Periodica Polytechnica Civil Engineering, 69(3), pp. 976–990, 2025

Façade Fire Separation Distances: A Critical Overview and Further Investigations

Krisztián Sándor Oláh[1]*, Lajos Gábor Takács[1]

[1] Department of Building Constructions, Faculty of Architecture, Budapest University of Technology and Economics, Műegyetem rkp. 3., H-1111 Budapest, Hungary
* Corresponding author, e-mail: krisztian.olah@edu.bme.hu

Received: 22 July 2024, Accepted: 02 July 2025, Published online: 28 July 2025

Abstract

By the second half of the 20th century, the protection of building façades against fire spread became a considerable challenge in fire safety engineering. In the 1950s, several theoretical and experimental research projects were launched simultaneously, in order to determine the size of the separation distance which can stop the opening-to-opening façade fire propagation. In spite of the fact that the first major studies have already elucidated several limitations in connection with this approach, different separation distances are still widely used, without their practical objective and actual effectiveness having been clarified. This paper briefly summarizes the relevant conclusions of the research to date, explains the original protection objectives and highlights the shortcomings of the existing regulations. With the use of a numerical model based on the standard Hungarian façade fire testing method, the study presents some potential new opportunities for improving both our test methods and regulations.

Keywords

façade, fire propagation, leap frog effect, secondary opening, spandrel height, separation distance, objectives, efficiency, FDS

1 Introduction

At the beginning of the 20th century, the issue of façade fire propagation emerged as a new challenge in the fire protection of buildings. With the proliferation of modern architectural formations, the large glass surfaces on façades, the increasing number of storeys, as well as decreasing floor heights, it became progressively more difficult or even impossible to maintain those distances between the edges of vertically adjacent windows that were previously considered safe. In the 1950s, a number of theoretical and experimental research projects were launched simultaneously, in order to determine the risks connected to the phenomenon of opening-to-opening façade fire propagation. However, the conclusions of these research studies raise some crucial questions concerning the attainable objectives of vertical separation distances on façades, and concerning the definition of adequate safety levels even in those cases where the façade system does not influence the fire propagation process.

1.1 The architectural and structural origins of façade fire propagation

The flame exiting the window and the ensuing fire propagation was already a phenomenon defined in the very first fire safety regulations, appearing at the beginning of the 20th century. Initially, the issue was addressed due to the increasing urban density, in connection with the potential fire spread between neighboring buildings – at places where the sufficient separation distance could not be kept, the surface area of openings in the façade was limited [1], or, in case of buildings that were considered high-risk due to their functions, it was forbidden to design façade openings facing neighboring buildings [2].

Early in the century, the types of slab constructions most commonly used in multi-storey buildings were often made out of combustible materials like timber and they typically had a fire resistance limit of 15, at most 60 min. It must be noted here that in the first half of the 20th century, building constructions were usually categorized as fireproof or non-fireproof [3], and fire resistance-rating values – as we use them today – were developed later. Back then, fire spread among the floors within the building – even in case of a slab construction that was considered fireproof – was occurring at a faster pace than it could have done on the façade, so the phenomenon of fire propagation through the openings of the façade either did not even occur or was

Cite this article as: Oláh, K. S., Takács, L. G. "Façade Fire Separation Distances: A Critical Overview and Further Investigations", Periodica Polytechnica Civil Engineering, 69(3), pp. 976–990, 2025. https://doi.org/10.3311/PPci.37938

not really observable. Photographs of contemporary fire events clearly show that the slab constructions disappeared from behind the masonry façades which had much higher fire resistance performance (Fig. 1) [4]. With the spread of reinforced concrete floor structures, the fire resistance of floor slabs improved significantly, thus making it easier to observe that the plume – now confined from all directions within a given space – exits the room through the window and then adheres back to the plane of the façade.

Yet the beginning of the 20th century did not only entail innovations in building technology. The advance of modern architecture also involved some radically new directions where façades were concerned. With the diversification of the wall-window ratio, and the rationalization of earlier, more generous building proportions and storey heights, the separation distances that were until then evident or specifically recommended [5:p.498] – and more favorable from the aspect of preventing façade fire propagation – were reduced or completely eradicated. Presumably in response to these markedly unsafe trends, as early as from 1928, the NFPA has required that a minimum distance of 3 feet (cca. 91 cm) be maintained between the top and the bottom of façade openings positioned vertically above each other [1]. Although façades with glass curtain walls – increasingly popular in the interwar period – were no longer architecturally compatible with the previously most widely used brick spandrels. Some of the structures built at the time in Great Britain, taking into account the newly recognized risks, were already constructed with "fire resisting" spandrel panels [1]. Based on the experience of World War II bombings and consequent fires, the Post-War Building Studies journal, published in 1946, already came to the conclusion that "if the storeys of a building are separated at all points from one another by fire resisting construction of a sufficient grade to resist a complete burn-out, there still remains risk of spread of fire between storeys *via* windows" [6].

Fig. 1 Ruins of Wayne Building after 1930 fire (Ringer Collection) [4]

2 The research dedicated to determining the necessary fire separation distance on façades

By the 1950s, the problem of fire exiting *via* the façade openings and spreading vertically between storeys has become more widely recognized, in response to which the first rules addressing the issue have been added to fire safety regulations (for example, in the UK) [7–9]. At the same time, the new regulations hindered the expansion of contemporary architectural trends and the application of novel structural solutions like curtain walls to such an extent that the building industry also began to push for their expeditious revision [1]. At the end of the 1950s, several series of fire tests were carried out worldwide in order to scientifically determine the necessary height of fire-resistant spandrels. It is important to note that as an alternative to the requirement of the vertical separation distance, certain researchers have already begun exploring the potential effects of horizontal projections placed between façade openings.

2.1 Investigating the effectiveness of the original three-foot-high spandrel panels

The first, relatively widely known study conducted in Europe, authored by Ashton and Malhotra [10] summarizes a series of experiments comprising eleven real-scale fire tests. These were carried out with the specific goal of defining safety standards that are at least compatible with the building practices of the time, but could at best slightly mitigate the 'strict' rules adopted from the NFPA. As stated in the introduction: "[t]he attention of the Joint Fire Research Organization was drawn by the Building Research Station to the need to examine the problem of protection against spread of fire from storey to storey of a building through the windows, on the grounds that the present requirements were onerous and were restrictive in the use of some forms of construction which were desirable for other reasons" [10:p.2].

The experiments were carried out on a four-storey test-building. At the ground floor of the building there was a fire compartment of 3 × 3 × 2.4 m (total area 9 m^2), with a 50 kg/m^2 average amount of combustibles. The first floor of the test building was equipped with furniture, curtains, and, in some cases, with wall- and ceiling-covering typical to the period. They conducted eleven tests with different fire loads, window sizes, spandrel heights and in two cases, with balconies (Table 1). In the test series there were six façades with only non-combustible, and five with combustible façade materials, but in this article, we are only focusing on the non-combustible ones. All the windows were timber framed and glazed. Temperature data were measured in the combustion chamber, on the inner side of the spandrel panels and typically on the side of the furniture placed 80 cm behind the first-floor window.

During the entire duration of the tests (maximum 50 min), none of the furniture mentioned above caught on fire on any occasion; however, the first-floor window broke on ten out of eleven occasions, and the curtains, as well as the combustible coverings on the ceiling (in case there were any), caught on fire just after the windows broke. The authors note that the fire did not spread from the curtains to the furniture. Based on the experiment results, Asthon and Malhotra concluded that neither the currently required three-foot (cca. 91.5 cm) vertical separation distance, nor any of the two-foot-wide (cca. 61 cm) horizontal projections could prevent the fire exiting onto the façade from spreading to the storey above, and stated that the distances required to avoid such an outcome have not yet been determined [10].

