Methodology for evaluating the safety level of current accepted design solutions for limiting fire spread between buildings

Van Coile R.[*/**], Maeso, D.[*]
[*]WSP | Parsons Brinckerhoff , London, UK
[**]Department of Structural Engineering, Ghent University, Ghent, Belgium
ruben.vancoile@wspgroup.com, david.maeso@wspgroup.com

Abstract: External fire spread between buildings is internationally considered as a major concern for buildings in dense urban environments. While design guidelines differ between countries, the fundamental methods currently used for limiting the risk of fire spread between buildings are generally limited to specifying the minimum required separation distance for a given unprotected façade area, or conversely, limiting the maximum allowable unprotected façade area for a given separation distance. The safety level associated with the current design guidelines is however unknown, making the implementation of innovative, safer and more cost-effective design solutions difficult. In order to assess the safety target implicitly incorporated in currently accepted design solutions, a methodology is developed for evaluating the annual probability of reaching unacceptable radiation intensities at the opposite façade. As a case study, the methodology is applied to a design which is in agreement with the current UK requirements specified in BR 187. This case study exposes inconsistencies in the current design guidelines, indicating the need for developing explicit safety targets.

Keywords: external fire spread, separation distance, safety target, BR 187

1 Introduction

Limiting the risk of external fire spread between buildings is a major concern in dense urban areas. Internationally, the main strategy applied to curb the risk of city conflagrations is to specify minimum separation distances between buildings as a function of the unprotected façade area. Specifically for the city of London, these requirements can be dated back to the aftermath of the 1666 Great Fire of London (BRE 2014). More recently, *BR 187 - External Fire Spread, Building Separation and Boundary Distances* has been the main reference for determining the required building separations in the UK, but similar requirements are included in for example NFPA 80A (Thomson et al. 2015).

Due to the development of new construction materials and insulation requirements, the proliferation of sprinkler system installations in modern buildings and the increased tendency for high-rise structures, the traditional guidelines may no longer be appropriate or efficient for every situation. This has been explicitly acknowledged in the recently published second edition of BR 187, where a number of caveats requiring fire engineering solutions are acknowledged (BRE 2014).

Consistency across innovative designs and building materials can be ensured by specifying a target safety level for external fire spread between buildings. However, the current safety margin incorporated in for example BR 187 is unknown – as explicitly acknowledged in the document itself (BRE, 2014).

As a step towards defining an explicit safety target for external fire spread, the safety level of currently accepted design solutions has to be evaluated. This paper describes a methodology for evaluating the annual failure probability associated with building designs and can be applied to evaluate the implicit safety targets incorporated in current design guidelines. As a case study, the methodology is applied to evaluate the failure probability associated with a design situation that is in agreement with BR 187.

2 Defining “failure”: the limit criterion

When considering external fire spread between buildings, a distinction should be made between ‘offensive’ fire spread where a fire in the building under consideration (i.e. the building being designed, building A) results in fire ignition at an opposing building (building B), and ‘defensive’ fire spread where fire in the opposite building B results in fire ignition at building A.

This distinction seems to be mostly neglected in current guidelines, but the difference can be important as the legal requirements and responsibilities may be different, as well as the engineering solutions applied to limit the risk. The legal implications are not further investigated in this paper, but it is tentatively suggested that the building owner may have some margin in accepting an increased defensive fire spread risk (for example by increasing the area of glazed non fire-rated façade) if the consequences are considered acceptable, while this would not immediately be the case when considering the risk of offensive fire spread.

The physical phenomenon of fire ignition is however very difficult to characterize. As discussed in (Drysdale 1998), the initiation of flaming combustion requires a sufficient mixture of oxygen and volatilized combustibles. In order for the combustion process to continue (or accelerate), this mixture should transfer a sufficient amount of heat to the fuel source for a continued volatilization of combustibles at a sufficiently high rate. Consequently, ignition of a solid material depends not only on the material characteristics and surface temperature, but also on the heating and cooling conditions.

BR 187 conservatively defines a risk of fire ignition to exist when the radiation intensity at a given location exceeds 12.56 kW/m^2 (BRE 2014). This value corresponds with the radiation intensity at which dried wood has been found to ignite in the presence of a pilot flame. The same value (12.5 kW/m^2) is used in NFPA 80A (Thomson et al. 2015). In general, the value of 12.56 kW/m^2 is considered as a lower bound for fire spread to the opposite building to occur, since most materials would require higher radiation intensities under the same test conditions. However, Hare and Burrel (2006) state that a value as low as 10 kW/m^2 may be more appropriate for plastic building materials, as acknowledged in (BRE, 2014).

