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# ON A FIRE DETECTION ON STAIRCASE IN MULTI-STOREY BUILDINGS

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**Abstract**. *Staircases are very important from the point of view of fire protection. There are several reasons for this standpoint, but two are particularly significant. The first is that stairs are an important means of evacuation in multi-storey buildings, and the second is that the moment of detection of fire is crucial for the beginning of the evacuation. The first fact refers to the stair's location in buildings and the dimensions of stairs and landings. The importance of the second fact is obvious – the location and numbers of fire detectors directly affect early fire detection, and consequently the beginning of evacuation. The worst-case fire scenario from the aspect of building design - a staircase in the center of the building - was chosen for the simulation described in the paper, because in Serbia, there are many structures like this For the simulation described in the paper, the worst-case fire scenario was selected from the aspect of building design - a staircase in the centre of the building, because there are many, such in our country. On the other hand, recommendations for the location and number of fire detectors on a staircase are different in world-leading standards. For these reasons, in this paper, the simulations were performed in an eight-story building for various dimensions of spaces between stairs. On the basis of a comparison of the regulations outlined in European, British, German, American, and Russian standards, simulation parameters are defined. Parameters for simulations are defined on the basis of a comparative analysis of rules stated in European, British, German, American and Russian standards. Taking into account that some emergency evacuations entail moving through smoke-filled areas, building engineers must understand how the aforementioned factors affect smoke development in the event of a fire, and thus effective evacuation.*

**Key words**: *fire detection, multi-storey building, staircase, standards, simulation*

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## 1. INTRODUCTION

Point fire detectors siting on stairways are a special case in fire detection system design and almost all leading standards address this issue differently. The main reason for different approaches in standards is probably a lot of architectural solutions related to the dimension of stairs, landings and similar. In general, at least one fire detector must be installed on the stairs on top of the ceiling on the last floor. This rule applies if there are no door separations between the floors. If the floors are separated by a door, the detector should be placed on the ceiling in front of that door. The fact is that the space between stairs behaves like a "chimney", so, it is very interesting to check how space width affects smoke density on stairways, and consequently, the optimal location of fire detectors.

In this paper, simulations for various spaces between stairs are carried out to determine the optimal number of detectors and their position.

The rules from five leading standards: NFPA 72, EN 54-4, VDE 0833-2, BS 5839-1 and SP 5.13130.2009 (modified Russian standard NPB 88-2001) were used as a starting basis for the analysis of the best position of fire detectors on a staircase.

## 2. SMOKE DETECTION ON STAIRCASES – RULES FROM FIRE DETECTION SYSTEM DESIGN STANDARDS

Regardless of the fact that the number and location of detectors are determined by the design of the stairs, European standard EN 54-14 defines only one rule for manual call points that should be located on escape routes - at (inside or outside) each door to escape stairs and at each exit to the open air, without considering point smoke detectors [1].

German standard VDE 0833-2 takes into account the clear width of stairwells in staircases as a starting point in consideration. According to this fact, where no stairwell of the specified clear width is in place, detectors shall be installed for every single floor. Additional detectors shall be installed in these areas in cases where the corresponding stair landings exceed the values shown in the next figure [2].

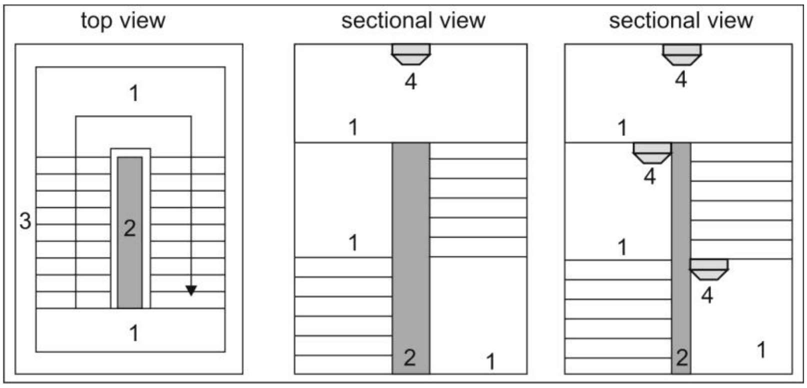



**Fig. 1** Smoke detector positions depending on stairwell width according to German standard *Legend*: 1 - *stair landing*, 2 - *stairwell: clear width of airspace, enclosed by stair landings*; *the figure in centre >0.5 m in width, figure in centre <0.5 m in width*, 3 - *stairwell hole*, 4 - *fire detector*.

Stairwells in staircases of clear width, the minimum dimension of which is not below 0.5 m, may be monitored up to room height according to rules for standard compartments. This means that the detector may be mounted on the ceiling of each third-floor landing (one up to 12 m in height).

