able to meet the dimension requirements of oversized specimens. Therefore, the size of test specimens is limited in practice by the size of available furnaces. Variations in the dimensions of certified doors are possible, based on whether an extended time is reached in the certification test according to the overrun time requirements indicated in EN 1634-1 [1], as reported in Table 1. In the case of steel doors that do not meet the overrun requirements, a decrease up to 50% in width and 75% in height is allowed, while any size increase is not possible. On the other hand, the door dimensions can be reduced without limitation when the overrun requirements are fulfilled, while increases in height and width are possible provided that the surface is not increased more than 50%. A further extension of door size is possible according to the additional requirements prescribed in the extended field of application for fire doors [2], in which the maximum increase of door width and height may be up to 100% and 75% respectively.

Special requirements for fire doors used in maritime applications are specified by the International Maritime Organization (IMO) [3]. In this case, a typical width opening may be 2.74 m for a double-leaf hinged door and 3.2 m for a single sliding door [4]. These dimensions exceed the standard specimen size of 2.44 m × 2.50 m (width × height) by 12% and 31% respectively, as indicated by the IMO guideline [5]. They also exceed the dimensions of furnaces available in most laboratories. Furthermore, large roller shutters, such as the ones used to compartmentalize large open shopping areas on passenger ferries, may reach a width of 15 m and a height of 9.25 m [6], thus making the real scale testing of such components utterly unfeasible. According to the IMO recommendations [5], a numerical approach can be employed to extrapolate the size of certified fire doors based on relevant finite element analyses. In this context, the surface of a door can be increased up to 50% accounting for an appropriate numerical model that is validated against the pertinent test results. It is noted that the size extrapolation based on numerical simulations is only allowed in the case of doors for maritime applications [5].

1.2. State of the Art

Early experimental tests on steel and wooden doors subjected to natural fires were performed by Joyeux [7]. The relevant test results were used to assess differences in the fire behavior of hinged doors under natural fire scenarios compared to stan-

Table 1
Overrun Time Requirements for the Classification of Fire Doors [1]

Classification time (min)	15	20	30	45	60	90	120	180
Extended time (min)	18	24	36	52	68	100	132	196

standard fire testing. Nassif et al. [8] conducted standard fire tests on single-leaf steel doors which were mounted on drywall or masonry walls. In this study, the direction of door opening as well as the type of wall frame were found to significantly affect the fire resistance rating. Detailed numerical models of fire doors subjected to standard fire curves were developed by Tabaddor et al. [9] highlighting the challenges of validating detailed numerical models of fire doors against experimental test results. A numerical and experimental study on steel door frames was presented in [10] and [11], while the influence of gaps on the smoke spread of doors was investigated by means of computational fluid dynamic simulations in [12]. The fire performance of hinged doors with opening into and away from the furnace was examined by Capote et al. [13]. In this work, the main physical phenomena of hinged doors encountered during standard fire testing were presented. A combined thermo-mechanical analysis on a single leaf hinged naval door was carried out by Boscariol et al. [14], while single-leaf and double-leaf doors of large-scale were examined by Bozzolo et al. [15]. Based on these results, improved door configurations in terms of fire resistance were proposed by Moro et al. [16]. As evidenced in the literature findings, fire doors typically exhibit a complex fire performance associated with the variety of constructional details comprising the door assembly, as well as the aleatory and epistemic uncertainties related to the material properties. The accuracy of relevant numerical simulations is highly dependent on calibration and validation of pertinent numerical models against experimental test results. The existing studies on fire doors are limited by the scarcity of experimental data, which are focused on hinged doors. Despite the increasing demands for large sliding doors in the building industry, there are not available relevant numerical or experimental studies in the literature.

1.3. Scope and Objectives of the Study

In the present work, a series of large-scale furnace tests on fire-resistant sliding doors is performed in the facilities of the Danish Institute of Fire and Security Technology (DBI). The test specimens comprise typical and commercially available door solutions for building applications. Similar doors of approximate dimensions 3 m × 3 m and 5 m × 3 m (width × height) are examined to assess the effect of width opening on the fire resistance rating. The test specimens of standard (ca. 3 m × 3 m) and oversized (ca. 5 m × 3 m) doors are mounted on representative wall frames, as used in the building practice, while separate tests are conducted for each side of exposure to fire. Appropriate measuring devices are employed to obtain the developed temperatures and deflections during fire tests. The test results are compared in terms of transient temperature and deflection measurements, while thermographic views are used to obtain comparative overviews of the temperature distributions. The test results are discussed, and the overall fire behavior of sliding doors is evaluated.

2. Failure Modes of Fire Doors

Fire doors exhibit a complex fire behavior associated with the variety of constructional details comprising the door assembly. The door assembly, referred herein as doorset, typically consists of the door frame and a single or multiple door-leaves. The high insulation capacity of materials incorporated in the door leaves is mostly contributing to the door's fire performance. As the size of door increases, the use of stiffeners within the door leaf is required to provide rigidity. Internal spacers that penetrate through the door may also be used to connect the door-leaf faces one to the other. To prevent the passage of smoke and flames, special labyrinth joints are used at the door frame to interlock with the door-leaf when the door is closed (c.f. Section 3). Similar joints are also employed at the interconnections of the door leaves in the case of two or more leaves. Sliding doors are usually hanged from the top side through a suspension guide that is part of the upper frame, while in some cases the doors may lean directly on the ground.