It would be most interesting to incorporate an evaluation of fire ignition criteria in a probabilistic framework; however, for the purpose of this study and considering the wide-spread acceptance of the 12.56 kW/m^2 limit for the incident radiation intensity, the offensive and defensive failure probabilities $P_{f,O}$ and $P_{f,D}$ are defined through equations (1) and (2), with I being the received radiation intensity, and the index AB indicating radiation emitted from A to B, and vice versa for the index BA. In order to consider a meaningful timeframe for the evaluation of (1) and (2), a single year is considered (annual exceedance probability).

$$P_{f,O} = P\left[I_{AB} > 12.56\, {}^{kW}\!/_{m^2}\right] \tag{1}$$

$$P_{f,D} = P\left[I_{BA} > 12.56\, {}^{kW}\!/_{m^2}\right] \tag{2}$$

As in (Van Coile et al. 2015) the point with the highest exceedance probability on the façade is considered to define the overall façade performance. This is a logical definition since radiation intensities received at different locations along the opposite façade are highly correlated, or even perfectly correlated, in the framework of BR 187. Therefore, equations (1) and (2) should be evaluated by taking the maximum values across the façade.

3 Calculation methodology

The failure probabilities defined by equations (1) and (2) indicate the annual probability of exceeding the limit criterion for incident radiation I (also called irradiation). Naturally, the risk of fire spread from building A to building B and exceedance of the irradiation limit at B's façade can only occur when a fire initiates in building A. Furthermore, if the fire is immediately extinguished by the occupants of A or quickly suppressed by the attending Fire and Rescue Service, no risk of external fire spread exists. Similarly, a successful fire control or suppression by sprinklers (when present) will prevent the temperature in the fire compartment from reaching levels which may result in external fire spread (BRE, 2014). In conclusion, unacceptable radiation levels are only possible (within reason) for post-flashover fires. Note that for large floor plates, the term post-flashover fire as used above is applied as well to a fire fully engulfing a significant portion of the total floor plate.

The above discussion is represented by a fault tree analysis in Figure 1. This analysis is similar to the fault-tree given in BS 7974-7:2003 (BSI, 2003) and visualizes the path up to a fully developed fire. Given the occurrence of a fully developed fire in A, the (conditional) probability of exceedance the irradiation limit at the façade of building B is defined as $P_{f,fi,AB}$.

Considering the fault tree of Figure 1, the failure probability $P_{f,O}$ of equation (1) is given by equation (3), with p_{ig} the annual probability of fire ignition in building A, $p_{f,u}$ the probability that the occupants (users) fail to suppress the fire, $p_{f,fb}$ the probability that the Fire and Rescue Service (fire brigade) fails to suppress the fire, and $p_{f,s}$ the probability that sprinklers fail to control or suppress the fire ($p_{f,s}$ = 1 if no sprinklers are installed). The contributions of occupants, Fire and Rescue Service, sprinklers (and any other possible measures not considered here) are combined into p_{sup}, i.e. the probability of successful early fire control or suppression (with early control or suppression defined as the avoidance of flashover).

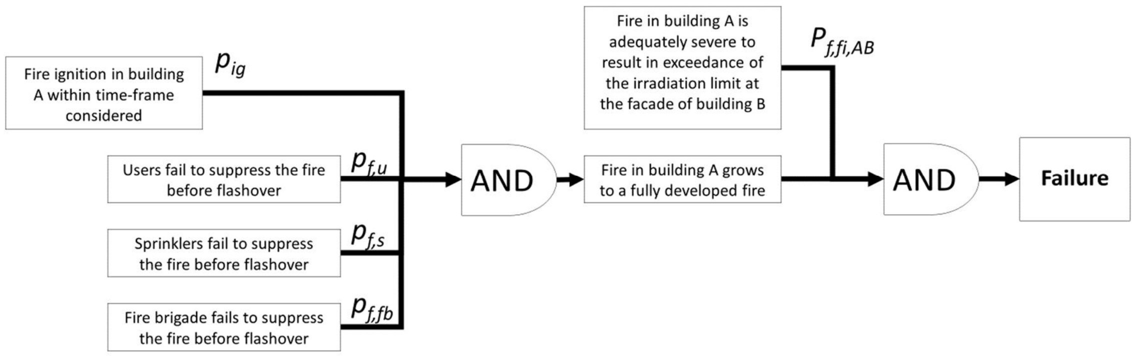

Figure 1: Fault tree indicating uncertain events resulting into

$$P_{f,O} = p_{ig} \cdot p_{f,u} \cdot p_{f,fb} \cdot p_{f,s} \cdot P_{f,fi,AB} = p_{ig} \cdot (1 - p_{sup}) \cdot P_{f,fi,AB} \quad \textbf{(3)}$$