British standard BS 5839-1 references that enclosed stairways should have a detector at the top and each main landing, and the detector should be mounted within 1.5 m of any opening. The main idea of this approach is to detect products of combustion before they pass up the stairway and as they pass out of the stairway. [3]

American standard NFPA 72 states that stairways can be equipped with smoke detectors but the number and location are determined by the design of the stairway. Generally, at least one smoke detector should be located at the top of the stairway. Additional detectors should be located on additional floors to achieve design objectives. [4]

Finally, Russian standard SP 5.13130.2009 states only one rule (Appendix N, table N1) for multi-storeyed buildings where detectors should be mounted on each landing, without detailed explanations related to the location of detectors. [5]

Obviously, the mentioned rules from all five standards are not quite enough for a reliable simulation basis. Further, it is necessary to take into consideration recommended alarm thresholds from ANSI/UL 268, Standard for Smoke Detectors for Fire Alarm Systems, and more precisely, smoke detector test acceptance criteria for different coloured smoke. According to this ([4], NFPA 72, table B.4.7.4.2), the acceptable response range of the detector is 1.6-12.5 %/m, and 5.0-29.2 %/m for grey and black smoke, respectively.

**Table 1** ANSI/UL 268 Smoke Detector Test Acceptance Criteria for Different Colored Smoke

| | Acceptable Response Range | |
|---|---|---|
| Colour of Smoke | %/m | %/ft |
| Gray | 1.6–12.5 | 0.5–4.0 |
| Black | 5.0–29.2 | 1.5–10.0 |

Detectors respond at different optical density levels to different fuels and different types of smoke (examples given in Table B.4.7.4.3), and if it is assumed that detector responds at an optical density of 0.15 $m^{-1}$ (10 %/ft), it can be assumed that detector will respond within 2 minutes (NFPA 72, B.4.8.2.4.). Finally, fuel load or lack of fuel load within the stair affect fire development, optical density and so forth. In the next table optical density alarm thresholds for open fires are shown.

**Table 2** Average OD alarm threshold and nominal detector sensitivities for flaming fires

| OD alarm | Ionization detector | | Photoelectric detector | |
|---|---|---|---|---|
| threshold | OD/m | Obs | OD/m | Obs |
| 20% | 0.007 ± 0.004 | 1.6 %/m | 0.031 ± 0.016 | 7.2 %/m |
| 50% | 0.021 ± 0.005 | 4.9 %/m | 0.063 ± 0.029 | 14.0 %/m |
| 80% | 0.072 ± 0.027 | 16.0 %/m | 0.106 ± 0.039 | 23.6 %/m |

The threshold value of optical density at which a detector will alarm depends on many variables which affect the response of a smoke detector, such as fuel type, detector design, burning mode, etc. There is general agreement that the measured smoke optical density at detector response varies widely, however, UL upper limit specification of 0.14 OD/m (9.4 %/m), or 0.15 OD/m (10 %/ft) is a rough estimate of the optical density at which detectors are likely to operate. On the other hand, manufacturers usually provide limited information regarding the response of smoke detectors to their specifications. This response information indicates only their nominal response values with respect to gray smoke, not to black, and is often provided with a response range instead of an exact response value.

## 3 Simulations Parameters

Because of mentioned factors, the basic settings for simulation were as follows. The height of the building for simulation is eight floors because a standard fire ladder can reach about seven to eight stories depending on its height. Also, this factor is important for timely evacuation, and it is known that if the building is taller than 24 m, if the story area is greater than 600 m$^2$, or if more than 100 people can be present in the building, then (in addition to the normal stairway) an additional fire-protected stairway or an exterior fire escape is required. The dimensions of stairs are chosen according to the standard for buildings in Serbia our country, but it is not very much different from other standards - (the length and width of stairs are 1.2 m × 0.33 m, respectively, and 0.17 m stair height).

The CFD software package Fire Dynamics Simulator (FDS) was used to simulate fire parameters. The FDS hydrodynamic model numerically solves Navier-Stokes equations applicable to thermally guided fluid flows, such as the mass maintenance equation, the moment maintenance equation, the sensory enthalpy transport equation, and the gas mixture state equation. Since the focus of this paper is on the thermal flow of smoke, which is conditioned by its "buoyancy", the FDS method of large eddy currents (LES) was used for numerical simulations. Simulations were made for three various clear widths between stairs: 0.5 m (limit value according to German standard), 1.0 m and 2.0 m. The number of floors is eight, the height of each floor is 3 m, and consequently, whole domains for simulations are: for stairwell 0.5m - 2.9 m × 13 m × 28.2 m, for stairwell 1.0 m - 3.4 m × 13 m × 28.2 m and for stairwell 2.0 m – 4.4 m × 13 m × 28.2 m. Cell size was 0.15 m uniform, and according to this number cells of mesh are: 288360 for a stairwell width of 0.5 m, 314280 for a stairwell width of 1.0 m, and 466560 cells for a stairwell width of 2.0 m.

Fire smoke detectors are located at the top of each landing, and mounted at a distance of 1.5 m from stairs (according to British standards) in the middle of the ceiling, while the duration of simulations was 600 s. The fuel used is Polyurethane G27 with critical flame temperature = 1327.0, CO yield = 0.042, and soot yield = 0.198. Chosen fire growth coefficient is medium - 0.017 kW/s$^2$, and maximum HRR 1550 kW/m$^2$, and Rump-Up Time is t$^2$ and set of 300 s, as shown in the following figure.