Fire doors may fail due to the violation of insulation or integrity criterion during the fire resistance tests. Maintaining a good balance between the insulation and integrity capacity of fire doors is essential for obtaining a high fire resistance rating but also comprises a challenging aspect of fire design, as shown in Fig. 2. Based on the design practice of fire doors, the use of connectors (stiffeners, spacers, joints, etc.) within the door leaf increases the stiffness and strength resistance by preventing buckling failures. Such connectors typically create thermal bridges that allow the heat transfer from the exposed to the unexposed side of door leaf, thus could promote loss of insulation (Fig. 2, left). On the other hand, the presence of insulation material creates a temperature gradient over the door thickness. This is responsible for inducing thermal bowing deflections towards the fire, which

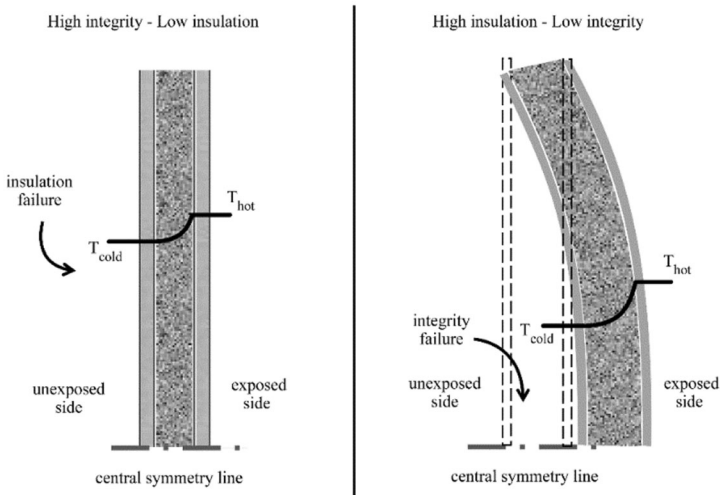


Figure 2. Failure modes of insulated steel doors. Left: Insulation failure (I); Right: Integrity failure (E).

could lead to gap openings and loss of integrity (Fig. 2, right). Thus, integrity failure may prevail in the attempt of mitigating insulation failure and vice-versa.

For the certification of fire-resistant doors that are asymmetric towards the fire exposure, execution of separate tests is required for the door mounted inwards or outwards the furnace [1]; in the former case the loadbearing components (hanging mechanism) are placed inside the furnace, while in the latter case they are placed outside the furnace. When a sliding door is tested inwards the furnace, a larger door surface is directly exposed to fire and thus a lower insulation resistance is expected. Regarding the integrity resistance, larger deflections are usually encountered when the supporting system is inwards the furnace, and failure may be associated with the passage of flames or smoke. Based on the previous, it is expected that the most onerous side of testing a sliding door is inwards the furnace. However, it is not possible to draw a firm conclusion without fire testing, thus asymmetric sliding doors must be tested separately on both sides for certification purposes [1].

3. Experimental Set-Up

A series of large-scale standard tests is carried out on sliding doors consisting of a single door-leaf along with the frame construction, as shown in Fig. 3. Views of the examined doors and pertinent details are illustrated schematically in Figs. 4 and 5, respectively. The door leaf consists of prefabricated sandwich panels of thickness 100 mm, comprising mineral wool insulation of density 135 kg/m^3 , thermal conductivity 0.026 W/m K , and specific heat 700 J/kg K , bonded between thin-walled steel sheets of thickness 0.6 mm. The sandwich panels of width 1150 mm are cut in the appropriate dimensions and connected along vertical joints using self-drilling screws every 150 mm. A steel profile of Channel section $\text{C}100 \times 50 \times 2.5$ is employed for closing the edges at the perimeter of door-leaf. The door-leaf is hung from the top side via a suspension guide underlying the door frame. In this context, a set of rollers is used for sliding the door into a

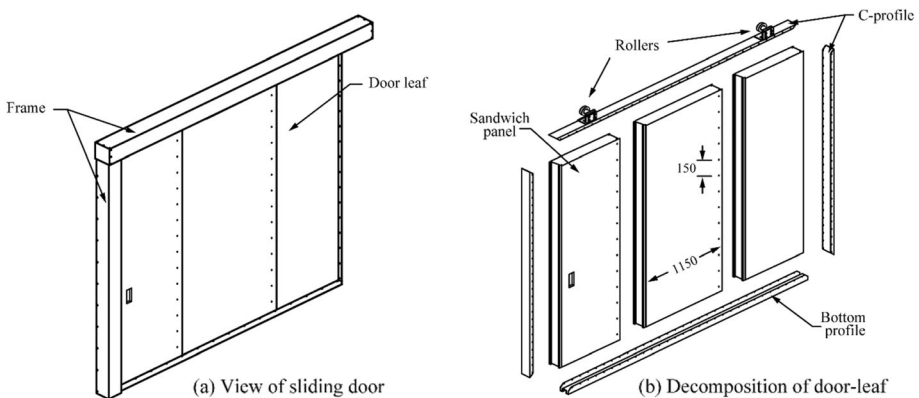


Figure 3. Typical assembly of sliding door.