Note that when building A has multiple fire compartments, the probability $P_{f,fi,AB}$ will be different for each compartment. In the general case, also p_{ig} and p_{sup} can be considered dependent on the specific compartment. In order not to introduce unnecessary complexity, the derivations in this paragraph consider a single fire compartment for building A.

Probabilities of fire ignition p_{ig} are given in PD 7974-7:2003 (BSI, 2003). While these values apply specifically to the UK, data for other countries can be found in literature, see for example (Fontana et al. 1999) for Switzerland and (Rahikainen and Keski-Rahkonen 2004) for Finland. Early fire suppression failure probabilities are specified in Handbook 5 of the Eurocodes (Holicky et al. 2005) and have been applied by (Albrecht and Hosser 2010). PD 7974-7 indicates a sprinkler failure probability of 5%. This effectiveness of sprinklers in preventing flashover is illustrated by the damage area statistics given in Annex A of PD 7974-7.

Considering the above, only the probability $P_{f,fi,AB}$ of exceeding the irradiation limit given the occurrence of a fire in building A remains unknown. All other variables can be readily found in national and international guidance documents.

A methodology for calculating the conditional failure probability $P_{f,fi,AB}$ has been presented in (Van Coile et al. 2015). The methodology uses Monte Carlo simulations to evaluate equation (4), where $I_{AB,fi}$ is the irradiation at B given a fire in building A as defined by equation (5). In (5), φ is the viewfactor, ε is the emissivity of the fire compartment (considering the model assumptions of BR 187), σ is the Stefan-Boltzmann constant, and T is the temperature of the fire compartment in Kelvin.

$$P_{f,fi,AB} = P\left[I_{AB,fi} > 12.56 \, {}^{kW}\!/_{m^2}\right] \quad \textbf{(4)}$$

$$I_{AB,fi} = \varphi \varepsilon \sigma T^4 \quad \textbf{(5)}$$

The Stefan-Boltzmann constant is a clearly defined physics constant and the view factor φ is a geometric property fully defined by the layout of the two opposing facades and both are consequently deterministic. As part of the methodology the maximum viewfactor for any point of the opposite (“cold”) façade should be considered. The emissivity ε is less clearly defined. Whereas the concepts underlying BR 187 consider ε = 1 (the physical maximum), a value in the range 0.7 to 1.0 can be considered more realistic. Heated bricks for example emit radiation with an emissivity of approximately 0.75 (Drysdale, 2009), while for concrete an emissivity of 0.7 is considered in EN 1992-1-2 (CEN, 2004). For the case study discussed further ε is modelled by a uniform distribution in the range 0.7 to 1.0.

The compartment temperature T is dependent on the fire load density q, the opening factor O and the thermal absorptivity of the compartment enclosure b. For a given design b can reasonably be considered deterministic and b = 1700 J/m^{2}s$^{0.5}$K will be considered further (being a reasonable value for concrete). The fire load density q on the other hand is highly uncertain, with British Standards specifying a stepwise cumulative density function in function of the building use, as applied in (Van Coile, 2015). Alternatively, mean fire load densities are given in EN 1991-1-2 (CEN, 2002a) and reference is made to a Gumbel distribution with a coefficient of variation 0.3. In the case study given in the next section the British stepwise distribution is used.

Finally, the opening factor is dependent on the uncertain breakage of windows during fire. In (Van Coile, 2015) the uncertain window breakage is modelled through a uniform distribution for the (physically possible) area of broken windows and a uniform distribution for the associated (physically possible) average height of the broken areas. For a given (stochastic realization of) window breakage, the opening factor O is analytically defined through the definition given in EN 1991-1-2.

Considering the failure criterion incorporated in (4), and considering Monte Carlo simulations and the stochastic variables discussed above, an evaluation of $P_{f,fi,AB}$ can be made.

