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FIRE SAFETY ENGINERING FOR AN AUDITORIUM ANALYSIS

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Abstract: *A new level of the modelling approaches of spaces set on fire is analysed where the particularities of the functional is carefully treated. This article presents the fire analysis of an auditorium which has various functions and therefore depending on the performance, people may sit down or stand, leading to different evacuation fire scenarios. Based on this, the analysis of the differences form the evacuation scenarios of a group of people was performed for two different situations: one standing and one sitting. For the analyses FDS, Smoke view and Pyrosim software were used.*

Key words: *safety, fire, engineering, evacuation, finite volume, auditorium*

1. Design Fire for Chosen Fire Scenario

The paper presents the cumulated experience of the authors regarding the engineering approach of fire safety related to human evacuation from auditoriums.

This article presents a case study of an auditorium evacuation scenario, considering it has a group of 175 persons. The modelling of the fire space presented in Figure 1 was performed in the software Pyrosim/FDS (Fire Dynamics Simulator). The starting place of the fire is considered to be the wardrobe with an area of A=5.145 m^2. The inflammable content is provided through the textile clothing deposited there, characterised by a net calorific value of H_u=20 MJ/kg. It is considered that each of the 175 person deposited a 0.9 kg content of textile clothing, reaching a total of 157.5 kg.

The characteristic values of the fire load, $Q_{fi,k}$ and the fire load density, $q_{fi,k}$are computed in Equation 1 and 2 [1, 2, 4]

$$Q_{fi,k} = \sum Q_{fi,k,i} = \sum M_{k,i} \cdot H_{ui} = 157.5 \cdot 20 = 3150\, MJ \tag{1}$$

$$q_{f,k} = \frac{Q_{fi,k}}{A} = \frac{3150}{5.145} = 612.25 \approx 612.5\, MJ/m^2 \tag{2}$$

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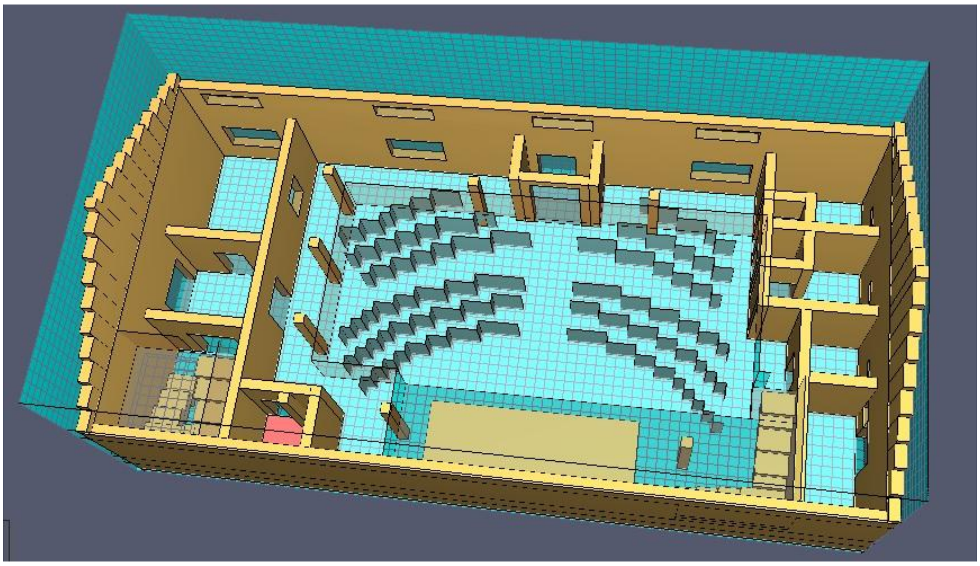

Fig. 1. *The auditorium finite volume model in Pyrosim*

The design value of the fire load density, $q_{fi,k}$ and the value of the total energy contained in the fuel, E_t, are presented in the Equations 3 and 4.

$$q_{f,d} = m \cdot q_{f,k} \cdot \delta_{q1} \cdot \delta_{q2} \cdot \delta_n = 0.8 \cdot 612.5 \cdot 1.1 \cdot 1 \cdot 1.17 = 630.37\, MJ/m^2 \quad (3)$$

$$E_t = q_{fi,d} \cdot A = 630.37 \cdot 5.145 = 3243.24\, MJ \quad (4)$$

Taking into account that in the wardrobe there is a potential vertical opening (e.g. door or window) of an area A_v=2.1 $m^2$with a medium height h_{eq}=2.1 m, the maximum flow of the heat is computed in Equation 5 (fire controlled ventilation):

$$Q_{max} = 0.10 \cdot m \cdot H_u \cdot A_v \cdot \sqrt{h_{eq}} = 0.10 \cdot 0.8 \cdot 20 \cdot 2.1 \cdot \sqrt{2.1} = 4.869\, MW \quad (5)$$