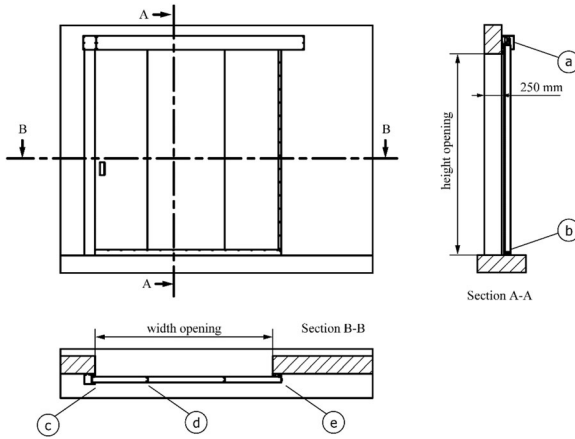


Figure 4. Front and section views of sliding door.

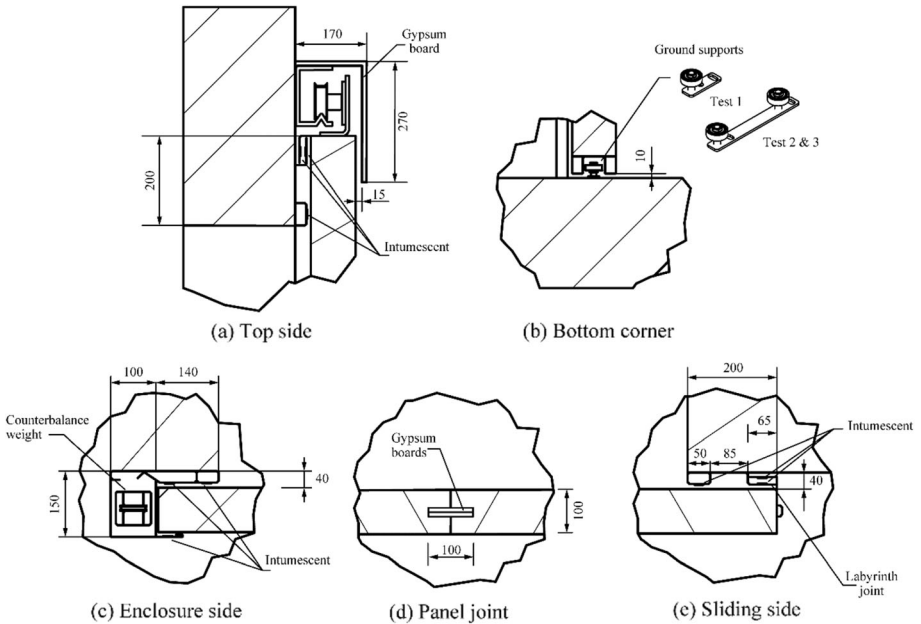


Figure 5. Details of sliding door: vertical (a, b) and horizontal (c-e) sections (as indicated in Fig. 4).



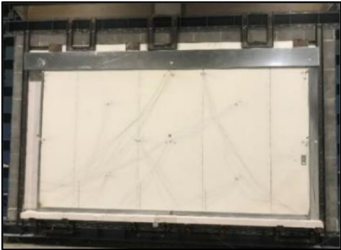
guide track fixed to the wall (Fig. 5a). The door is guided through ground supports at the bottom corners (Fig. 5b); the supports are encapsulated in a special-shaped steel profile, fixed at the bottom of door-leaf, restraining any out-of-plane movements. A counterbalance weight is installed at the enclosure side of the frame allowing for the door self-closing (Fig. 5c).

Although the performance of fire doors is mainly associated with the high insulation capacity of non-combustible panels, the panel connections are usually more prone to an insulation or integrity failure under fire conditions. In order to reduce the heat dissipation through the panel joints, two layers of 10 mm thick gypsum boards are installed within the joint sections; the gypsum boards of width 100 mm are symmetrically placed along the vertical joints covering the whole height (Fig. 5d). The presence of gypsum boards is considered beneficial for the fire behavior as the chemically bound water decreases the heating rate under fire conditions due to the gypsum dehydration effect. A layer of 10 mm thick gypsum board is also installed at the top frame of the door in order to reduce the heat dissipation at the suspension components (Fig. 5a). The passage of flames through the perimeter gaps is prevented by employing labyrinth joints between the frame and door-leaf (Fig. 5e). Intumescent strips of thickness 2 mm and width 20 mm are installed at several locations around the door frame, in order to seal the gaps through the expansion under the action of fire.

The door specimens are mounted on appropriate wall frames made of aerated concrete. This type of structure is considered representative of the supporting walls in typical building applications. Aiming at assessing the effects of scaling, similar door specimens of two different width opening are examined. The examined door specimens exhibit clear openings of 2500 mm × 2700 mm and 4500 mm × 2500 mm (width × height), which are appropriately selected to fit the size of testing furnaces and correspond to standard and oversized sliding doors, respectively. In all cases, similar door frames are employed while the size of door leaves is varying. In the case of oversized doors, larger ground supports (Fig. 5b) are employed at both corners, aiming at reducing the developed deflections of the bottom profile. As the examined doors are asymmetrical towards the exposure, the fire performance is highly dependent on the side of exposure to fire. Therefore, a fire test is initially performed regarding the standard door mounted inwards the furnace, followed by two separate tests of the oversized door mounted inwards and outwards the furnace. The overall testing configuration is summarized in Table 2.