While the above discussions focussed on the offensive failure probability $P_{f,O}$, the defensive failure probability $P_{f,D}$ can be readily calculated by applying the same methodology starting from building B and evaluating the irradiation exceedance rate at the façade of building A. If multiple buildings B_i are in the vicinity of building A, the methodology has to be applied for each of these buildings and the exceedance probabilities have to be combined to determine the overall $P_{f,D}$.

4 Evaluating the safety level of currently accepted design solutions: case study UK guidance BR 187

4.1 Case study introduction and standard application of BR 187

The methodology described above is applied to evaluate the safety target for exceeding unacceptable radiation levels as implicitly incorporated in BR 187 (BRE, 2014). Note that the case-study described further is only a specific example and that many more evaluations are required before a definitive conclusion can be made with respect to the implicit safety targets underlying BR 187.

Consider the façade locations as indicated in Figure 2. Building A is a 15 m high, 12 m wide and 20 m deep office building where every floor is a separate fire compartment with a height of 3 m. The separation in different fire compartments has the advantage of flexibility with respect to the possibility of multiple tenants occupying different floors or a future change in use. The opposite building B is also an office building, but with a height of 21 m, a width of 40 m and 20 m depth. Building B has been designed as a single fire compartment in accordance with BS 9999:2008 (BSI, 2008). Both buildings have a fully glazed façade and have been positioned as close to the "notional boundary" as allowed by BR 187 (applying the Enclosing Rectangle method) in order to maximize the available floor area. Furthermore, the centres of both façades (floor plan) are perfectly opposite each other.

The Enclosing Rectangle method is effectively tabulated data of acceptable design solutions. By determining the smallest rectangular shape enclosing the unprotected areas in the façade, a table applies which specifies values for the minimum distance to the notional boundary in function of the height and width of this enclosing rectangle and the area percentage of the rectangle which is constituted by the unprotected areas. When applying the Enclosing Rectangle method, the resultant design can be considered to be in accordance with BR 187.

The Enclosing Rectangle specifies minimum distance to the "notional boundary". This notional boundary as used in the application of BR 187 generally refers to the site-boundary, but can also extend to the middle of a public road in between both buildings. The distinction is of no importance for the discussion further, although changing the definition of the "notional boundary" in the future may allow to alleviate the inconsistencies described further.

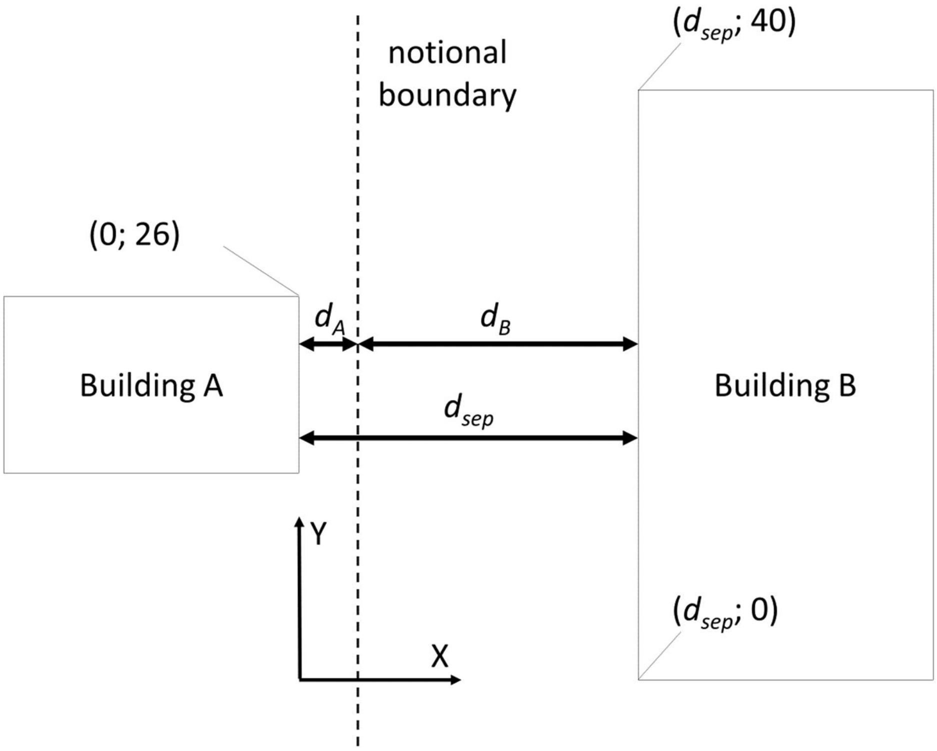

Figure 2: Case study building location and geometry

As every floor in building A is a separate compartment (with a height of 3 m), the Enclosing Rectangle with height 3 m and width 12 m applies. For a 100% unprotected façade BR 187 indicates a minimum distance d_A of 4 m to the notional boundary. Building B has not been subdivided in different fire compartments, and thus the applicable Enclosing Rectangle has a height of 21 m and a width of 40 m. For a 100% unprotected façade a minimum boundary distance d_B of 19 m is prescribed by BR 187. Consequently, the total building separation distance d_{sep} = 23 m. These values refer to the 'low fire load' category of BR 187 since both buildings have been classified as office buildings.