Therefore, as they suggest: "The indications are that the fire resistance required of the spandrel wall could be substantially reduced even below a 1/2 h, without any significant reduction in fire safety to a building or its occupants" [10:pp.7–8]. These findings prompted British legislators to conclude that maintaining such an ineffective requirement had no practical significance at all; thus, by the 1990s at latest, the mandatory separation distance had been removed even from local building regulations [1]. Even if there is no way to confirm that the claims of Ashton and Malhotra [10] directly resulted in separation distance requirements being abandoned in other countries, the example of Great Britain clearly illustrates the approach

Table 1 Table based on the test layouts and their respective results obtained by Ashton and Malhotra [10] (tests conducted only with non-combustible materials marked with bold)*

Test no.	Quantity of combustibles (kg/m^2)	Fire compartment window size (cm)	Vertical separation distance (cm)	Wind direction / mean speed (m/s)	Maximum measured temperature on contents of first-floor (°C)	Time to break windows in first-floor room, after flaming began from windows of ground floor room (min)
1	**24.4**	**122 × 183**	**91.5**	**S.W. (side wind) 2.0115**	**20**	**Window did not fall**
2	**39.1**	**122 × 184**	**91.5**	**W. (diagonal wind) 5.0064**	**140**	**1**
3	48.8	106.75 × 152.5	91.5	N.W. (back wind) 3.576	30	2.5
4	**48.8**	**106.75 × 244**	**30.5**	**S. to S.W. (~side wind) 3.0396**	**100**	**2**
5	48.8	106.75 × 152.5	91.5	S. to S.W. (~side wind) 4.1124	100	2
6	48.8	106.75 × 152.5	91.5	N. (back wind) 1.5198	100	1
7	**48.8**	**106.75 × 244**	**30.5**	**N. (back wind) 1.9221**	**300**	**1**
8	**48.8**	**106.75 × 244**	**30.5 + 61 balcony**	**N. to W. (leeward) 1.9221**	**20**	**2**
9	**61**	**106.75 × 244**	**30.5 + 61 balcony**	**E. (diagonal wind) 0.5811**	**160**	**7.5**
10	61	106.75 × 152.5	30.5	S.E. to S.W. (windward) 2.8161	40	10.5
11	34.2	106.75 × 152.5	30.5	W. (back wind) 2.4138	140	1

* Acronyms of Table 1: S.W.: Southwest wind direction; W.: West wind direction; N.W.: Northwest wind direction; S.: South wind direction; N.: North wind direction; E.: East wind direction; S.E.: Southeast wind direction

of those countries (e.g., Austria [11], Germany [12], Switzerland [13]) where there is no such requirement at all.

2.2 Determining the height of the spandrel necessary for preventing vertical façade fire propagation

Also published in 1960, the second study, penned by Sizuo Yokoi [14], addressed the same issue with much more caution and nuance. Based on four real-scale fire tests, a number of small-scale fire tests, as well as the significant contemporary research concerned with the phenomenon, Yokoi [14] developed a calculation method for determining vertical separation distances. Relying on the results of small-scale fire tests, he determined the shape and the distribution of temperature within the plume spurting out from openings of various formats, as well as the typical distribution of temperatures within the plume. The results thus obtained were converted into non-dimensional quantities, then recalculated to the scale of the maximum intensity of an actual fire (reached at 30 min after ignition). The calculations assume that the window of the compartment breaks simultaneously with the moment of ignition, therefore the rate of perfect combustion (x) and the excess air factor (n) were, respectively, presumed to be $x = 0.6$ and $n = 1.0$. Adopting this method, Yokoi [14] carried out a sample calculation to determine the required size of the separation distance in case of a room whose size is $4 \times 5 \times 4$ m ($w \times d \times h$) (total area 20 m^2), depending on the vertical and horizontal dimensions of the opening in the façade, and the amount of combustible materials per floor area of the room. In the study, the loss of integrity of the first floor windowpane was considered as a main condition for the fire spread into the room above the combustion chamber. Since the results of his calculations could only be described in terms of temperature data, Yokoi [14] also had to describe the phenomenon of glass failure in terms of critical temperature. Based on his own test results, and in agreement with the results of other research [14] conducted at that time, he established that the failure of the glass pane of a 3 mm thickness, under the effects of external fire, occurred at 500 °C. Thus, he first determined the isothermal line at which the temperature inside the plume is a maximum of 500 °C, and then he confirmed that distance as the required separation distance between two façade openings. Thereby, he took a considerable step towards simplification, in favor of safety, since the origin of the flame exiting through the opening is considered to be the theoretical height of the neutral zone, positioned well below the top of the combustion chamber's window.

As a conclusion to his sample calculation, he stated that in case the aesthetic requirements of the building necessitate the inclusion of large windows (over 200 × 200 cm), the required separation distance – even if it exceeds the height of a full storey – cannot be an acceptable solution to prevent fire spread. In continuation of this investigation, Yokoi [14] proceeded with an impact assessment of horizontal projections perpendicular to the plane of the façade. A series of small-scale fire tests were carried out to examine how the shape of the plume spurting out of the façade opening is influenced by horizontal projections of various width, where several cases of differently shaped openings and various fire performances were analyzed. The potential effects of the horizontal projections repeated on every storey were also investigated, since balconies, for example, are often repeated at each floor. The results of the latter examination were derived with the same methodology and level of detail as those used in tests conducted on planar façades, and were then verified by real-scale test results. The results showed that the vertical distribution of temperatures (the shape of the plume) was not significantly affected by the use of horizontal projections, however, the temperatures within the plume decreased proportionally with the extending width of the projections. Yokoi [14] then recalculated the matrix for planar façades by taking into account a cantilevered slab extending to 50 m, and also indicated any deviations from the original. According to Yokoi's table, unless the size of the opening exceeds 200 × 200 cm, a cantilevered slab alone should be sufficient to guarantee that temperatures reaching the glass surface at the storey above the combustion chamber remain under 500 °C [14]. It should be noted that this conclusion is inconsistent with Asthon and Malhotra's research [10], even if the threshold was set in a substantially different way.

Concerning his multi-step calculation process, Yokoi [14] states that the fire propagation under investigation depends on so many factors that it cannot be accurately described with easily applicable rules, and that the necessary vertical separation distance may only be determined on the basis of calculations executed in a laboratory environment, while also taking into account all the case-specific conditions [14]. To date, no comprehensive study is known to have verified or refuted Yokoi's calculations, but the current regulation in Japan still requires a 0.9 m vertical separation distance (the same as it was before his research) or a 0.5 m wide horizontal projection to prevent opening-to opening-façade fire propagation. However, even if it is difficult to prove any direct link between this research study and such regulations that were originally created nearly sixty years ago, we can recognize that the mean values indicated in Yokoi's tables (highlighted with grey in Table 2) largely coincide with the façade fire separation distances introduced in the 1960s and 1970s in several Eastern and Northern European countries.

2.3 A Hungarian attempt aimed at re-examining the necessary vertical separation distance

The majority of the full-scale standard test methods can typically only provide data concerning how a façade cladding system placed onto the façade influences the process of façade fire propagation. These test methods usually rely on a test rig that is dedicated only to this purpose and neglects all the circumstances that are not investigated and would cause uncertainties in the measurements. However, the Hungarian MSZ 14800-6:1980 [15] is one of the oldest [16] standardized full-scale façade fire test methods in Europe that models the whole process of opening-to-opening fire propagation, and its original setup was intended to be able to measure the full process step by step. The test building has a combustion room whose size is 4 × 4.4 × 2.65 m (total area 17.6 m^2) and with a 47.2 kg/m^2 amount of combustibles. In the early version of the test, on the first floor there is an "observation room" – with a secondary window and a cotton curtain with an ignition temperature between 390–400°C – in which the fire propagation is measured with thermocouples. On both floors, the windows were sized 1.2 × 1.2 m (Fig. 2) [15]. In accordance with the standard, the resistance of the combustion chamber's window against indoor fire is maximized at 5 min (at which point the window is opened). This is a fire resistance limit that is realistic (but one that also errs on the side of safety), based on previous research and real-life experience. The wood-framed, double-glazed observation room window (that is, the one above the combustion chamber), is ruined without intervention, due to the heat exposure from the plume exiting the opening.