The large-scale fire tests are performed in accordance with EN 1634-1 [1]. Two different furnaces are employed due to the size requirements of the door specimens. A furnace of internal dimensions 3.2 m × 3.2 m × 1.5 m (width × height × depth) is used in the case of standard-size specimen (Test 1). This furnace exhibits 12 propane gas burners located on the walls. The furnace's maximum power is 2.5 MW, while the temperature inside is controlled by 16 plate thermocouples. A larger furnace of dimensions 5.5 m × 3.1 m × 4.2 m (width × height × depth) is employed in the case of oversized specimens (Test 2 and Test 3). This furnace has a maximum power 10 MW and can be efficiently used for testing both horizontal and vertical elements, for which it is called multi-furnace. The heat is generated through 18 propane gas burners located on the walls, while the temperature is controlled by 12 plate thermocouples. In all cases, the average temperature inside the furnace is following the ISO 834 standard curve [17], and the maximum pressure difference between the top and bottom level is equal to 20 Pa. The standard size furnace and the multi-furnace are shown in Fig. 6.

Table 2
Experimental Test Configuration

Test No	Clear wall opening (width × height)	Testing side (side of mounting)	Experimental set-up
1	2500 mm × 2700 mm	Inwards	
2	4500 mm × 2500 mm	Inwards	
3	4500 mm × 2500 mm	Outwards	

The developed temperatures at the unexposed face of door are measured using K-type thermocouples (TC). The installation of measuring points and the accuracy of measurements is in accordance with EN 1634-1 [1]. The average temperature is determined using five thermocouples 1.1 to 1.5, which are placed at the center of the door leaf and at the center of each quarter section, all positioned at least 100 mm away from the edges and not closer than 50 mm from any joint. The maximum temperature is measured using five thermocouples 2.1 to 2.5, placed 100 mm from the visible edges. Four thermocouples 3.1 to 3.4 are employed to obtain the developed temperatures at 20 mm from joints. For the door tested outwards the furnace, four thermocouples 4.1 to 4.4 are installed at 100 mm from the edges of visible frame. In all cases, a thermographic camera (FLIR A65) is used to obtain an overview of the developed temperature distribu-

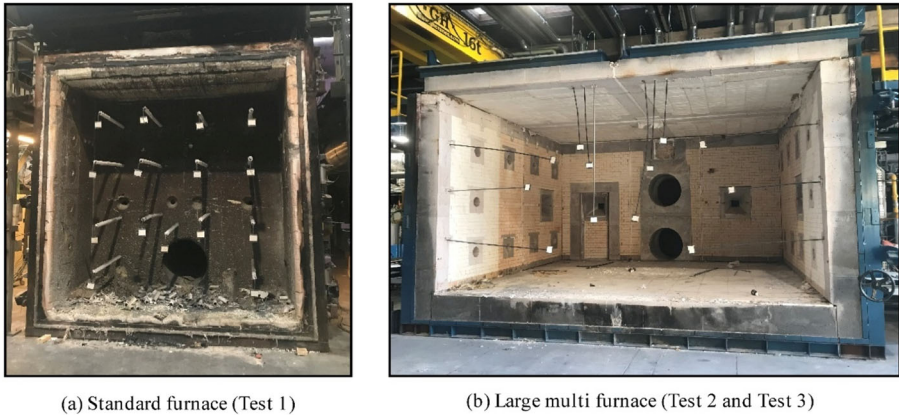


Figure 6. Fire testing furnaces (photo courtesy DBI).

tions at the unexposed face; the thermal measurement is based on the infrared energy of a body that is depending on its temperature. The developed displacements at the unexposed face of door are measured using appropriate measuring devices. The measuring technique is based on the digital image correlation method [18], consisting of a multiple camera system that allows capturing the three-dimensional displacements of target points. In this context, a set of nine target points Z_1 to Z_9 are placed at the center of door leaf, as well as at its middle and the ends of visible edges. The measuring points are shown in Fig. 7.

4. Fire Test Results

In this section, the fire test results are presented in terms of transient temperature and deflection measurements at the positions of measuring points.

The average temperature at the unexposed side of door leaf is obtained from TCs 1.1 to 1.5 (Fig. 7). The temperature rises of relevant thermocouples from Test 1, Test 2, Test 3, and the average temperature rise of each test, is shown in Fig. 8. A good agreement is evidenced in all cases. The sliding doors meet the insulation requirement on average temperature, which should be lower than $140\text{ }^{\circ}\text{C}$ at the unexposed side [1]. In the first test, the average temperature rise is found to be approximately $80\text{ }^{\circ}\text{C}$ at 60 min, while the corresponding temperature of the other two tests is approximately $90\text{ }^{\circ}\text{C}$. The temperature variations in the first test are attributed to the placement of TCs 1.1 to 1.4 placed close to the panel joints where the presence of gypsum boards decreases the heat dissipation in contrast to TC 1.5 that is placed away from the joints (Fig. 7a). As it is evidenced, the opening width of sliding door and the side of exposure to fire have a negligible effect on the average temperature distribution at the unexposed side.