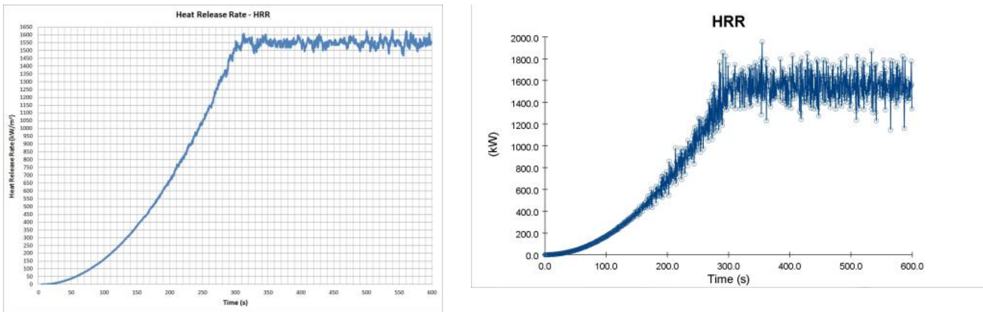



**Fig. 2** Heat release rate

The location of detectors (denoted **sd gl** on ground level, **sd1** to **sd7** on floors and **sd c** at the top of the highest ceiling), and the position of the burner are shown in the following figures.

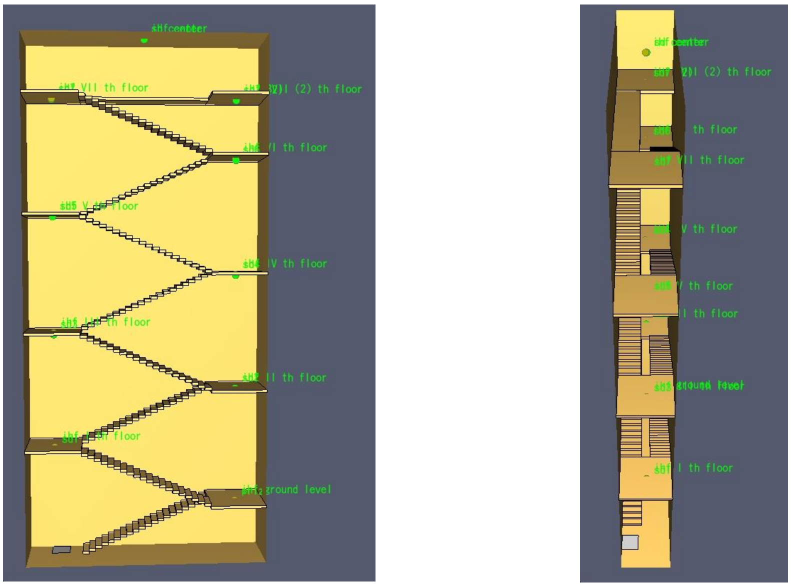
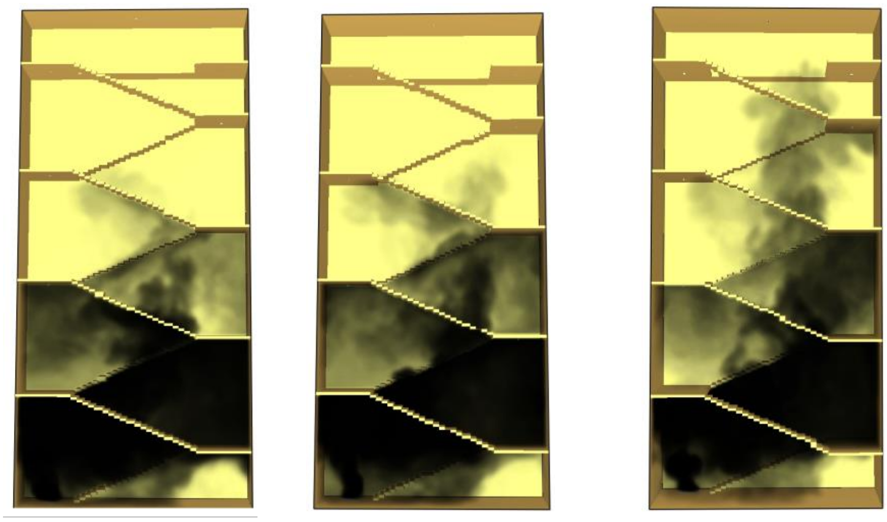


**Fig. 3** Location of detectors

Although smoke detectors are located on each floor, it is interesting to determine time instances for reaching some of the alarm thresholds defined by the criteria given in the table. During the simulations, it is observed time instances for reaching obscuration of 7 %/m, 10 %/m and 14 %/m, and consequently, the difference in time needed for reaching these alarm thresholds for the detector on the first floor and detector located at the top of the building.

Time instances for obscuration of 7%/m, 10%/m, and 14%/m are observed during the simulations, and as a result, the time required to reach these alarm thresholds for a detector on the first floor and a detector at the top of the building differs. This value is important for possible conclusions related to evacuation time, the need for an additional ("slave") control panel, and similar factors which affect evacuating and extinguishing after the detection of fire at an early stage.

In the next figure the fire development at time instance of 105 s, for stairwells of 0.5 m, 1.0 m, and 2.0 m from left to right, respectively, are shown.