A series of tests carried out in 2004 [17] in accordance with the abovementioned MSZ 14800-6:1980 [15] standard gives a good indication as to how exactly the process of fire propagation from one floor to another unfolds (assuming that the façade system does not accelerate the process), and to how the vertical separation distance delays the fire spread, if it is increased step by step from 1.3 m to 1.6 m. Under the following boundary conditions, test results have shown that the first-floor window lost its integrity in every case, even if the vertical separation distance was 1.6 m (0.3 m more than required in the National Fire Protection Code in Hungary) [17]. However, it was only in the case where a 1.6 m separation distance was kept that the cotton curtain did not catch fire. It is also important that in

Table 2 Yokoi's table listing the calculated values of the necessary spandrel height (cm) [14]

Calculated values of the necessary spandrel height (cm)							
Dimensions of opening (m)		Quantity of combustibles in the room (kg/m^2)					
Horizontal	Vertical	25	50	75	100	150	200
1	1	4	4	4	4	4	4
2	1	31	35	35	35	35	35
3	1	41	57	57	57	57	57
4	1	49	70	76	76	76	76
1	2	42	53	53	53	53	53
2	2	73	111	122	125	125	125
3	2	95	135	161	170	176	176
4	2	95	140	173	191	211	223
1	3	102	121	129	129	129	129
2	3	138	184	202	214	225	225
3	3	120	215	242	261	280	292
4	3	74	226	269	291	322	334
1	4	128	164	183	195	201	201
2	4	154	231	256	286	303	320
3	4	83	264	301	318	362	375
4	4	7	243	335	363	386	415

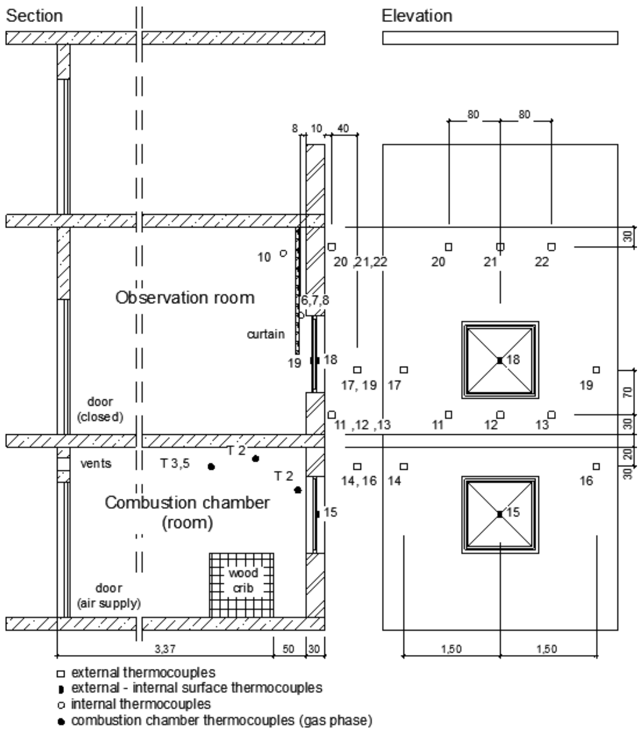

Fig. 2 The testing facility employed to determine the size of the vertical fire barrier based on MSZ 14800-6:1980 [15, 17]

the cases of 1.3–1.5 m separation distances, around 20 min after the ignition of the wood crib in the combustion room, the first floor window also lost its integrity, and typically after another 5 min, the curtain behind the window caught on fire [17], while there was no consistent relation between the increase of the safety distance and the time elapsed until the curtain was ignited (Table 3). Based on the results, the developers of the standard concluded that the amount of combustibles should be reduced to ~37 kg/m^2 and the window structure and curtain on the first floor must be removed from the standard test method to eliminate the uncertainties caused by the material properties of the glass and the cotton [18]. These modifications then appeared in the MSZ 14800-6:2009 [19].

According to the National Fire Protection Code [20] currently in place in Hungary, at least 45 min of delay in the fire spread should be guaranteed with a non-combustible façade structure that does not contain air gaps or cavities, and with keeping a distance of 1.3 m between the openings. However, based on the results discussed above, the time frame of the fire propagation is about half of that time – a finding that may be alarming, but it is important to note that the development of the fire in the combustion room of the testing facility based on MSZ 14800-6:2009 [19] is controlled according to the ISO 834-1:1999 standard [21] indoor fire curve which neglects the initial stage of the fire development. Therefore, if the initial stage of the fire propagation is taken into account, the events in the test most likely occur about 3–4 min later in a real-life scenario. Additionally, it is worth taking into consideration that in the 1950s and 1960s, when this Hungarian regulation was developed, an average living room was equipped with furniture made of real wood and contained much less polymer materials, and thus much more time elapsed before the room fully caught on fire [22, 23].

3 Discrepancies in the current methodology

All the research described in Section 2 used slightly different test methods and criteria for investigating the process of façade fire propagation, but we can conclude that every one of these studies proved that in most cases, a vertical separation distance of a reasonably applicable size (less than 1.5–2 m) cannot stop the fire spread on planar façades. However, by conducting an overview of the rules and regulations in effect today in various countries, we can see that in most places, separation distances ranging from 0.6–1.3 m are used (Fig. 3). Based on certain studies (see e.g., Law and Kanellopoulos [1], and Nilsson [24]) we can assume that the separation distances currently in use are merely based on the dimensional coordination of buildings typical in the mid-20th century (e.g., presumably on the dimensional coordination associated with the prefabricated concrete panel technology prevalent in Northern and Eastern Europe) and that everywhere, these separation

Table 3 Table based on test layouts configured in accordance with the Hungarian MSZ 14800-6:1980 [15] and their results, data obtained by ÉMI [17]

Test no.	The vertical distance between the windows (m)	Weather conditions	Time elapsed until the windowpanes break / temperature on the inner window pane	Ignition time of the curtain / measured gas phase temperature next to the curtain
1	1.3 m	No wind	Outer: 15 min (~100 °C) Inner: 23–27 min (~415 °C)	28 min 129 °C
2	1.3 m	No wind	Outer: 12. min. (~75 C°) Inner: 22. min. (~307 C°)	23 min ~110 °C
3	1.5 m	Between 24–33 min wind and rain	–	–
4	1.5 m	0-0.5 m/s wind	Outer: 12 min (~45 °C) Inner: 18. min. (~126 C°)	19 min ~160 C°
5	1.6 m	0–0.8 m/s wind	Outer: 9 min (~75 °C) Inner: – (max. 305 C°)	–
6	1.6 m	0–0.4 m/s wind	Outer: 18 min (~80 °C) Inner: 41. min. (~360 C°)	50 min (312 °C) Curtain fell off – was not ignited
7	1.4 m	0.4–0.9 m/s wind	Outer: 22 min (~90 °C) Inner: 27 min (~400 °C)	27 min ~250 °C
8	1.4 m	No wind	Outer: 26–28 min (~ 250 °C) Inner: 35–38 min (~ 440 °C)	53 min ~250 °C

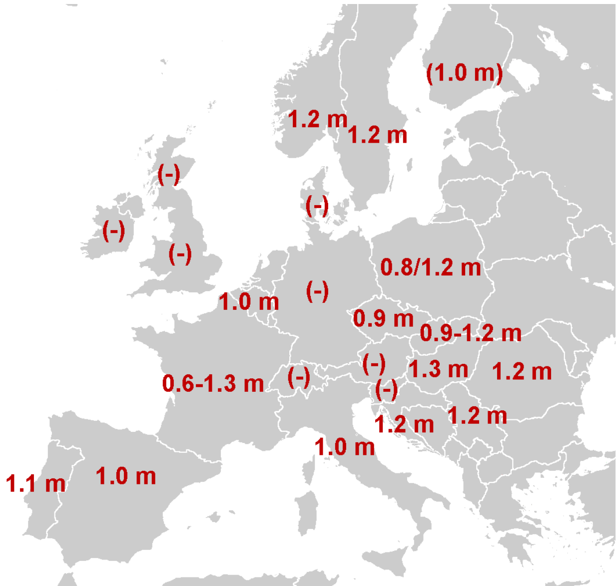

Fig. 3 Regulations pertaining to the required vertical separation distance between façade openings

distances constitute a compromise between the suggested fire safety requirements (based on the abovementioned research) and the available architectural possibilities.