Based on this conditions the evolution in time of the heat flow at the wardrobe level can be established:

- for fire development stage (supposing the rapid increase of the fire, t_a = 75 s, corresponding to auditoriums) the stage time interval divided by final stage time, $t_d/t_1$and the energy transformed into heat, E_d, are computed in Equations 6 and7.

$$t_d = t_a \cdot \sqrt{Q_{max}} = 75 \cdot 4.869 = 165.49 s \quad and \quad t_1 = t_d = 165.495\, s \quad (6)$$

$$E_d = \frac{t_d \cdot Q_{max}}{3} = \frac{165.495 \cdot 4.869}{3} = 268.6\, MJ \quad (7)$$

- for generalized fire stage (which starts in the maximum heat release rate moment, Q_{max}) the energy transformed into heat, E_g, the stage duration, t_g and the final time

- of the stage, t_2, are computed using Equations 8, 9 and 10.

$$E_g = 0.7 \cdot E_t - E_d = 0.7 \cdot 3243.24 - 268.6 = 2001.66\ MJ \tag{8}$$

$$t_g = \frac{E_g}{Q_{max}} = \frac{2001.66}{4.869} = 411.09\ s \tag{9}$$

$$t_2 = t_d + t_g = 165.495 + 411.09 = 576.59\ s \tag{10}$$

- for fire decay stage (evaluated to start after using 30% of the fuel) the energy transformed into heat, E_r, the stage duration, t_r and the final time of the stage, t_3, are computed in Equations 11, 12 and 13.

$$E_r = 0.3 \cdot E_t = 0.3 \cdot 3243.24 = 972.97\ MJ \tag{11}$$

$$t_r = \frac{2 \cdot E_r}{Q_{max}} = \frac{2 \cdot 972.97}{3243.24} = 399.65\ s \tag{12}$$

$$t_3 = t_d + t_g + t_r = 165.49 + 411.09 + 399.65 = 976.24\ s \tag{13}$$

Figure 2 presents the plot of the released heat flow variation.

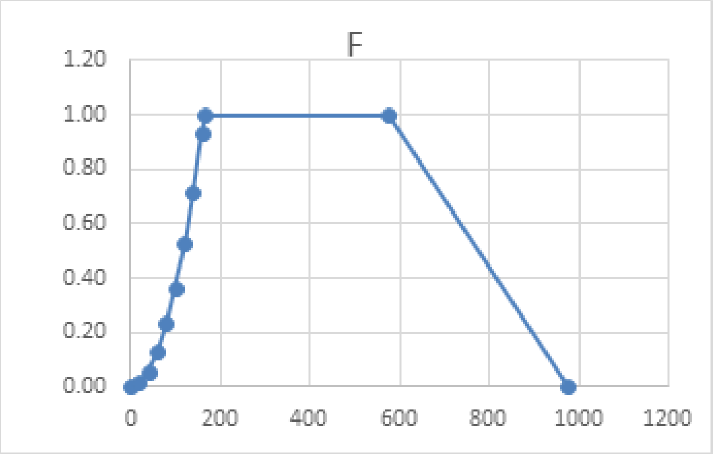

Fig. 2. *Released heat flow variation in auditorium*

2. Finite Volume Elements Modelling of the Auditorium

For the results accuracy the numerical simulator FDS, impose that the adimensional Equation D*/x should take values in between the interval 4÷16, where D* is the characteristic fire diameter and x is the nominal dimension of a finite volume. Considering the maximum released flow in this situation, $Q=Q_{max}$=4869.0 kW; the air density ρ=1.2014 kg/m^3; specific air heat c=1.005 KJ/ (kgK); air temperature T=293K and gravity g= 9.81 m/$s^2$the values of D* and x are computed in Equation 14. Based on these results the dimensions of the finite volume elements were chosen to be 0.35x0.35x0.35 m.