The maximum temperature at the unexposed side of door leaf is obtained from TCs 2.1 to 2.5 (Fig. 7). A comparison of the temperature rise at relevant TC positions between Test 1, Test 2, and Test 3 is shown in Fig. 9. As it is evidenced, the

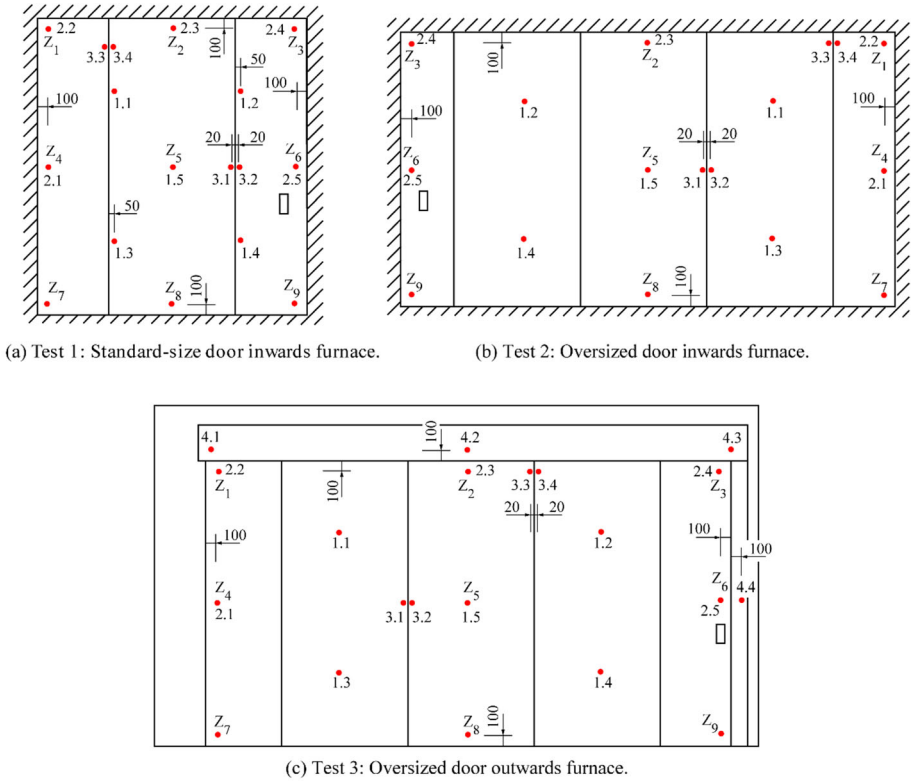


Figure 7. Measuring points at the unexposed side of sliding door.

temperature distribution close to the edges is not affected by the size of door specimens (Test 1 and Test 2). On the other hand, a significantly more favorable performance is obtained when the door is tested outwards the furnace (Test 3). This is explained by the fact that the wall is covering the edges of door leaf from direct fire exposure. In the first test, TC 2.5 failed to measure the developed temperatures. The high temperature increase measured from TC 2.3 in the beginning of Test 2 is probably due to the hot air coming from the labyrinth before the intumescent expansion start sealing the frame. The maximum temperature rise is found approximately 150 °C for Test 1 and Test 2 at the 60 min, while the corresponding temperature of Test 3 is approximately 90 °C. In all cases, the sliding doors meet the insulation requirement of maximum temperature rise lower than 180 °C [1].

The critical temperatures close to the joints of door-leaf are measured by TCs 3.1 to 3.4 (Fig. 7). The temperature rise obtained from relevant thermocouples of Test 1, Test 2, and Test 3 is shown in Fig. 10. In the second test, TCs 3.1 and 3.2 are placed 100 mm from the visible top edge, thus the transient temperature measurements are significantly higher due to the heat coming from the top. The effect of gypsum dehydration is causing a delay in heat transfer through the joints,

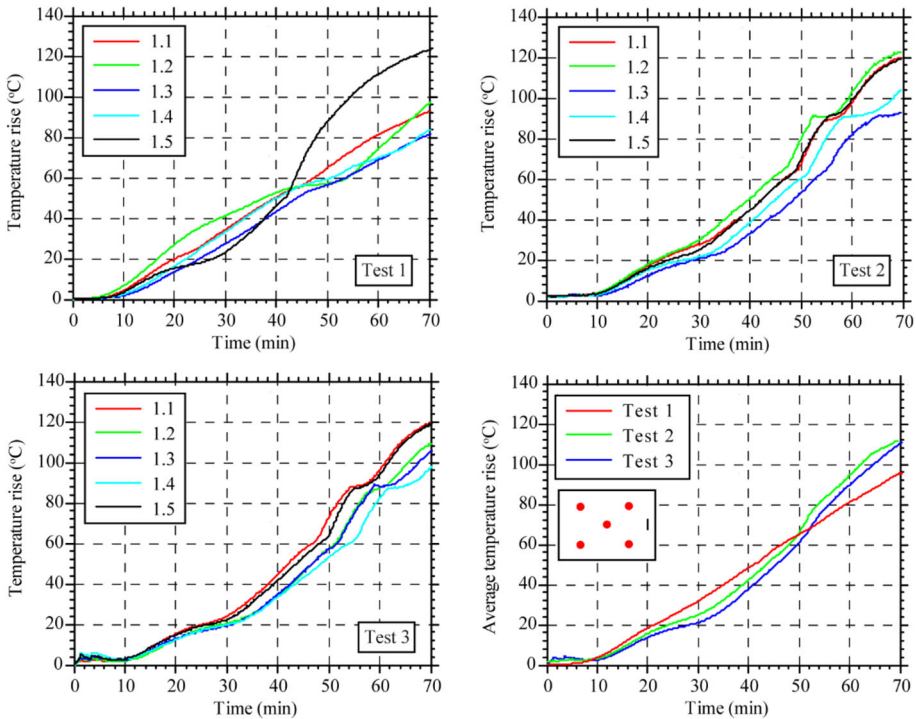


Figure 8. Temperature rise at the unexposed surface of door leaf and calculated average (≤ 140 °C).

which is evidenced in the characteristic temperature “plateau” at approximately 60 °C. In all cases, the joint temperatures meet the insulation requirement of maximum rise lower than 180 °C [1].