0.5 m 1.0 m 2.0 m

**Fig. 4** Smoke development in 105 s – stairwell = 0.5 m (on the left), stairwell = 1.0 m (in the middle), stairwell = 2.0 m (on the right)

## 4 Results of the Simulation

The results of simulations and detailed data are shown in the text below. Results are given for the ground level and every third floor starting from the first floor. The main reason for this approach is to check if there is a need to locate a detector on each floor or every third floor, which would cause financial savings in high-rise buildings.

### 4.1 Simulation for the stairwell width of 0.5 m

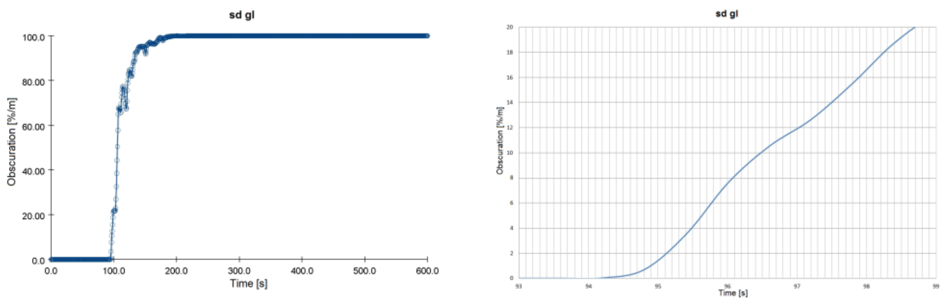



**Fig. 5** Obscuration vs. time - Ground level

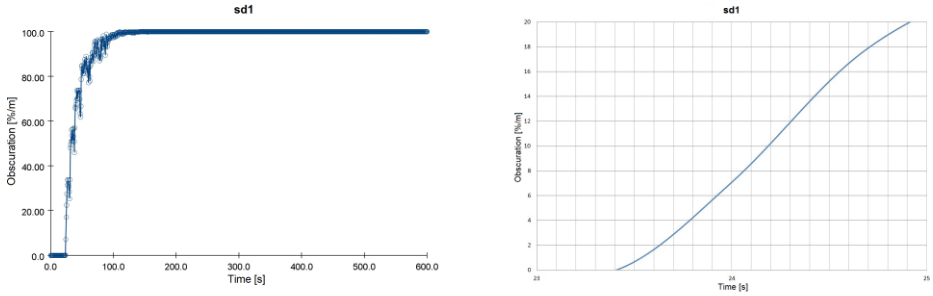



**Fig. 6** Obscuration vs. time - The first floor

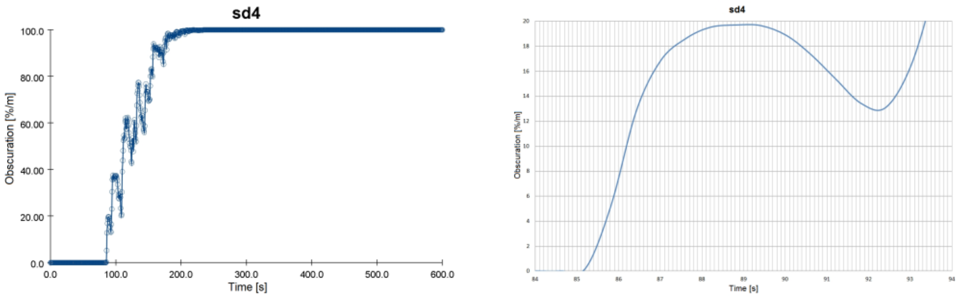



**Fig. 7** Obscuration vs. time - The fourth floor

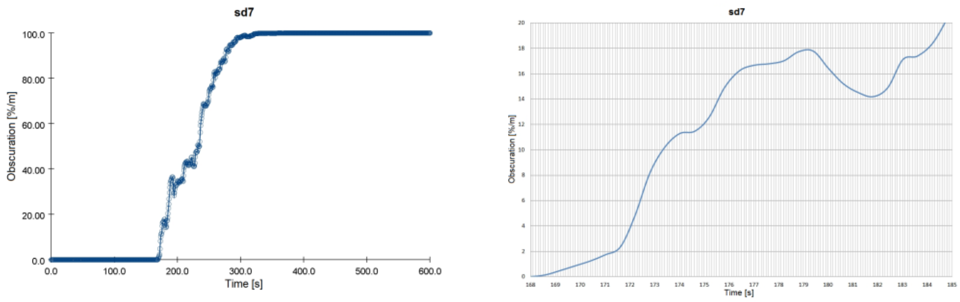



**Fig. 8** Obscuration vs. time - The seventh floor

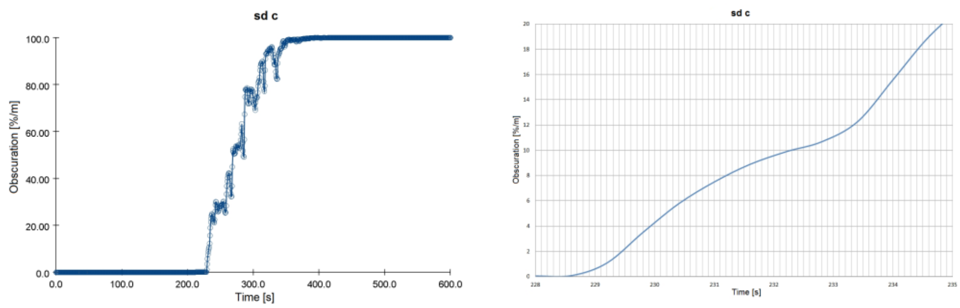



**Fig. 9** Obscuration vs. time - Ceiling of building

Summary results for obscuration times of thresholds 7%/m, 10%/m and 14%/m are shown in Table 3, in order to observe the time delays in achieving these thresholds.