$$D^* = \left(\frac{Q}{\rho \cdot c \cdot t \cdot \sqrt{g}}\right)^{\frac{2}{5}} = \left(\frac{4869}{1.204 \cdot 1.005 \cdot 293 \cdot \sqrt{9.81}}\right)^{\frac{2}{5}} = 1.806\ m \tag{14}$$

and

$$x \in [0.11m; 0.45\ m]$$

3. Evacuation Modelling Under Fire Circumstances

3.1 Check of the safety evacuation of humans in fire

The engineering approach of human evacuation under fire circumstances as in case of unique buildings is performed by comparing Available Safe Escape Time, ASET and Required Safe Escape Time, RSET [5, 6, 7]

The difference between these two time factors is a safety margin, Δt_{sig} given in the Equation 15 [5, 6]:

$$\Delta t_{sig} = ASET - RSET \tag{15}$$

The specific time steps for evacuation are:

- t_{det}, detection time, measured from the fire start moment until the fire detection moment;
- t_{reac}, reaction time, measured from the fire detection moment until the moment thelast humans are lead to the exit ways,
- t_{depl}, necessary time for developing the evacuation process, measured from the moment the last humans are heading to the exit ways until the moment all humans are evacuated and located to a safe place.

The software environments use as input data t_{det} and t_{reac} of humans and provide as outputs t_{depl}.

The time t_{det} measured by an automatic detection system or by the building's inhabitants (PD 7974-6:2004), is the time interval in which the humans are unaware of the danger and they behave naturally. PD 7974-6:2004 defines the alarming time as the time interval in between the fire detection occurs until the general fire alarm triggers. Throughout this case study, for an easier definition of the input data of the software FDS+Evac, the alarming time is included in the detection time.

The time t_{reac}(before movement time) is the time in which humans realise the danger and start several actions such as: gathering personal belongings, grouping around the familiar people or taking a decision on choosing an exit way. Due to human unpredictability a universal reaction time cannot be established. Based on real fires some criteria were established in order to approximate the reaction time of humans depending on the types of buildings, the geometrical complexity of it, the levels of alarming and on fire management.

Building classification Table 1

Building categoty	**Inhabitants characteristcs**	**Level of familiarity of inhabitants**	**Inhabitants density**	**Number of rooms**	**Building destination**
A	Awake	familiar	low	One or more	Office buildings or industrail halls
B1	Awake	unfamiliar	high	One or few	Shopping centers or restaurants
B2	Awake	unfamiliar	high	A central room	Cinemas or theaters
Ci	sleeping	familiar	low	few	Individual housing
Cii	sleeping	familiar	low	few	Block of flats
Ciii	sleeping	unfamiliar	low	many	Hotels, Pensions
D	under medical care	unfamiliar	low	many	Medical buildings
E	awake	unfamiliar	high	many	Train statitions, stations and airports

Table 1 presents the building classification according to specific rules for different types of structures (PD 7974-6:2004).

According to PD 7974-6:2004 different geometrical complexity levels are established:

- B1, for simple geometrical structures, in plane rectangular, with one level, with one or few rooms, with short exit ways and many exits that lead outside the building (e.g. supermarket);
- B2, for simple geometrical structures, with several levels and rooms (e.g. office buildings);
- B3, for complex geometrical structures, with many levels and rooms, the main characteristic of these buildings being the complexity of the exit ways (e.g. patrimonial buildings, hotels, airports).

The fire management rules from PD 7974-6:2004 have different levels of management as seen in Figure 3:

- M1, the building's inhabitants are well trained for fire evacuation, the exit ways are well signalled, fire emergency trials are regularly performed; there is enough staff to lead all people to the exits. In general, this type of management is find in buildings with proper designed exit ways, level B1 or B2and equipped with automatic fire detection systems or vocal notification system;
- M2, similar to M1, a small number of humans that permanently work in the building; regularly this type of management is found in structures with geometrical complexity level B2 and alarming level;
- M3, where the inhabitants are not well trained for fire evacuation, this kind of management is found in B3 geometrical complexity level and alarming level.