For the door mounted outwards the furnace, the developed temperatures at the visible frame are measured by TCs 4.1 to 4.4 (Fig. 7). The temperature rise obtained from relevant thermocouples of Test 3 is shown in Fig. 11. As it is evidenced, very low temperatures are developed at the frame, meeting the requirement of maximum temperature 360 °C [1].

The deflection measurements at the unexposed side of door-leaf are obtained from points Z_1 to Z_9 (Fig. 7). A comparison of deflections at corresponding locations between Test 1, Test 2, and Test 3, is shown in Fig. 12. In all cases, deflections towards the furnace are denoted as negative. Relatively small deflections (less than 25 mm at 60 min) are exhibited close to the edges of door-leaf (Z_1 , Z_2 , Z_3 , Z_4 , Z_6 , Z_7 , Z_9), indicating that the contact with frame is sufficiently restraining any out-plane movement. Large deflections are encountered at the middle of bottom profile (Z_8) towards the furnace due to the temperature gradient (thermal bowing effect). The thermal bowing deflection is almost similar in the case of Test 2 and Test 3 (~ 85 mm at 60 min), while the thermal bowing deflection is lower in Test 1 (~ 40 mm at 60 min) due to the shorter width opening of the door-leaf.

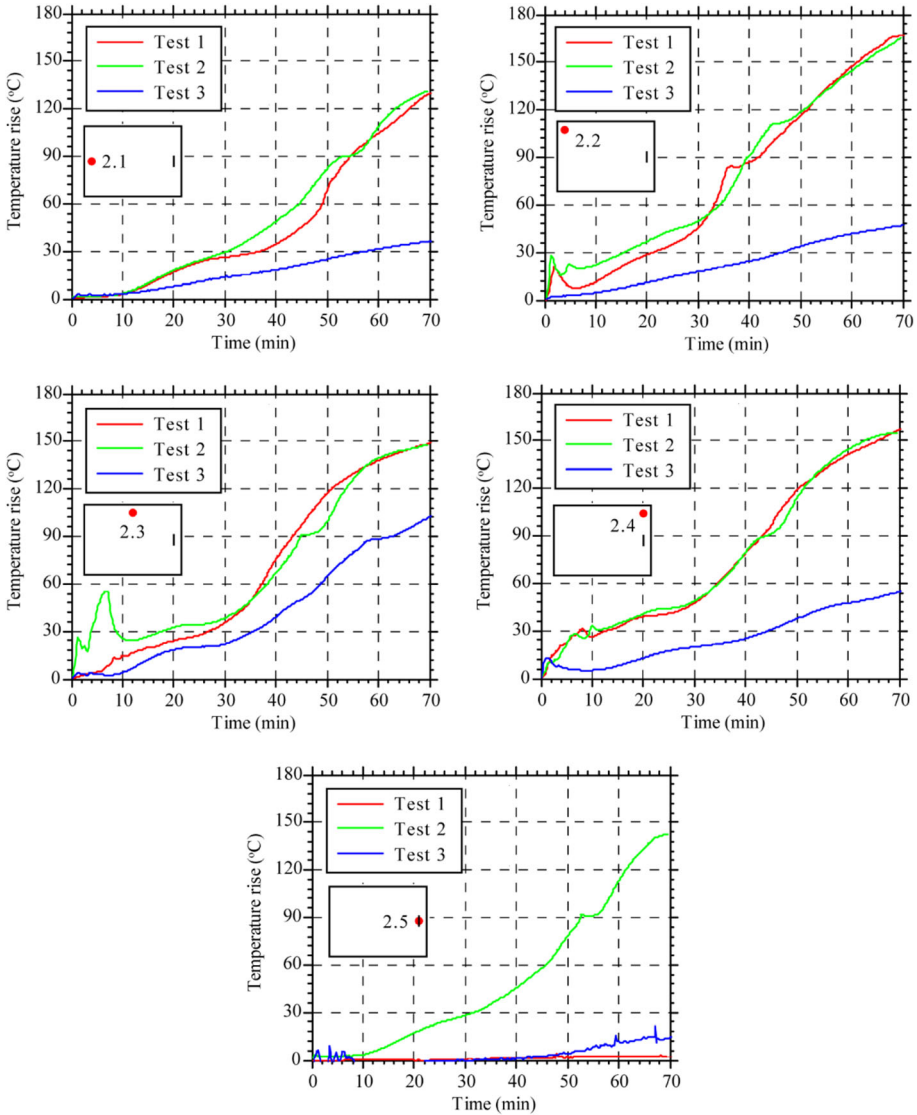


Figure 9. Temperature rise at 100 mm from the visible edges of door leaf (≤ 180 °C).