**Table 3** Times for obscuration for the 0.5m the stairwell width

| Stairwell width 0.5 m | Time for obscuration | | |
|---|---|---|---|
| Detector mark and location | 7%/m | 10%/m | 14%/m |
| sd gl - detector above ground level | ~ 96 s | 96.5 s | 97.5 s |
| sd1 - detector at the top of the first floor | ~ 24 s | 24.2 s | 24.42 |
| sd4 - detector at the top of the fourth floor | ~ 86 s | 86.3 s | 86.7 s |
| sd7 - detector at the top of the seventh floor | ~ 172.5 s | 173.3 s | 175.6 s |
| sd c - detector at the top of the ceiling of the building | ~ 230.8 s | 232.3 s | 233.7 s |

### 4.2 Simulation for the stairwell width of 1.0 m

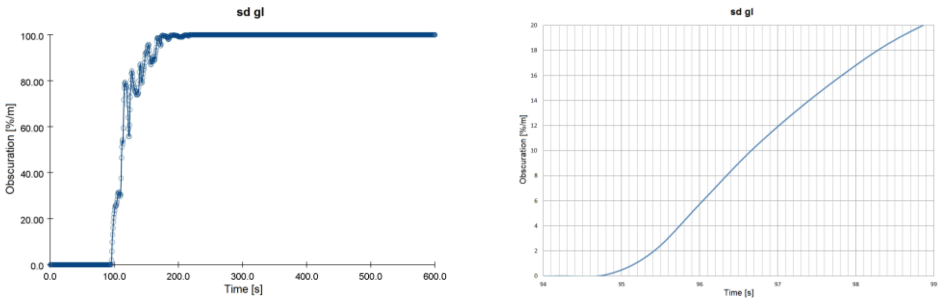



**Fig. 10** Obscuration vs. time - Ground level

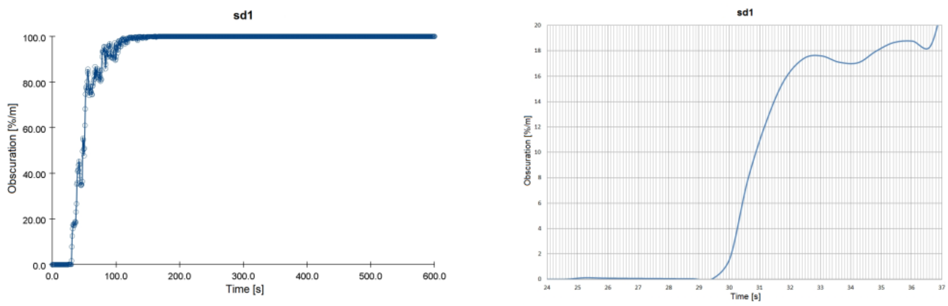



**Fig. 11** Obscuration vs. time - The first floor

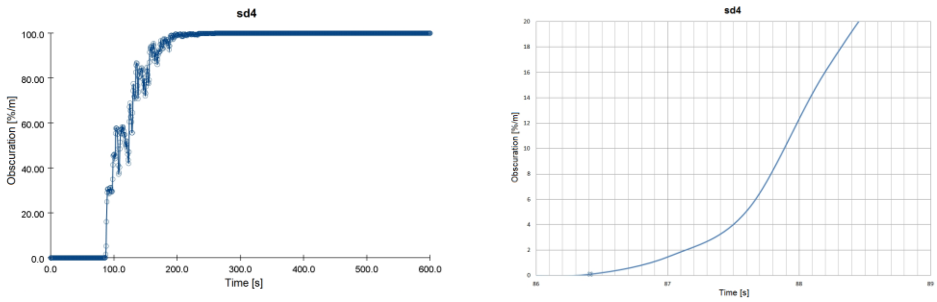



**Fig. 12** Obscuration vs. time - The fourth floor

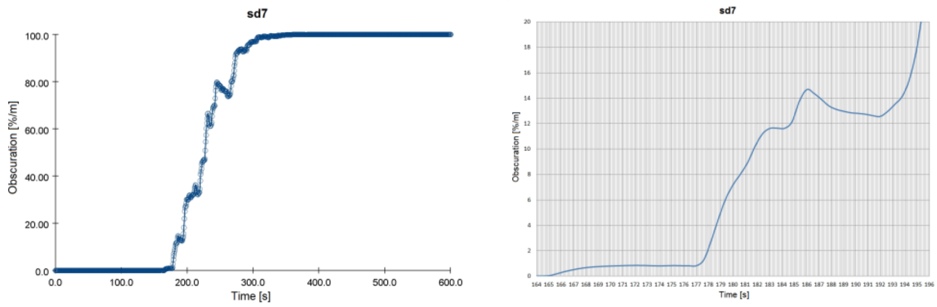



**Fig. 13** Obscuration vs. time - The seventh floor

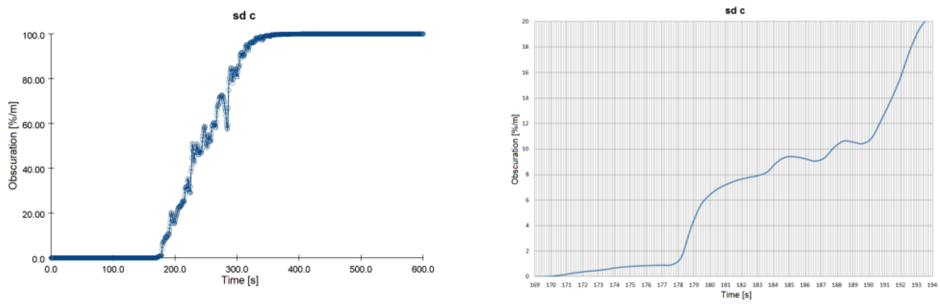



**Fig. 14** Obscuration vs. time - Ceiling of building

For the same reason as in the previous simulation, the times for reaching various obscuration thresholds are shown in Table 4 for a stairwell width of 1.0 m.

**Table 4** Times for obscuration for 1.0 m stairway width

| Stairwell width 1.0 m | Time for obscuration | | |
|---|---|---|---|
| Detector mark and location | 7%/m | 10%/m | 14%/m |
| sd gl - detector above ground level | ~ 96.2 s | 96.7 s | 97.4 s |
| sd1 - detector at the top of the first floor | ~ 30.5 s | 30.9 s | 31.5 s |
| sd4 - detector at the top of the fourth floor | ~ 87.7 s | 87.9 s | 88.1 s |
| sd7 - detector at the top of the seventh floor | ~ 180 s | 181.7 s | 185.5 s |
| sd c - detector at the top of the ceiling of the building | ~ 180.5 s | 187.6 s | 191.5 s |