The minimum distances to the notional boundary are supposed to limit the risk of exceeding the irradiation limit in case of fire, but are based on a "mirror-concept" where the opposing building is (implicitly) assumed to be identical to the building being designed – as explicitly acknowledged in the background information for BR 187 (BRE, 2014). In other words: if a minimum separation distance of 8 m would be required to an opposing "mirror building", BR 187 would prescribe a minimum distance of 4 m to the notional boundary – as is the case for building A. However, as d_A and d_B are different, there may be a mismatch between the offensive / defensive failure probabilities of both buildings.

4.2 Calculation of the conditional probabilities $P_{f,fi,AB}$ and $P_{f,fi,BA}$

Applying the methodology described above, $P_{f,fi,BA}$ equals 0.18, while $P_{f,fi,AB}$ is smaller than 10^{-6}. Note that the offensive failure probability for building A equals the defensive failure probability for building B, and vice versa (considering a single compartment of building A).

In the above, the probability $P_{f,fi,BA}$ refers to the point of the building A façade opposite the centre of building B (i.e. at X = 0 m, Y = 20 m, and at a height of 10.5 m, see Figure 2). The failure probability $P_{f,fi,AB}$ relates to the façade of building B located opposite the centre of building A (i.e. the point at a location X = 23 m and Y = 20 m), at mid-height of the specific compartment (floor) of building A where the fully developed fire occurs. As every floor is identical, the same maximum failure probability relates to different heights along the façade of building B dependent on the fire location in building A. Façade areas further away from this central point have a lower failure probability as they have a smaller viewfactor with respect to the compartment of building A, as illustrated by Figure 3 where the viewfactor along the façade of building B is illustrated at mid-height of a fire compartment in building A for different separation distances d_{sep}.

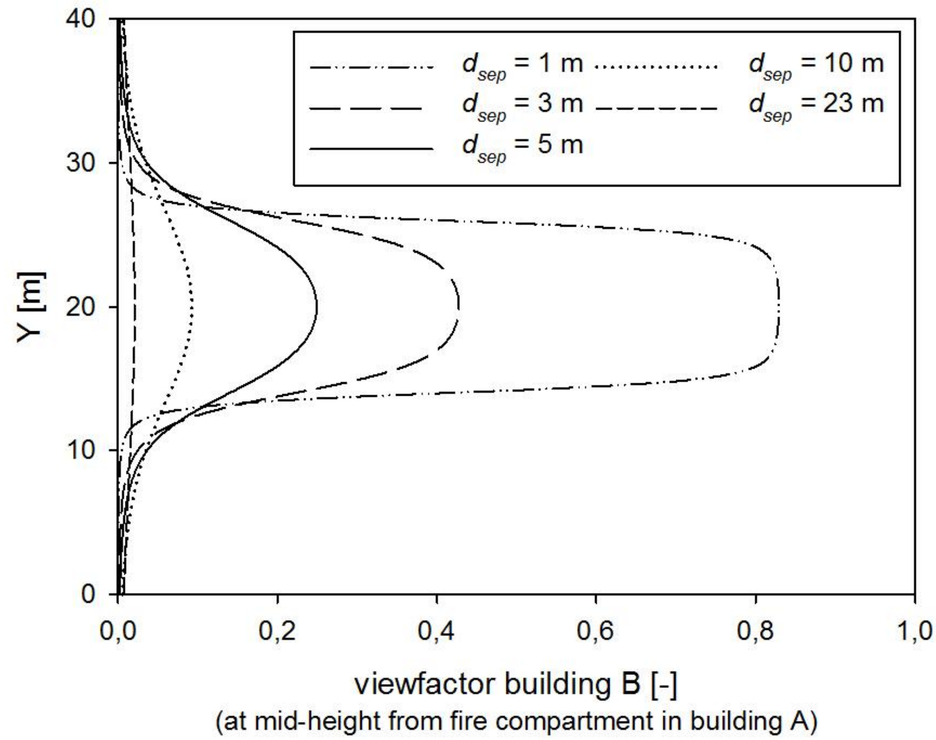

Figure 3: Viewfactor along the facade of building B at mid-height of the fire compartment in building A, for different separation distances d_{sep}