In our opinion, this discrepancy is, to a great extent, due to the fact that the objectives and criteria for preventing opening-to-opening façade fire propagation have not been clarified since the original criterion – aimed at stopping fire spread – failed. Therefore, we can assume that the attitudes that differ (in some cases, radically) from country to country were formed on the basis of the subjective opinion of the regulators. In all probability, in those countries where a vertical separation distance is still in force, it was suggested that real fire conditions would be less severe than test scenarios, or it was simply concluded that using a separation distance, even if it is subject to compromise, is still safer than not using any. On the one hand, though this decision evidently seems to increase safety, unless the aims and the current efficiency of the separation distances are defined, their use still involves risk because such undefined parameters cannot be consistently integrated into our prescriptive fire safety design. At the moment, we do not know how much of a practical risk is actually entailed by not having any separation distance, and of how effective a 90 or 130 cm separation distance (presently in place in many countries) may actually be. On the one hand, it is not denied by any of the studied discussed here [1] that the radiation (virtually independent of the integrity of the glass structures above the combustion chamber) affecting the 100–150 cm above the combustion chamber's opening is so intense [25, 26], that it results, within a short time, in the ignition of any combustible materials placed nearby the upstairs opening, thus accelerating the fire propagation process; however, the scale of such acceleration is still unknown. On the other hand, based on the abovementioned studies, and on the experience of real-life fires [27], it is clear that in cases where intervention by the fire brigade is not fast or effective enough, fire spread between building storeys tends to occurs even if adequate separation distances are kept as per regulations, and even if there are only non-combustible materials on the façade.

Based on the test series carried out in accordance with the Hungarian MSZ 14800-6:1980 [15], even if we apply one of the strictest separation distances (1.3 m), it cannot stop the fire spread for a longer period of time or for a period equivalent to the fire resistance limit of the surrounding slab or wall structures. On the one hand such findings suggest that it may be well worth reviewing certain conceptual fire safety considerations (e.g., defense in place, protection of stairwells and evacuation routes against fire spread from the façade). On the other hand, the use of different separation distances can delay the fire spread, thereby increasing the available safe egress time [28] and the probability of successful intervention by the fire brigade, which are crucial aspects in fire safety and should be considered essential when revisiting the purposes of the separation distance.

3.1 The estimated efficiency of separation distances in the 21st century

The regulations enforced in Hungary are one of the strictest in Europe (except for those based on hand calculation method e.g., Netherland), therefore it logically follows from the conclusions outlined above that in places where the required separation distance is less than the one specified in the Hungarian standard [19], or non-existent, fire propagation through the openings in the façade will certainly occur in less than 20 min, an ever shorter time than what is implied by the results of the Hungarian test series. Moreover, based on Yokoi's research [14] – even without any consideration of the structures and active systems – the expected trajectory and therefore the rate of fire propagation also depends, to a great extent, on factors such as room size, fire load and the size of the openings.

Yokoi [14] concluded that above a 50 kg/m^2 amount of combustibles, the bigger the opening, the higher the flame height. From the second half of the 20th century, we can observe both a drastic increase in the average fire load of the rooms [22, 23], and a dramatically accelerated growth phase of the fire caused by the excessive use of polymers prevalent in our contemporary lifestyle. Beside that it seems evident that the average size of façade openings will not be reduced due to current trends in architectural design and building energetics [29]. Thus, the effects of these tendencies on the process of fire propagation also reinforce each other, resulting in more severe fire loads and excess heat releases.

Due to these changes, even if the results of the abovementioned test series were reliable at the time of their conception, even erring on the side of caution (because the test fire conditions were more severe than those of real fire spread processes tend to be), they can no longer be considered accurate; that is, they no longer provide the same margin of safety. Taking into account the abovementioned factors, we cannot be certain that even the façades designed in accordance with the Hungarian regulation will be able to guarantee the required fire safety level in all practical situations (e.g., in case of larger windows), as opposed to what is suggested by the Hungarian test series. However, with relatively few scientific studies being based on the results of real-scale fire tests, and without a precise definition of the limit state, at present it is not possible to determine exactly how much the process of fire spread is accelerated if, instead of a 130 cm separation distance, a 110 cm, a 90 cm, or at least a 60 cm separation distance is applied, as per the conventions of other European countries.

3.2 Clarification of the fire spread criterium

All the analyzed studies focused on the fire spread to the first-floor window, but these studies defined limit states in three different ways: by identifying it with the moment that the secondary window breaks, with the moment that the curtains ignite, and with the moment that the critical temperatures in the plane of the window and near the curtain are reached. These different approaches themselves raise the question of what the most realistic limit state is (that is, the point when we can state that the fire spread has occurred), because, even if these limit states are strongly connected and follow one another closely in time, it is clearly visible that in the tests, there were notable deviations in the occurrence of these events in terms of measured temperatures and times elapsed.

It is safe to state that the modern double or triple glazed structures can increasingly provide improved fire resistance [30], potentially decreasing the risk of fire spread. However, in most cases, there is no guarantee that the windows will be closed when a fire occurs (as current regulations do not require self-closing mechanisms for standard windows); a concern exacerbated by the anticipated increase in longer periods of hot weather, while in many buildings, natural ventilation remains the only available method for cooling interior spaces. In addition, curtains or other kinds of easily flammable sun-shading materials are often used, especially in residential buildings where the circumstances are even less favorable from the viewpoint of façade fire propagation. Therefore, for the sake of safety, at least in the case of tests dedicated to the re-examination of the efficiency of separation distances, we should focus only on the moment of ignition of flammable curtains covering the total area of the façade opening and should disregard the potential role of window structures, at least until the efficiency of this passive fire protection measure is determined.

The use of real-life structures, furniture, and materials can create the impression that the given test models real-life scenarios; yet, while the uncertainties caused by such structures could be instructive in themselves, the Hungarian test series showed that the deviations even in the properties of the same material can hinder the repeatability of the tests. Therefore, it is crucial to convert the abovementioned limit states and critical material properties (e.g., the ignition temperature of the curtain) into limit values that could then be measured with precise devices, just as it is done in the standard test methods.

4 Numerical methods in the research of façade fire propagation

While of course there have been a number of other studies on this topic (e.g., Oleszkiewicz [26], and Tobek [31]) besides the three papers analyzed here, such studies are few in number and are not necessarily widely accessible; furthermore, we do not have any information on whether any test series in connection with this topic have been conducted in the last 20 years. However, to answer the questions raised in Section 3, the abovementioned 23 full scale experiments are far from enough to reconsider the objectives and the efficiency of the vertical separation distances. Therefore, in order to carry out such a re-examination, an extensive sensitivity analysis must be conducted, with a larger number of experiments. Numerical methods like Computational Fluid Dynamics (CFD) – and Fire Dynamic Simulator (FDS) in the case of fire modeling – are widely used to study and solve complex fluid dynamics problems, especially when phenomena that cannot be adequately captured through (direct) observation or physical measurement devices need to be recorded. Although these numerical models are (currently) inconceivable without large scale real-life experiments, which still serve as a source of reliable input and validation data (that is, they are required to validate the data provided by the numerical model), they have crucial advantages over large scale tests, such as cost-effectiveness and repeatability.

In order to help address the lack of sufficient test results and to compensate for the inflexibilities of the standardized full-scale fire tests, some excellent attempts have already been made to translate these tests [e.g., 32–42], and even some non-standardized test series focusing on externally venting flames [43, 44], into a numerical simulation environment. Crucially, the potential inherent in these simulations could also give new impetus to research into the many unresolved questions surrounding façade fire propagation.

4.1 Reconsidering the purported effects of the separation distance on the delay in façade fire spread with a numerical model based on the MSZ 14800-6:2009 test method

To demonstrate the potential of the numerical modeling of standard façade fire tests and to reflect on the questions raised above, we conducted a numerical study relying on two simulations using the FDS model of the MSZ 14800-6:2009 test method [19] (Fig. 4). This analysis relied on a validated model, originally developed during the authors' previous research project [45, 46].