### 4.3 Simulation for the stairwell width of 2.0 m

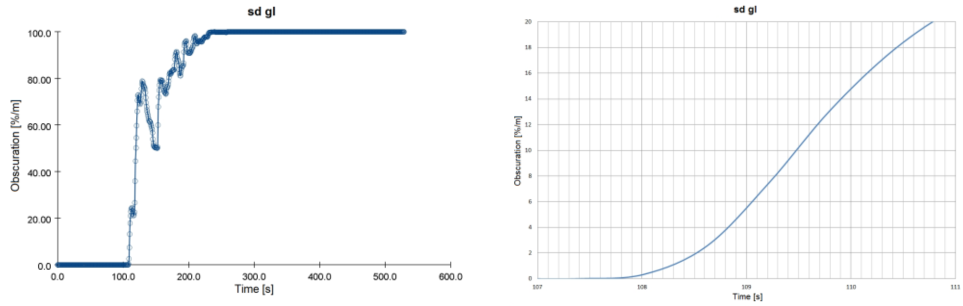



**Fig. 15** Obscuration vs. time - Ground level

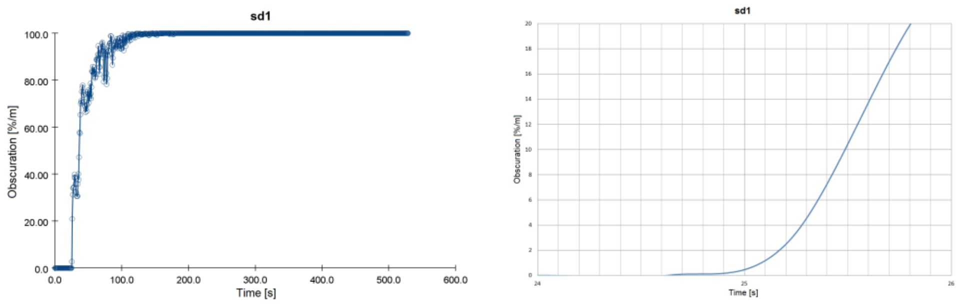



**Fig. 16** Obscuration vs. time - The first floor

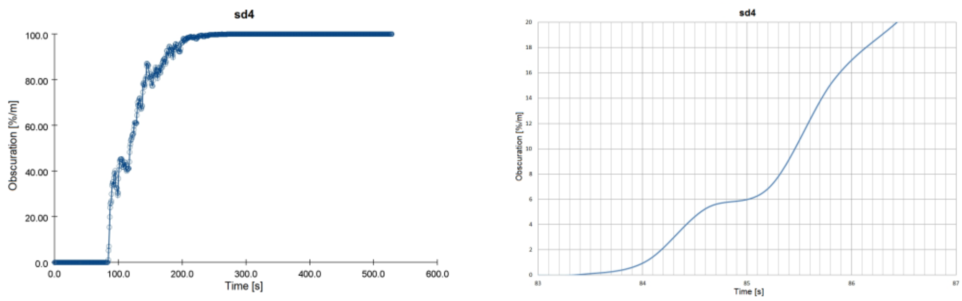



**Fig. 17** Obscuration vs. time - The fourth floor

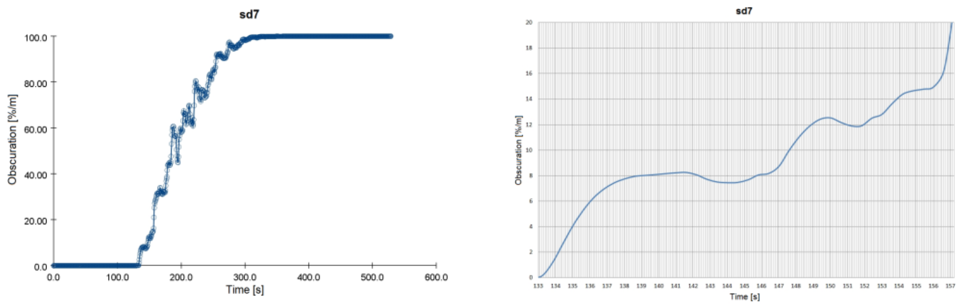



**Fig. 18** Obscuration vs. time - The seventh floor

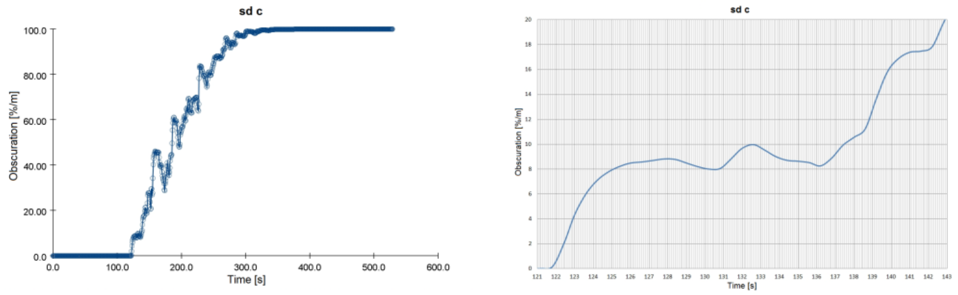



**Fig. 19** Obscuration vs. time - Ceiling of building

Finally, obscuration times for a stairwell width of 2.0 m are given in Table 5.

**Table 5** Times for obscuration for of the stairwell width of 2.0 m

| Stairwell width 2.0 m | Time for obscuration | | |
|---|---|---|---|
| Detector mark and location | 7%/m | 10%/m | 14%/m |
| sd gl - detector above ground level | ~ 109.1 s | 109.5 s | 109.9 s |
| sd1- detector at the top of the first floor | ~ 25.4 s | 25.5 s | 25.6 s |
| sd4 - detector at the top of the fourth floor | ~ 85.2 s | ~85.5 s | 85.7 s |
| sd7 - detector at the top of the seventh floor | ~ 137 s | 147.6 s | 153.9 s |
| sd c - detector at the top of the ceiling of the building | ~ 124.2 s | 132.5 s | 139.3 s |

## 5. Analysis of Obtained Results

The analysis of the difference in response time of individual detectors on different floors should be observed first from the aspect of the time needed for evacuation. First, let us consider how much time will be needed for evacuation when analyzing the variance in response times of individual detectors on different floors. In other words, what is the impact of delayed alarm signalization on individual floors at the start of evacuation? Furthermore, the effect of stratification will cause not only panic and crowd but significantly extend evacuation time.