5. Assessment of Fire Behavior

The examined sliding doors exhibited satisfactory fire performance meeting the classification requirements for an overall time of 68 min. The integrity criterion was fulfilled for the whole test duration. It may be assumed that the examined doors would probably not be failing due to integrity after that time, since: (i) the thermal gradient is almost stabilized thus gap openings remain constant, and (ii)

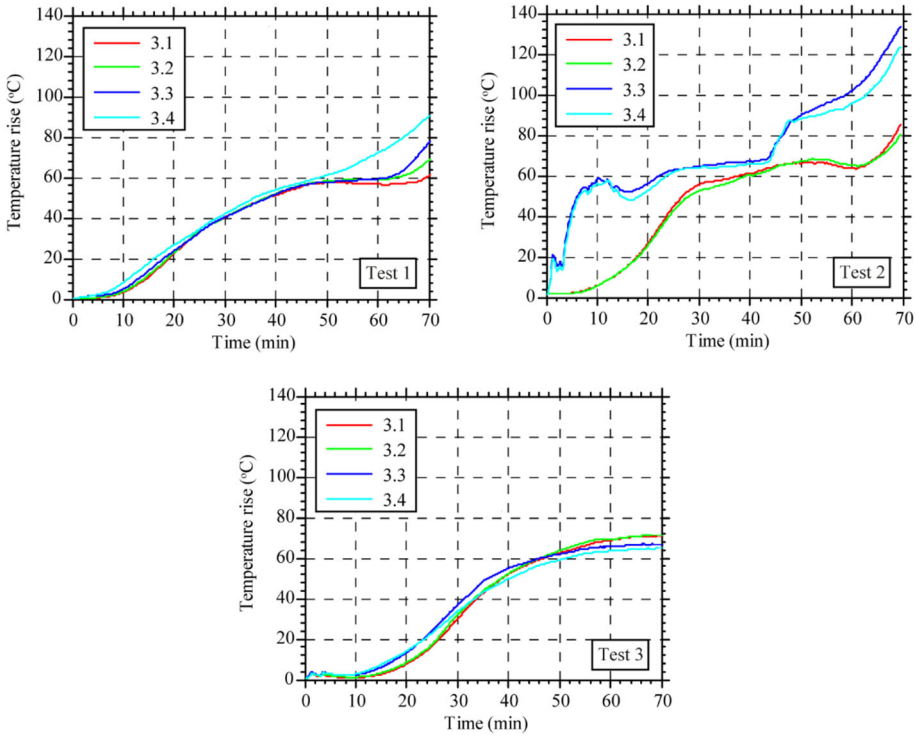


Figure 10. Temperature rise at 20 mm from the joints of door leaf ($\leq 180^\circ\text{C}$).

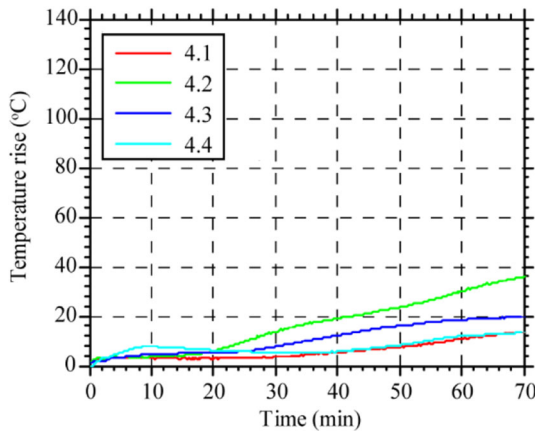


Figure 11. Temperature rise at the frame of doorset ($\leq 360^\circ\text{C}$).

possible combustible material that may exist in the construction (i.e., glue at mineral wool) has been eliminated by that time. Post-fire views at the end of the door

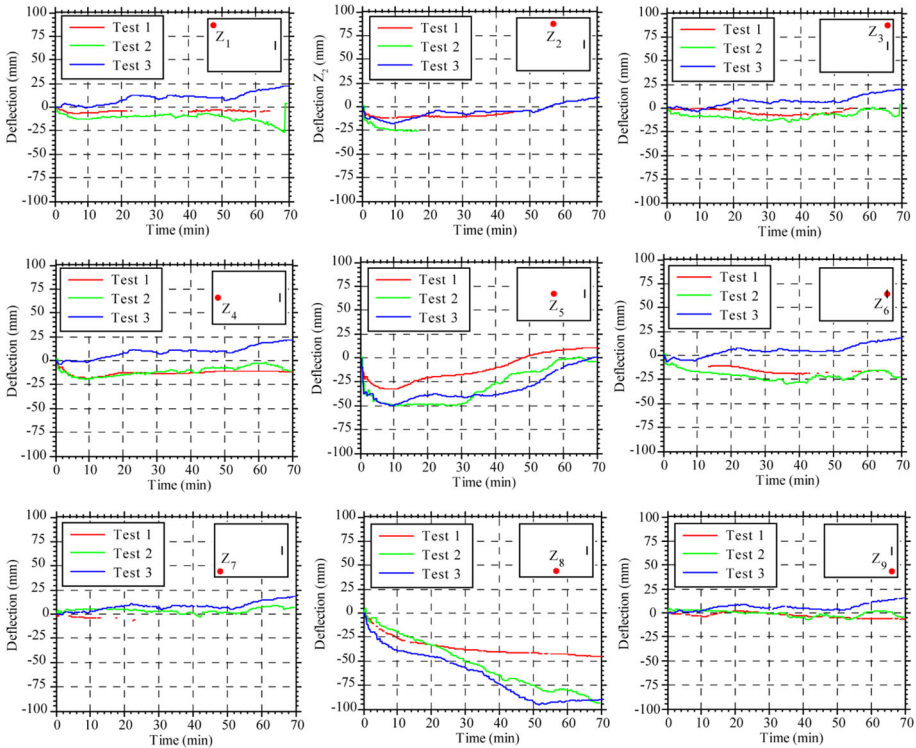


Figure 12. Deflection measurements of door leaf.