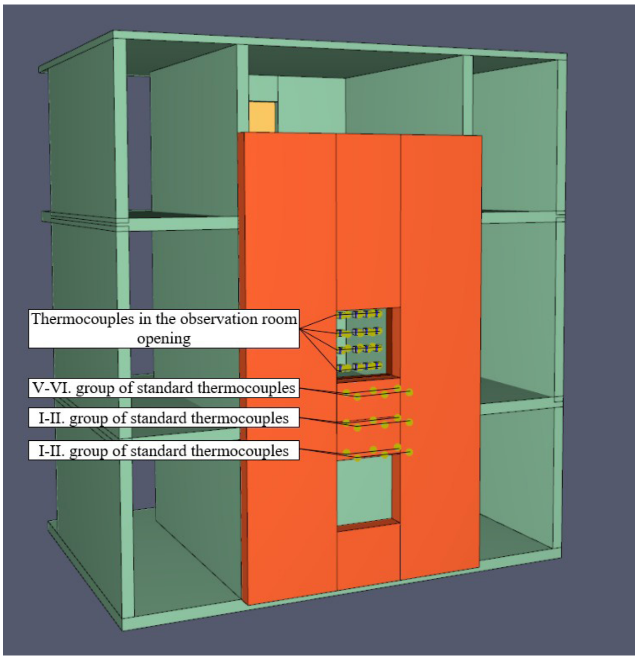

Fig. 4 The FDS model of the MSZ 14800-6:2009 [19] test facility and its instrumentation

The aim of the test was to measure differences in the estimated time needed for façade fire spread between two façade configurations: one in line with the Hungarian regulations and another with an identical structure but featuring a French balcony-like opening on the first floor. The criterion of the fire spread – the ignition of the curtain – even originates from the Hungarian test method's former version, but the technique of the measurements and the instrumentation of the test rig were developed on the basis of the conclusions of Section 3.2.

The test configurations were modelled in the FDS 6.8.0 environment developed by NIST. The external plume, caused by burning approximately ~40kg/m^2 of pine wood in the combustion chamber [19], was calibrated on the basis of the thermal data procured from a real test carried out on a noncombustible façade system. During the validation process, the comparison of the recorded real and numerical results showed that, apart from some fluctuations due to ventilation conditions, there is only a difference of about 10% between the real and the numerical results (Fig. 5). Such a level of discrepancy is acceptable, not only because of the comparative nature of the test, but also because a similar degree of uncertainty may also occur in the results of real standard tests. In other studies concerned with the numerical modeling of standard

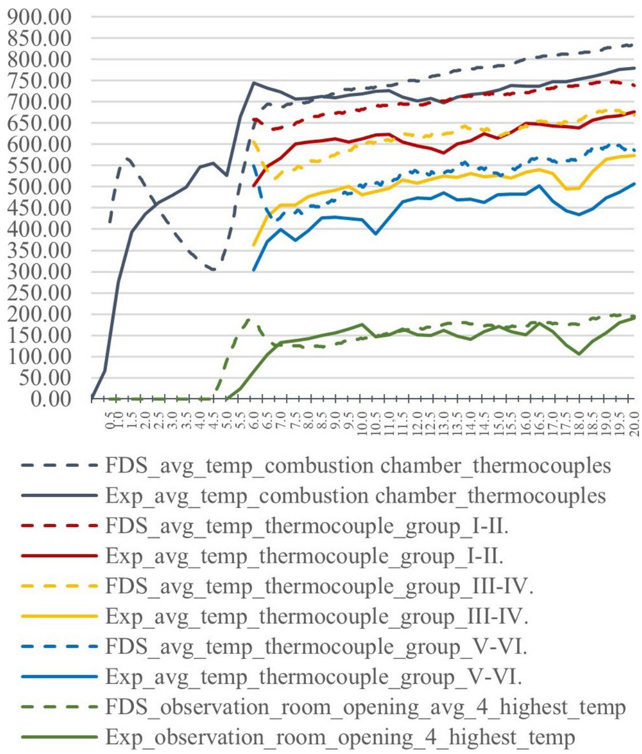

Fig. 5 Comparison of the thermal results obtained during the full-scale experiment and *via* the numerical model

façade fire test methods [e.g., 34–37], comparable (minor) discrepancies have also been noted.

Both façade layouts created for this comprehensive study were based on the test building specified in the standard [15, 19], therefore, the dimensions of the combustion chamber, the planes of the slabs and the position and format of the combustion chamber openings were given. The only difference between these two numerically modeled façade layouts was the removal of a parapet wall above the ground floor slab (in the case of the façade with a French balcony). In this way – even in the case of the façade featuring the French balcony opening – there was a 60 cm vertical distance between the top of the combustion chamber opening and the bottom of the first-floor opening.

Both configurations were modeled as non-combustible, homogeneous structures, to focus only on how geometric properties alone influence fire propagation patterns. However, the thickness of the wall structures was modeled as if the basic masonry walls of the test building were equipped with 30 cm non-combustible cladding (representing a state-of-the-art, well-insulated façade). This approach takes into account the fact that that cladding systems – exempt from fire resistance requirements but remaining intact during fire exposure – can significantly impact flame spread, effectively functioning as if they were integral components of the building structure. Such claddings can affect flame spread in a positive manner (containing or decelerating fire propagation), or, under unfavorable circumstances, in a negative direction as well (enhancing fire spread).

The Hungarian test facility is originally equipped with K-type thermocouples which measure the gas temperatures around the device effectively. However, this type of thermometer lacks sufficient sensitivity for measuring radiation, making it inadequate for accurately reflecting the temperatures of any material that has a larger surface exposed to the flames. When the aim is to predict whether a specific material will reach its ignition temperature or not, plate thermometers appear to provide the optimal solution, explaining their widespread use in standard façade fire testing methods [e.g., 47]. In FDS simulations, plate thermometers are usually modeled using the adiabatic surface temperature tool. This numerical instrument shares key characteristics with those of physical plate thermometers but functions as a theoretical measurement device that neither absorbs nor loses heat to the environment. Consequently, the measured temperature reflects the theoretical maximum temperature that a given surface could reach, based on the incoming convection and the radiation [48]. While this tool evidently errs on the side of the caution, in cases where a lightweight curtain is applied, the level of discrepancy is not so high as to produce misleading results. In line with the aforementioned considerations, additional adiabatic surface temperature devices (five in a row) were also placed alongside all thermocouples (Fig. 6). that were modeled based on/according to the Hungarian standard [19].

In the framework of the extended instrumentation, two distinct limit states were evaluated. The first criterion, based on MSZ 14800-6:2009 standard for French balconies [19], was triggered when the average of the four highest temperatures measured by the thermocouples, placed at the same height, reached 140 °C above ambient temperature (originally set to 20 °C). The second criterion was met when the average of the five highest temperatures recorded by the adiabatic surface temperature devices, placed at the same height, reached 400 °C, corresponding to the ignition temperature of the cotton curtain as specified in the MSZ 14800-6:1980 standard [15].