The results for $P_{f,fi,AB}$ and $P_{f,fi,BA}$ indicate a mismatch between failure probabilities for both buildings. However, for the single compartment of building B a fire temperature calculation considering travelling fires could be more appropriate and may reduce $P_{f,fi,BA}$. Note that the single compartment of building B falls outside the principal applicability range of the Eurocode parametric fire curve, but opting to maintain this fire curve allows the results to be in agreement with the background documentation included in BR 187.

Note: $P_{f,fi,AB}$ has been specified above as being smaller than 10^{-6}. This result is based on 10^{8} Monte Carlo simulations. This number of simulations would result in a coefficient of variation for a $P_f = 10^{-6}$ of approximately 0.1. The fact that not a single failure was observed in the entire set of Monte Carlo simulations therefore corresponds with an astronomically small probability that $P_{f,fi,AB}$ would nevertheless be larger than 10^{-6}. It is suggested that there are physical limits to irradiation intensities which can be achieved at a given distance of a fire. When considering for example an emissivity ε of 1 and a (maximum) viewfactor φ_{AB} of approximately 0.02 (see d_{sep} = 23m in Figure 3), equation (5) results in a compartment temperature of 1530°C. It may be physically impossible to reach this temperature for the considered compartment geometry. This argument is not further evaluated in this paper.

4.3 Annual failure probabilities associated with the BR 187 design

The probabilities $P_{f,fi,AB}$ and $P_{f,fi,BA}$ are conditional on the occurrence of a fully developed fire. The associated annual failure probabilities are calculated through equation (3), considering the fire ignition frequencies and suppression success rates given in Table 1, where A is the total building floor area.

Table 1: Fire ignition frequencies and suppression failure probabilities, based on (Albrecht and Hosser, 2010) and PD 7974-7:2003 (BSI, 2003)

Parameter	Building A	Building B
$p_{ig} = aA$ $a = 1.2 \cdot 10^{-5}$ / m^2	0.0144 / year (A = 1200 m^2)	0.0672 / year (A = 5600 m^2)
$p_{f,u}$	0.5	0.5
$p_{f,fb}$	0.2	0.2
$p_{f,s}$	1.0	1.0

Considering 5 fire compartments in building A, each with a floor plate of approximately 240 m^2, the frequency of fully developed fires in building A is estimated at 0.00144 and the annual probability $P_{f,AB}$ of exceeding the irradiation limit at building B because of a fire in building A is thus considered to be smaller than $1.5 \cdot 10^{-9}$. This exceedance probability is many orders of magnitude smaller than commonly accepted failure probabilities in design. When considering for example the design of new structures in accordance with EN 1990 (CEN, 2002b), the target failure probability for the strength criterion of structural elements is $7.23 \cdot 10^{-5}$.

Applying the same considerations to building B results in an annual exceedance probability $P_{f,BA}$ of 0.0012.

Many improvements can be made to the calculations, however, the annual exceedance probabilities calculated above are considered to give a reasonable estimation of the order of magnitude (and variability) of the actual annual exceedance probabilities associated with the BR 187 design concept.

When sprinklers are installed in the building, the annual exceedance probabilities will drop accordingly. Similarly, an improved fire suppression success rate of the occupants or Fire and Rescue Service would reduce the calculated failure probabilities, as would other management procedures directly influencing the fire ignition frequency. In order to allow for a fast comparison of different design situations, Figure 4 visualizes the calculated probabilities $P_{f,AB}$ and $P_{f,BA}$ as a function of the annual frequency of a fully developed fire λ, together with curves for other (hypothetical) conditional exceedance probabilities $P_{f,fi}$. Referring to equation (3), λ is calculated as $p_{ig} \cdot (1-p_{sup})$.

When installing for example sprinklers in building B with a success rate of 0.95 in accordance with BR 187, λ = 0.00034 per year, resulting in $P_{f,BA} = 5.96 \cdot 10^{-5}$ / year from Figure 4.