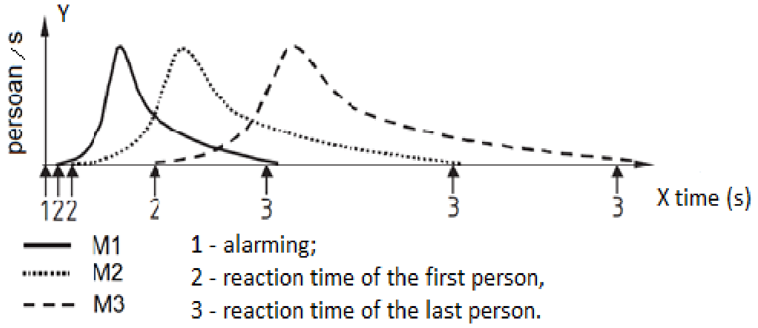

Fig. 3. *Time reaction distribution of humans on each management level*

(PD 7974-6:2004)

The time t_{reac} for a building can be obtained by correlating the alarming level of the building, the geometrical complexity level and fire management level. According to table from PD 7974-6:2004 with values of t_{reac}, for this case study the B combination was considered, namely awake inhabitants and unfamiliar with the building, M2, B1, A1-A2 for which t_{reac}= 60 s.

3.2 Tenability limits fire safety evacuation

The main objective of fire safety is the possibility of inhabitants to move to safe areas before the tenability limits exceeds in the exit ways, therefore putting in danger human lives. The previous mentioned conditions are (Poh, 2011;Purser, D.A, 1995):

- Concentration of narcotic and irritant gasses (disabling humans through conscience loss or death);
- Visibility through a smoke layer;
-Convective and radiant heat(disabling humans through skin pain, conscience loss, hyperthermia, burns in lungs and skin).

According to (Poh, 2011)the maximum bearable conditions at 2 m from the floor level are:

- maximum air temperature of 100^0C ;
- maximum radiant thermic flow of2.5 kW/m^2 ;
- FED parameter (Fractional Effective Dose, which quantifies the level of gas toxicity) for adults, 1;
- Visibility through a smoke layer,in case of large rooms, 10m.

FDS software has certain limitations, namely it doesn’t take into account human influences by opening doors.

The gas concentration of O_2, CO_2 and CO are used to compute FED parameter. Smoke density is used for influencing the agent (human) displacement speed but also for influencing the selection of exit ways algorithm.

Another use of smoke density is that it can accelerate fire detection but on should take into account that human factor is unpredictable, therefore the concentration levels necessary for smoke detection may be under the actual prediction precision of FDS. One should take into account that the radiation effects and gas temperatures are not implemented in the software, therefore agents (humans) are not trying to avoid the fire unless the user is defining the evacuation geometry. For bearable conditions analysis against the exit doors temperature, radiant heat flow, FED and visibility virtual detectors were installed. In case the limit values are overlapped it is considered that the agents (humans) that pass though these conditions are dead.

3.3 Human evacuation in the case study

The case study considers two human evacuation scenarios (Filimon N., 2017):

-S1 scenario, where at the initial time the humans are sitting on the chairs but the chairs are not considered as being obstacles and both exit ways are open/clear;

-S2 scenario, where at the initial moment the humans are sitting on the chairs but now the chairs are considered as obstacles and both exit ways are available/open.

4. Conclusions

In S1 scenario case (Figure 4.a.), human evacuation starts after 60 seconds and finishes when the last person that exits the building in 120 seconds. The temperatures at 2 m height above the doors is around +50°C for the first exit door and +40°C for the second exit door. FED coefficient for gas toxicity doesn't reach the critical value of 1. The only parameter that endangers human lives is the decrease of visibility under 10 m at 115 seconds.

In S2 scenario case (Figure 4.b.), human evacuation starts after 60 seconds and finishes when the last person that exits the building in 132 seconds. The temperatures at 2 m height above the doors is around +50°C for the first exit door and +40°C for the second exit door. FED coefficient for gas toxicity doesn't reach the critical value of 1.The only parameter that endangers human lives is the decrease of visibility under 10 m at 115 seconds.

Finally it can be concluded that exactly what was expected happened, namely the evacuation time in S2 scenario was longer that in S1 scenario. Never theless the time difference is not big due to the large space in-between the chair rows around 0.75m and the length of the exit ways through the chairs are relatively small. In order to check the accuracy of the results it is necessary to continue the analyses of the scenarios by refining the mesh as much as possible in FDS software. In this case difficulties may appear in the evacuation ways between the chair rows.

Also, as expected the presence of the chairs as obstacles do not influence the development of the fire.

It must be highlighted that this type of research in Romania is new and it opens the way in the research of the human evacuation under fire circumstances from auditoriums.

a. S1 scenariob. b. S2 scenario

Fig. 4. *Evacuation images at 63s in Smokeview*

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