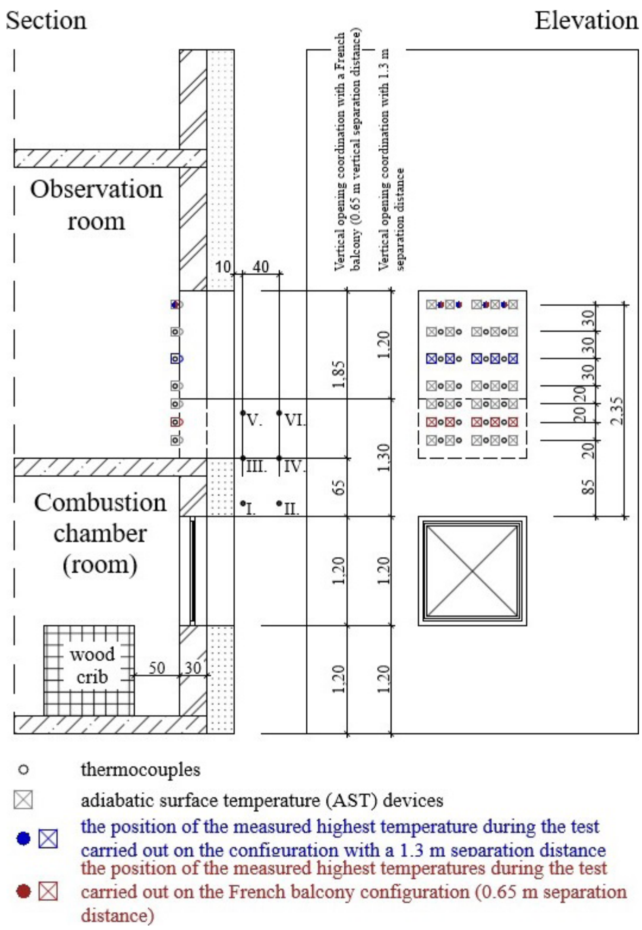

Fig. 6 The layouts of the test configurations and their instrumentation, the positions of the measured highest temperatures highlighted with red (French balcony) and blue (configuration with 1.3 m separation distance)

Our analysis of the measurements revealed that the two different limit states were reached approximately at the same time, but not in the same position. In both cases, the average of the four highest temperatures, measured at the same height by the thermocouples, were recorded at the top of the first-floor window, while the average of the five highest temperatures, measured at the same height by the adiabatic surface temperature devices, occurred near the lower edge of the same window. Although this positional difference aligns with the widely known principles concerning the changing dominance of convective versus radiative heat transfer relative to distance, these findings also demonstrate that when the goal is to reassess the efficiency of separation distances, it is crucial to employ measurement devices that are more radiation-sensitive than the standard thermocouples, and to position them at all heights across the first-floor window.

Concerning the potential risk in reducing separation distances, the results indicate that if the separation distance is decreased from 1.3 m to 0.65 m, the fire spread (equated with the theoretical ignition of a long cotton curtain covering the full window) accelerates by approximately 4 min (Fig. 7). It must be noted again that this 4-mine delay in the fire spread – occurring after the failure of the window in the room where the fire originated – is substantially less than the fire resistance requirement specified for slab and the wall constructions. However, if we take this criterion to be a – much-simplified – indicator of the available safe egress time, this 4-min timeframe is about two times longer than what the Hungarian prescriptive egress design framework allows for occupants to reach exit points or safety locations – an important contextual consideration.

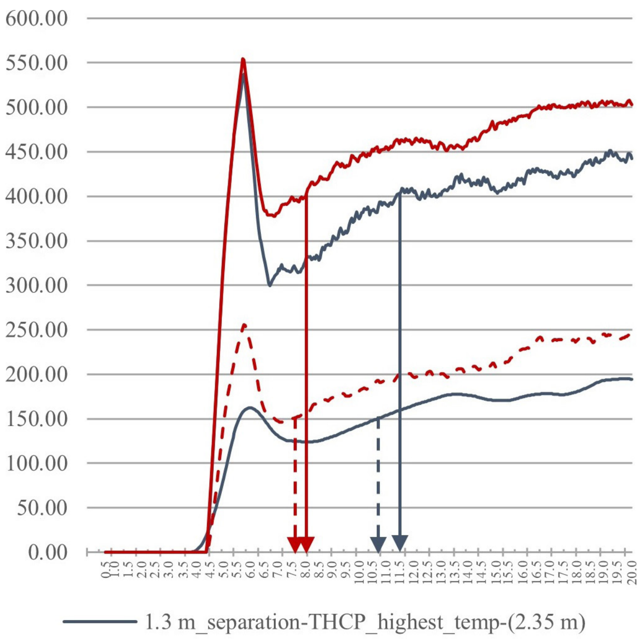

Fig. 7 The thermal results of the tests (configuration name – the size of the separation distance – device type – the vertical distance between the device and the top of the first floor window)

Beyond the conclusions described above, it is important to emphasize that these findings concerning the efficiency of the separation distance apply only to this specific scenario, without considering other variables such as different fire loads, opening dimensions or wind conditions. Although these circumstances are neglected in most of the current standardized test methods, a thorough reassessment of the practical efficiency of the separation distances would require conducting comprehensive sensitivity analyses in order to be able to re-evaluate their role in mitigating façade fire propagation.

5 Conclusions

By reviewing the historical background of opening-to-opening façade fire propagation and by analyzing the previous and current testing methods focusing on the phenomenon, the following conclusions can be drawn:

1. The separation distances that originated from the building habits of the first half of the 20th century, and were considered safe in that era, were only effective relative to the fire resistance of structures from that period. With regard to the fire resistance of reinforced concrete floor slab structures, the effectiveness of the original separation distance (0.9 m) between façade openings in preventing floor-to-floor fire spread appears minimal, therefore, in some countries, regulations concerning these distances were eliminated entirely.
2. Seminal research findings converge on the conclusion that the use of a vertical separation distance of a practical size (less than a full floor height) cannot effectively halt vertical façade fire spread. Without any (further) objective beyond stopping fire spread being clarified, the separation distances (that are less than 1.5 m) that are most commonly implemented at present are merely compromise solutions that could only provide limited delay in fire propagation.
3. There is a considerable fire safety risk in relation to direct façade fire propagation between openings – even in cases where a separation distance is kept – due to two critical factors: unclarified fire safety

objectives related to this issue, and significant variability in the estimated rate of the fire spread, which consequently cannot be consistently integrated into the prescriptive fire safety design of buildings. To eliminate these risks, we must re-evaluate fire safety objectives specifically for opening-to-opening façade fire propagation, and re-examine the efficiency of vertical separation distances from both evacuation and intervention perspectives.

4. To determine the differences in the rate of the fire spread associated with various separation distances between openings, a new criterion was proposed. Currently, there is no widely accepted limit state for direct opening-to-opening façade fire spread; and in our opinion, all the individual assessment methods [10, 14, 15] analyzed previously distort the results to some degree. Drawing from the findings of the former studies, we recommend defining this criterion as the moment wherein an imaginary curtain – positioned at the interior plane of the façade and covering the entire area of the empty (without any window structure) observation room opening – would ignite. The latter scenario must be described with specific critical surface temperatures that to ensure the repeatability of the tests.
5. The limited number of available full-scale fire tests, as well as their inconsistent repeatability have so far prevented an in-depth analysis of the efficiency of the different separation distances, particularly under varying conditions. However, numerical simulations based on standardized fire tests could offer a viable alternative to performing a large number of real-life tests (that would be extremely resource-intensive), enabling the compilation of a large pool of data, which in turn may be used to draw detailed conclusions about the flow characteristics of externally venting flames and their effects on façade fire propagation, at least on non-combustible facades.
6. The authors conducted a comprehensive numerical study using two tests based on the MSZ 14800-6:2009 [19] Hungarian façade fire test configuration. The analysis of the results highlighted the need for specifying limit state for direct opening-to-opening façade fire propagation, and indicated that (in that specific situation) reducing the separation distance from 1.3 m to 0.65 m shortened the time required for the ignition of an imaginary curtain by approximately 4 min. Although this result is representative only for one specific scenario, the magnitude of this time difference is potentially significant for evacuation and intervention purposes. Therefore, further investigations – under various conditions – would be essential to develop conclusions that can inform safer design practices.

6 Further paths of research

Revisiting the abovementioned questions requires the compilation of substantially more test data; yet the high cost of real-scale fire tests seems to have consistently limited research focused on opening-to-opening façade fire propagation. While the introduction of a unified European façade fire test standard – which it is currently being developed [49] – brings us closer to the possibility of comparing numerous full-scale experiments, the objectives and the methods of the standardized full-scale façade fire tests – evidently – diverge (increasingly) from the original problem of opening-to-opening façade fire propagation. Nevertheless, models calibrated on the basis of standardized test results could serve as appropriate tools for further investigations into this topic, at least in the case of non-combustible façade, which remain representative in many scenarios. This approach would constitute an important first step toward understanding how more complex systems perform under different conditions (such as different geometries or wind conditions).