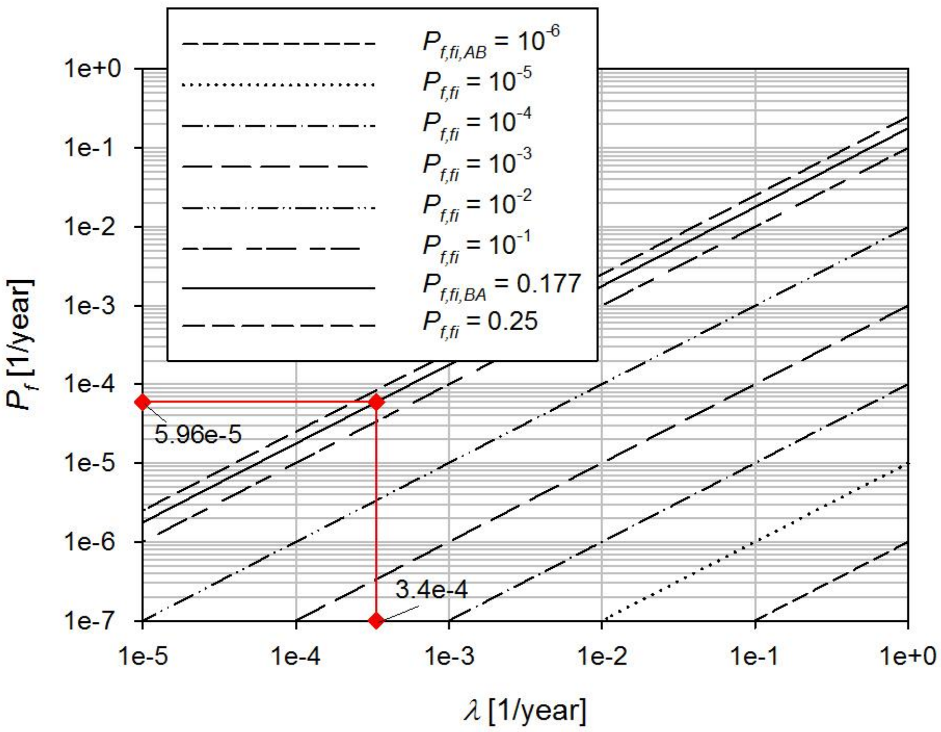

Figure 4: Annual exceedance probability of the irradiation criterion as a function of the annual probability of a fully developed fire, for different conditional probabilities $P_{f,fi}$

4.4 Parameter study: influence of the separation distance

The failure probability mismatch for the case study of Figure 2 can be more generally evaluated by considering different separation distances d_{sep}. Results are visualized in Figure 5 (linear scale) and Figure 6 (logarithmic scale). The asymptote in Figure 6 at approximately 16.2 m seems to confirm the hypothesis made earlier that there is a physical limit to the possibility of exceeding the irradiation limit.

$P_{f,fi,AB}$ is larger than $P_{f,fi,BA}$ for small separation distances due to the different fire temperature predicted by the Eurocode parametric fire curve as a function of the compartment size and ventilation conditions. For $P_{f,fi,BA}$ a larger fraction of fires has a fire temperature which does not result in exceedance of the irradiation limit (for a given separation distance). For a separation distance of approximately 4.45 m, $P_{f,fi,AB} = P_{f,fi,BA}$. While this means that a boundary distance of 2.2 m for both buildings would result in a very equitable design solution (as both designs would have the same “burdens” and “benefits”), the associated conditional exceedance probability may potentially be considered too high.

By combining the conditional probabilities calculated here with the interpolation graph of Figure 4, an immediate evaluation of the corresponding annual exceedance probabilities can be made.