In this paper, the speed of evacuation was not considered, but, in [6] it is suggested that the average walking speed on stairs can be regarded as 0.5 m/s for design purposes. The speed of evacuation was not taken into account in this paper, but in [6] it is suggested that for design purposes, the typical stair walking speed can be taken as 0.5 m/s. Other authors, for example [7] in models of evacuation define the velocity of each occupant ranging from 0.8 m – 1.0 m/s. Of course, the dimensions of stairs and landings used for simulation in this paper differ from the ones used in these models, but this fact does not significantly affect the general conclusion. Because of that, differences between the response times of detectors located on the first floor and the ceiling are shown in Table 6.

**Table 6** Response time delays between detectors located on the first floor and the ceiling for various stairwell widths

| Stairwell width | 7 %/m | | 14 %/m | |
|---|---|---|---|---|
| | sd1 | sd c | sd1 | sd c |
| 0.5 m | ~ 24 s | ~ 230.8 s | 24.42 | 233.7 s |
| 1.0 m | ~ 30.5 s | ~ 180.5 s | 31.5 s | 191.5 s |
| 2.0 m | ~ 25.4 s | ~ 124.2 s | 25.6 s | 139.3 s |

The first fact that is immediately apparent is that time for obscuration is shorter as the staircase gets wider. Also, the data presented in the previous table shows that several critical facts need to be addressed during the analysis. The first critical point is the smoke location within the stairways, especially in cases when stairways are being used during an evacuation of the building. Some of the facts obtained by simulations are as follows:

- The time intervals needed to reach obscuration from 7 %/m to 14 %/m, which is in fact time delay of response times for detectors sd1 and sd c are:
  - for stairwell width 0.5 m – about 1 s for detector sd1 and 4 s for detector sd c,
  - for stairwell width 1.0 m – about 1 s for detector sd1 and 11 s for detector sd c and
  - for stairwell width 1.0 m – less than 0.5 s for detector sd1 and about 15 s for detector sd c.
- However, time delays between detectors sd1 and sd c for obscuration of 7 %/m are:
  - almost 207 s for a stairwell width of 0.5 m,
  - about 150 s for a stairwell width of 1.0 m and,
  - almost 100 s for a stairwell width of 2.0 m.