References

[1] Law, A., Kanellopoulos, G. "The rise and fall of the UK's spandrel panel", Fire Safety Journal, 115, 103170, 2020. https://doi.org/10.1016/j.firesaf.2020.103170

[2] Magyar Királyi Belügyminisztérium "Magyarországi rendeletek tára 1936 - 180.000/1936. B. M. sz" (Collection of Hungarian Regulations 1936 - 180.000/1936. B. M. sz), Fővárosi nyomda részvénytársaság, Budapest, Hungary, 1937. (in Hungarian) [online] Available at: https://library.hungaricana.hu/hu/view/OGYK_RT_1936/?pg=910&layout=s [Accessed: 16 June 2024]

[3] Law, A., Bisby, L. "The rise and rise of fire resistance", Fire Safety Journal, 116, 103188, 2020. https://doi.org/10.1016/j.firesaf.2020.103188

[4] Local.News1.org "LOCAL HISTORY: Epic Fires that Tested Waynesboro's Mettle", Local.News1.org, 27 Febr. 2024 [online] Available at: https://localnews1.org/2024/02/27/local-history-epic-fires-that-tested-waynesboros-mettle/ [Accessed: 16 June 2024]

[5] Sobó, J. "VI. Szakasz Tervezés, építés és fentartás: I. Fejezet A tervezés: 8. A keresztmetszet megszerkesztése" (Section VI. Design, construction and maintenance: Chapter I The design: 8. Designing the cross section), In: Erdészeti építéstan: I. rész: Középítéstan: II. kötet (Forestry Building Studies: Part I. Public Building Studies: Volume II.), Országos Erdészeti Egyesület, Joerges Ágost Özv. és Fia Könyvnyomója, Selmecbánya, Austro-Hungarian Monarchy, 1899, pp. 496–499. (in Hungarian)

[6] Joint Committee of the Building Research Board of the Department of Scientific & Industrial Research and of the Fire Offices' Committee "Post War Building Studies – Fire Grading of Buildings: Part 1: General Principles and Structural Precautions", The Ministry of Works, London, UK, No. 20, 1946. [online] Available at: http://www.highrisefire.co.uk/docs/HMSO%2046_Fire%20grading%20of%20buildings%20Part%201.pdf [Accessed: 16 June 2024]

[7] Ministry of Housing and Local Government "Modal byelaws, Series IV", Buildings, London, UK, 1952.

[8] Langdon-Thomas G.J., Law M. "Fire Note 8: Fire and the External Wall", Ministry of Technology and Fire Office's Committee Joint Fire Research Organisation, London, UK, 1966.

[9] London County Council "1930-39 London Building (constructional) by - Law", London County Council, London, UK, 1952. [online] Available at: https://www.scribd.com/document/428362051/LCC-By-Law-1952 [Accessed: 16 June 2024]

[10] Ashton, L. A., Malhotra, H. L. "The Protection of Openings against Spread of Fire from Storey to Storey", Ministry of Works, London, UK, Fire Research Notes 436, 1960. [online] Available at: https://publications.iafss.org/publications/frn/436/-1 [Accessed: 16 June 2024]

[11] Österreichisches Institut für Bautechnik "OIB-330.2-029/23 OIB-Richtlinie 2 Brandschutz" (OIB-330.2-029/23 OIB Guidline 2 Firesafety), Österreichisches Institut für Bautechnik, Vienna, Austria, 2023. [online] Available at: https://www.oib.or.at/sites/default/files/oibrl_2_ausgabe_mai_2023.pdf [Accessed: 16 June 2024] (in German)

[12] Deutschen Instituts für Bautechnik "2023/1-MVV TB 2023/1 Veröffentlichung der Muster-Verwaltungsvorschrift Technische Baubestimmungen" (2023/1-MVV TB 2023/1 Publication of the Model Administrative Regulation Technical building regulations), Deutschen Instituts für Bautechnik, Berlin, Germany, 2023. [online] Available at: https://www.dibt.de/de/aktuelles/meldungen/nachricht-detail/meldung/mvv-tb-20231-veroeffentlicht [Accessed: 16 June 2024] (in German)

[13] VKF " 1.12.2022 VKF Brandschutzvorschriften 2015" (1.12.2022 VKF fire protection regulations 2015), VKF, Isselburg, Germany, 2022. (in German)

[14] Yokoi, S. "Study on the Prevention of Fire Spread Caused by Hot Upward Current", The Building Research Institute, Ministry of Construction, Tsukuba, Japan, Rep. 34, 1960. [online] Available at: https://doctorfire.com/pages/Yokoi.pdf [Accessed 16 June 2024]

[15] MSZT "MSZ 14800-6:1980 Tűzállósági vizsgálatok. Tűzterjedési vizsgálat épülethomlokzaton" (Fire resistance tests. Fire propagation test method on buildings façade), Magyar Szabványügyi Hivatal, Budapest, Hungary, 1980. (in Hungarian)

[16] Tóth, P. "A homlokzati tűzterjedés hazai vizsgálatának története a rendelkezésre álló források alapján" (History of domestic testing of façade fire propagation – based on available sources), Védelem Tudomány: A Katasztrófavédelem Online Szakmai, Tudományos Folyóirata, 6(2), pp. 192–208, 2023. [online] Available at: https://ojs.mtak.hu/index.php/vedelemtudomany/article/view/13489 [Accessed: 16 June 2024] (in Hungarian)

[17] ÉMI "Vizsgálati jegyzőkönyv – a függőleges homlokzati tűzterjedési gát méretének meghatározásához lefolytatott vizsgálatokról" (Test report - on the tests carried out to determine the size of the vertical fire barrier), Építésügyi Minőségellenőrző Innovációs Kht. (ÉMI), Budapest, Hungary, 2004. (in Hungarian)

[18] ÉMI "A függőleges homlokzati tűzterjedési gát méretének meghatározása homlokzati tűzterjedési vizsgálatsorozattal" (Tests series to determine the size of the vertical fire barrier), Építésügyi Minőségellenőrző Innovációs Kht. (ÉMI), Budapest, Hungary, 2005. [online] Available at: https://www.emi.hu/webadatbazisok/Publikaciok.nsf/PublicationsPreviewHTMLByDate/47F3EEE612BFE002C1257004002CBC84/$FILE/Publ_2005_MezeiSGyula.pdf [Accessed: 16 June 2024] (in Hungarian)

[19] MSZT "MSZ 14800-6:2009 Tűzállósági vizsgálatok. 6. rész: Tűzterjedési vizsgálat épülethomlokzaton" (Fire resistance tests. Part 6: Fire propagation test method on buildings façade), Magyar Szabványügyi Hivatal, Budapest, Hungary, 2009. (in Hungarian)

[20] Belügyminisztérium "54/2014. (XII. 5.) BM rendelet az Országos Tűzvédelmi Szabályzatról" (Decree No 54/2014 of the Ministry of Interior (XII. 5.) National Fire Protection Regulation), Budapest, Hungary, 2022. [online] Available at: https://net.jogtar.hu/jogszabaly?docid=a1400054.bm [Accessed: 16 June 2024] (in Hungarian)

[21] ISO "ISO 834-1:1999 Fire-resistance tests — Elements of building construction — Part 1: General requirements", International Organization for Standardization, Geneva, Switzerland, 1999. [online] Available at: https://www.flammabilitytestingequipment.com/photo/flammabilitytestingequipment/document/10331/ISO834-1-1999Fire-resistancetests.Elementsofbuildingconstruction.Part1_Generalrequirements.pdf [Accessed: 10 July 2024]

[22] Ondrus, J., Pettersson, O. "Brandrisker - fönsterprofiler av plast, aluminium och trä. En jämförande studie genom experiment i fullskala" (Fire hazards of window- frames of plastics, aluminium and wood. Full scale experiments - a comparison), Department of Fire Safety Engineering and Systems Safety, Lund University, Rep. LUTVDG/TVBB--3037--SE, Lund, Sweden, 1987. [online] Available at: https://portal.research.lu.se/en/publications/brandrisker-f%C3%B6nster-profiler-av-plast-aluminium-och-tr%C3%A4-en-j%C3%A4m-f%C3%B6ra [Accessed: 16 June 2024]

[23] Dundar, U., Selamet, S. "Fire load and fire growth characteristics in modern high-rise buildings", Fire Safety Journal, 135, 103710, 2023. https://doi.org/10.1016/j.firesaf.2022.103710

[24] Nilsson, M. "The impact of horizontal projections on external fire spread - A numerical comparative study", Lund University, Lund, Sweden, Rep. 5510, 2016. [online] Available at: https://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=8719885&fileOId=8725572 [Accessed: 16 June 2024]

[25] Oleszkiewicz, I. "Heat transfer from a window fire plume to a building façade", National Research Council Canada, Institute for Research in Construction, Ottawa, Canada, No. 1662, 1989.