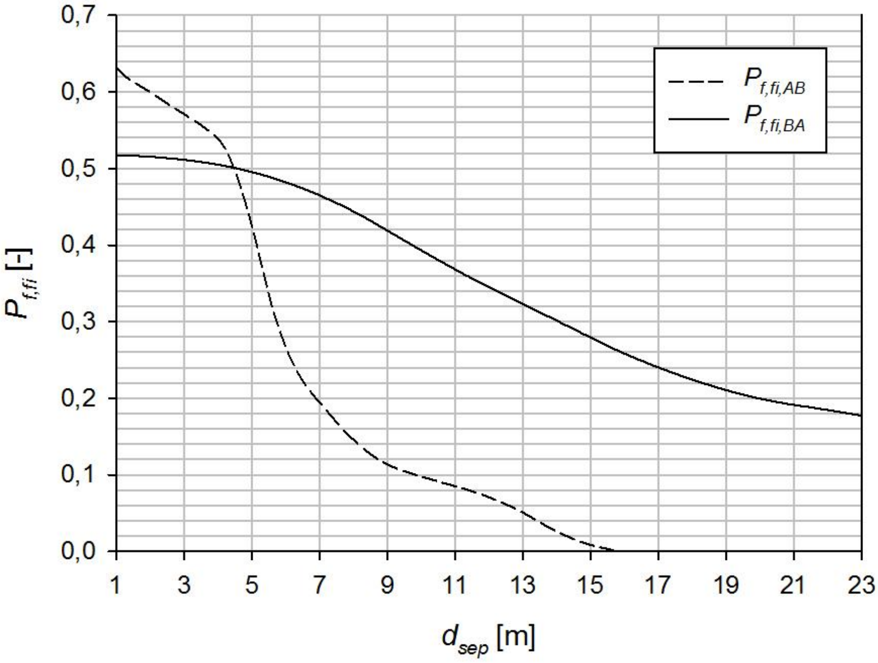

Figure 5: Conditional exceedance probabilities $P_{f,fi,AB}$ and $P_{f,fi,BA}$ for the case study of Figure 2, but considering alternative values for the separation distance d_{sep} (linear scale)

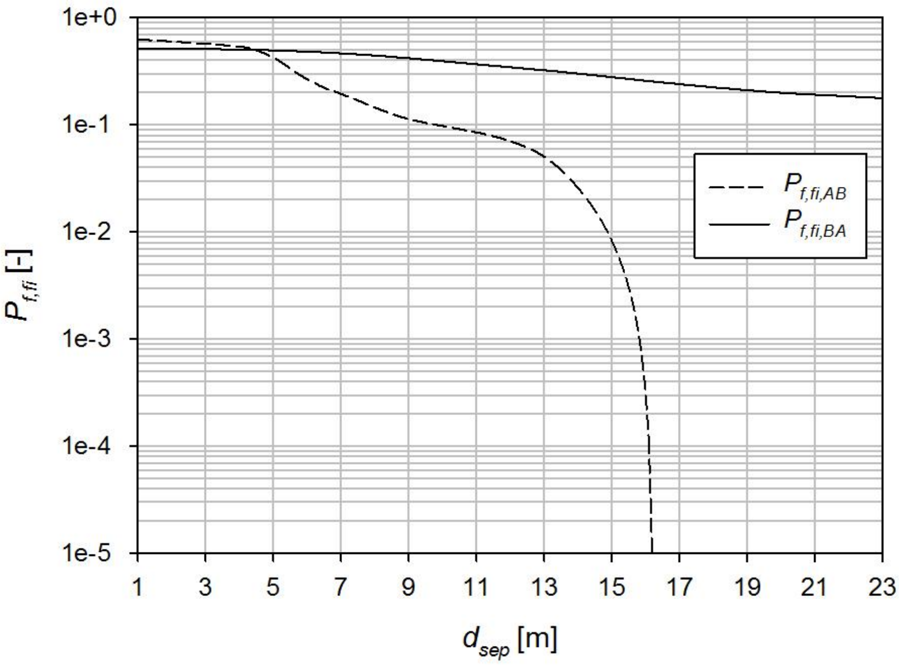

Figure 6: Conditional exceedance probabilities $P_{f,fi,AB}$ and $P_{f,fi,BA}$ for the case study of Figure 2, but considering alternative values for the separation distance d_{sep} (logarithmic scale)

5 Conclusions

External fire spread between buildings is a major concern in dense urban environments. In order to facilitate the safe implementation of innovative technical and/or architectural designs and alternative more cost-effective solutions, the application of a safety target for external fire spread would be beneficial. As a first step towards deriving explicit safety targets, a methodology is presented which allows to evaluate the safety level corresponding with currently accepted design solutions. The application of the proposed methodology to evaluate the safety level achieved by the commonly used UK guidelines of BR 187 indicates a very significant difference in failure probabilities between designs. The most onerous design calculated has an offensive failure probability – i.e. fire ignition at the opposite façade – below $1.5 \cdot 10^{-9}$ per year, while the same building has a defensive failure probability – i.e. irradiation exceedance at the building facade due to fire in the opposite building – of 0.0012 per year (for the specific case study considered). While further evaluations are required to fully map the range of safety levels achieved by the BR 187 methods, the results presented in this paper seem to support the case for the application of quantitative risk-based approaches to design aspects related to external fire spread between buildings.

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