tests are illustrated in Fig. 13. The fire resistance rating of doors was determined based on the insulation capacity; the maximum temperature was found critical at 100 mm from the top corner at the sliding side. The deformed shape was similar for the door tests inwards and outwards the furnace (Fig. 13a, b). The placement of gypsum boards prevented the passage of flames through the panel connections, while the labyrinth joints along with the expansion of intumescent efficiently sealed the frame gaps. In terms of average temperature, the fire performance was mainly dependent on the high insulation capacity of the sandwich panels. Detachment of the steel sheets and the mineral wool insulation was evidenced at the exposed side after the fire tests without affecting the performance of door (Fig. 13c). The suspension guide (underlying the top frame) carried efficiently the door self-weight during the whole test duration (Fig. 13d). The intumescent strips expanded under the action of fire sealing the gaps at the door frame (Fig. 13e, f).

Based on the comparison between the standard and oversized doors (Test 1 and Test 2), it is evidenced that the fire resistance was not affected by the width opening of the door-leaf. This is mainly attributed to the boundary conditions of the examined doors which were similar in both cases. The contact with frame restrained sufficiently any out-plane movement which could introduce possible integrity failure due to gap openings. Moreover, as thermal expansion is not



Figure 13. Post-fire views of sliding door tests.

restrained in the horizontal direction (free to slide), the change of width dimension did not introduce any additional eigenstresses at elevated temperatures. Based on the comparison between the door tests inwards (Test 1, Test 2) and outwards (Test 3) the furnace, a remarkably more favorable fire behavior is encountered in the latter case because the wall covered the overlapping edges of door-leaf from direct fire exposure. Photos and thermographic views of the door specimens at 60 min after fire initiation are shown in Fig. 14. As it is evidenced, higher temperatures are developed at the door edges in Test 1 and Test 2 (orange color) compared to the corresponding locations in Test 3 (dark blue color).

6. Conclusions

An experimental program on the fire behavior of sliding doors has been performed in the facilities of the Danish Institute of Fire and Security Technology. Similar doorsets of approximate dimensions 3 m × 3 m and 5 m × 3 m (width × height) were examined, while separate tests were conducted for each side of exposure to fire. In all cases, the test specimens were mounted on appropriate wall

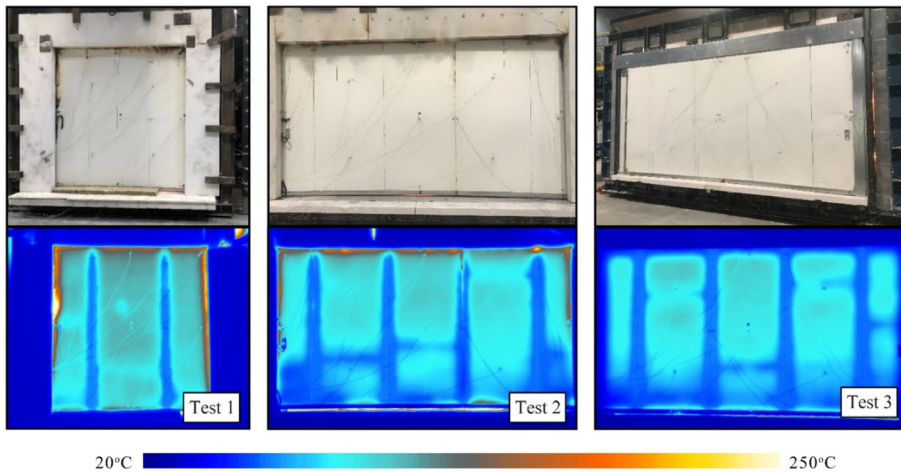


Figure 14. Photo and thermographic views of fire door tests at 60 min.

frames of aeriated concrete as used in practice. The test results were compared in terms of transient temperature and deflection measurements. The examined doors exhibited satisfactory fire performance meeting the classification requirements for an overall time of 68 min. The fire resistance rating was determined by the insulation criterion, which was based on the maximum temperatures close to the edges. The fire performance was not affected by the width opening, while a significantly more favorable performance was obtained in the case of door test outwards the furnace compared to those inwards the furnace.

The fire performance was similar in the case of standard (Test 1) and oversized (Test 2) doors mounted inwards the furnace, as the door frame restrained sufficiently the deflections at the edges that could introduce possible integrity failure. In the case of the door mounted outwards the furnace (Test 3), a higher fire resistance was obtained, since the wall was covering the overlapping edges of door-leaf from direct fire exposure. This result is consistent with the relevant standard provisions regarding the most onerous side of exposure to fire [1]. The experimental findings show that the extrapolation of fire door size is possible when failure is based on the insulation criterion and given that the size increase is realized in such way that does not affect the integrity failure. It is worth noting that more experimental tests on sliding doors would be useful for fire engineers to develop a reliable methodology allowing for the assessment of doors that exceed the dimensions of testing furnaces.

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