[26] Oleszkiewicz, I. "Vertical separation of windows using spandrel walls and horizontal projections", Fire Technology, 27(4), pp. 334–340, 1991.
https://doi.org/10.1007/BF01039884

[27] Fővárosi Katasztrófavédelmi Igazgatóság "Lakástűz a X. kerületben" (Apartment fire in the district X.), Fővárosi Katasztrófavédelmi Igazgatóság, 02 Jan. 2023. [online] Available at: fovaros.katasztrofavedelem.hu/26128/hirek/271924/lakastuz-a-x-keruletben#top [Accessed: 16 February 2024] (in Hungarian)

[28] Hulida, E., Pasnak, I., Koval, O., Tryhuba, A. "Determination of the Critical Time of Fire in the Building and Ensure Successful Evacuation of People", Periodica Polytechnica Civil Engineering, 63(1), pp. 308–316, 2019.
https://doi.org/10.3311/PPci.12760

[29] Szabó, L. "Effect of Architectural Glazing Parameters, Shading, Thermal Mass and Night Ventilation on Public Building Energy Consumption under Hungarian Climate", Periodica Polytechnica Civil Engineering, 59(2), pp. 209–223, 2015.
https://doi.org/10.3311/PPci.7091

[30] Wang, Y. "Experimental and Numerical Study of Glass Façade Breakage Behavior Under Fire Conditions: Fire Safety Engineering", Springer Nature, 2019. ISBN 978-981-13-6483-9
https://doi.org/10.1007/978-981-13-6484-6

[31] Tobek, J. "Šíření požáru vně požárního úseku. Závěrečná zpráva dílčího úkolu" (Spread of fire outside the fire compartment. Final report of the tests), VÚPS, Praha, Czech Republic, Rep. P 12-114-201/02, 1980 (in Czech)

[32] Anderson, J., Jansson, R. "Façade fire tests - Measurements and modeling", MATEC Web of Conferences, 9, 02003, 2013.
https://doi.org/10.1051/matecconf/20130902003

[33] Anderson, J., Boström, L., McNamee, R., Milovanović, B. "Fire Dynamics in Façade Fire Tests, Measurement, modeling and repeatability", presented at: Applications of Structural Fire Engineering: 2015: Proceedings of the International Conference in Dubrovnik, Dubrovnik, Croatia, Oct. 15–16. 2015.
https://doi.org/10.14311/asfe.2015.059

[34] Anderson, J., Boström, L., Jansson McNamee, R., Milovanović, B. "Modeling of fire exposure in façade fire testing", Fire and Materials, 42(5), pp. 475–483, 2018.
https://doi.org/10.1002/fam.2485

[35] Nilsson, M., Husted, B., Mossberg, A., Anderson, J., McNamee, R. J. "A numerical comparison of protective measures against external fire spread", Fire and Materials, 42(5), pp. 493–507, 2018.
https://doi.org/10.1002/fam.2527

[36] Dréan, V., Schillinger, R., Auguin, G. "Fire exposed façades: Numerical modelling of the LEPIR2 testing facility", MATEC Web of Conferences, 46, 03001, 2016.
https://doi.org/10.1051/matecconf/20164603001

[37] Dréan, V., Girardin, B., Chiva, R., Guillaume, E., Fateh, T. "Numerical Investigation of the Thermal Exposure of Façade During BS 8414 Test Series: Influence of Wind and Fire Source", Fire Technology, 59(1), pp. 217–246, 2023.
https://doi.org/10.1007/s10694-022-01274-7

[38] Hostikka, S., Bytskov, G. "Numerical simulations of the ISO 13785-2 façade fire tests", MATEC Web of Conferences, 46, 03003, 2016.
https://doi.org/10.1051/matecconf/20164603003

[39] Li, Y., Wang, Z., Huang, X. "An exploration of equivalent scenarios for building facade fire standard tests", Journal of Building Engineering, 52, 104399, 2022.
https://doi.org/10.1016/j.jobe.2022.104399

[40] Sun, X., Yoshioka, H., Noguchi, T., Nishio, Y., Hayakawa, T., Zhou, B. "Experimental and numerical investigation of façade flame with respect to varied distances between sidewall and main wall opening", Thermal Science and Engineering Progress, 54, 102842, 2024.
https://doi.org/10.1016/j.tsep.2024.102842

[41] Abu-Zidan, Y., Rathnayaka, S., Mendis, P., Nguyen, K. "Effect of wind speed and direction on facade fire spread in an isolated rectangular building", Fire Safety Journal, 129, 103570, 2022.
https://doi.org/10.1016/j.firesaf.2022.103570

[42] Szikra, C., Takács, L. G. "Validation of CFD Simulation Model of French Balcony Façade Fire Test with Parapet Glass", presented at Fire and Evacuation Modeling Technical Conference (FEMTC), Gaithersburg, MD, Oct. 01–03. 2018. [online] Available at: https://files.thunderheadeng.com/femtc/2018_d1-06-szikra-paper.pdf [Accessed: 29 June 2025]

[43] Wang, D., Ju, X., Yang, L. "Experimental studies of the effect of burner location on the development of building fires", Journal of Building Engineering, 65, 105680, 2023.
https://doi.org/10.1016/j.jobe.2022.105680

[44] Duny, M., Dhima, D., Garo, J. P., Wang, H. Y. "Numerical investigation on window ejected facade flames", Journal of Building Engineering, 8, pp. 305–312, 2016.
https://doi.org/10.1016/j.jobe.2016.05.002

[45] Oláh, K. S. "A síkból kimozdított épülethomlokzatok homlokzati tűzterjedési vizsgálata mérnöki módszerekkel" (Fire propagation test of multi-planar facades with fire safety engineering methods), Védelem Tudomány: Katasztrófavédelmi OnlineTudományos Folyóirat, 7(3), pp. 1–28, 2022. (in Hungarian) [online] Available at: https://ojs.mtak.hu/index.php/vedelemtudomany/article/view/13578/10995 [Accessed: 29 June 2025] (in Hungarian)

[46] Oláh, K. S., Takács, L. G. "Fire propagation test of multi-planar façades with CFD simulations", Bauphysik, 47(3), pp. 205–213, 2025.
https://doi.org/10.1002/bapi.202400044

[47] Swedish National Testing and Research Institute "SP FIRE 105 External wall assemblies and facade claddings: Reaction to fire", SP Technical Research Institute of Sweden, Borås, Sweden, 1994. [online] Available at: https://assets.grenfelltowerinquiry.org.uk/INQ00014964_SP%20FIRE%20105%E2%80%94Method%20for%20fire%20testing%20of%20fa%C3%A7ade%20materials%2C%20Dnr%20171%E2%80%9079%E2%80%90360%20Department%20of%20Fire%20Technology%2C%20Swedish%20National%20Testing%20and%20Research%20Institute.pdf [Accessed: 29 June 2025]

[48] Wickström, U. "The adiabatic surface temperature and the plate thermometer", Fire Safety Science, 10, pp. 1001–1011, 2011.
https://doi.org/10.3801/IAFFS.FSS.10-1001

[49] Anderson, J., Sjöström,, L., Chiva, R., Dumont, A., Hofmann-Böllinghaus, A., Tóth, P., Lalu, O., Boström, L. "Finalisation of the European approach to assess the fire performance of façades", Publications Office of the European Union, 2024. ISBN 978-92-68-20808-3
https://doi.org/10.2873/7300386