Obviously, regardless of stairwell width, time for obscuration and consequently detector response times are in an interval of almost 2 minutes to 3 minutes between a detector on the first floor and a detector at the top of the ceiling of the building. This fact is particularly important when fire doors fail for some reason, and smoke or fire may make a staircase unusable. For example, based on an investigation in ([7], Fig. 4), the number of people evacuated in one minute can be almost one hundred. Obviously, during this time delay, a significant number of people can get evacuated. It is well known that the pre-evacuation phase, i.e. the time between notification and the time for people to evacuate may be important where scenarios are not dominated by flow and egress route capacities. The detection at the early stage is very important because, when evacuation through smoke is involved, the evacuation speed should not be greater than that appropriate for the expected density and irritation properties of the smoke. With the highly irritating smoke, the evacuation movement speed dropped precipitously once the extinction coefficient reached 0.4/m, figure 20 [6, Figure 3-14.6].

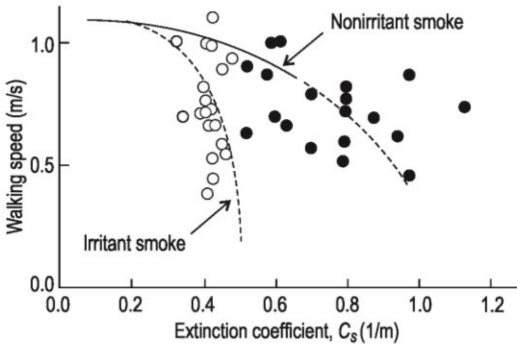



**Fig. 20** Walking speed in fire smoke

Due to the large number of data obtained by simulation, the data of the detectors located on the other floors are not shown, but the fact is that its mounting is necessary, since a fire can appear on each floor. Of course, the time delay between the response time of these detectors and the response of the detector at the top of the building is less than the times stated above. Finally, the time for obscuration for detectors on the ground level is almost close to the time for obscuration of detectors located at the top of the building, so, its placement only makes sense if there is an underground level or basement.

## 6 Conclusions

The basic stimulus for making simulations of this kind was a different approach in five world-leading standards related to the problem of detector placement at staircases. The usage of only one detector, located at the top of the ceiling of the building, in case of an enclosed staircase, may cause too much time delay needed for evacuation. Although simulations were not made under ventilation conditions, when stairwells behave like “chimneys”, stairwell width may not be the factor that determines the number of detectors. Placement of detectors on each floor is certainly the most reliable solution, but it is not economically justified taking into consideration obtained times for obscuration between floors. By mounting a detector on the ceiling of each third-floor landing, the response time of detectors and therefore response time of the whole fire detection system is not significantly smaller in terms of fire detection at an early stage. Finally, because of differences in times for obscuration of a detector at the top of the first floor and a detector at the top of the ceiling of the building impose the existence of a parallel (“slave”) control panel at each eighth floor for taller buildings.

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# O DETEKCIJI POŽARA NA STEPENIŠTU U VIŠESPRATNIM ZGRADAMA

*Stepeništa su veoma važna sa stanovišta zaštite od požara. Postoji više razloga za ovo stanovište, ali dva faktora su najvažnija. Prvi, stepenice su važno sredstvo evakuacije u višespratnicama, a drugi, trenutak detekcije požara je ključan za početak evakuacije. Prva činjenica se odnosi na lokaciju stepenica u zgradama i dimenzije stepenica i gazišta. Značaj druge činjenice je očigledan – lokacija i broj detektora požara direktno utiču na rano otkrivanje požara, a samim tim i na početak evakuacije. Za simulaciju opisanu u radu izabran je najgori scenario požara sa aspekta projektovanja zgrade – stepenište u centru zgrade, jer takvih u našoj zemlji ima mnogo. S druge strane, preporuke za lokaciju i broj detektora požara na stepeništu su različite u vodećim svetskim standardima. Iz ovih razloga, u ovom radu su simulacije izvedene u osmospratnici za različite dimenzije prostore između stepeništa. Parametri za simulacije su definisani na osnovu uporedne analize pravila navedenih u evropskom, britanskom, nemačkom, američkom i ruskom standardu. Uzimajući u obzir da neke hitne evakuacije podrazumevaju kretanje kroz dim, u građevinarstvu je neophodno znati kako navedeni faktori utiču na razvoj dima u slučaju požara, a samim tim i efikasnu evakuaciju.*

Ključne reči: *detekcija požara, višespratnica, stepenište, standardi, simulacija*