EXPERIMENTAL AND NUMERICAL STUDY OF BALCONY EFFECT IN EXTERNAL FIRE SPREAD INTO UPPER FLOORS

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Abstract

In this paper are presented the results of natural fire tests and numerical simulations using the Fire Dynamics Simulator (FDS) and analytical simulations using the methods of EN 1991-1.2 (2010). The main goal of the investigation is the validation of the values of fire safety regulations on distance between openings corresponding to successive floors in a façade and the effect of dimensions of balconies in the external fire spread into upper floors. It is intended to quantify and measure the height and width of flames projected through the windows and to measure the indoor and outdoor temperatures. The tests were performed in a compartment that was intended to represent a small office with two opposing openings, a door and a window. The distance between the openings in the successive floors was 1.10 m. The test 1 was carried out without any balcony above the opening and tests 2 and 3 had a balcony with different dimensions in length.

Keywords: fire simulations, natural fire tests, external fire spread

INTRODUCTION

The fires inside the buildings can sometimes spread to other buildings or from one floor to another floor, because the flames can be projected to outside through windows, doors, roofs or skylights. When projected the flame spreads the fire in façade by convection and radiation. So, limiting the fire spread in the façade is a challenging problem. Reducing the fire spread through the façade openings, many countries created fires safety regulations. The fire safety regulations require a distance between openings to prevent the spread of flames to the top floors and, on the other hand, this risk can also be reduced by a balcony above the openings. In the fire safety regulations around the World exist different proposed distances between openings and sizes of balconies. The distance between openings in Portugal is 1.10 m, but when there is a balcony, with a span at least one meter from each edge of the opening, this distance can be reduced by the span of the balcony. It is noticed that the balconies have to be at least a fire resistance of EI60 (Law 1532/2008). The prediction of the temperature distribution inside and outside (on the facades) a building during a natural fire should be as faithful as possible to the ones observed in reality, in such a way that the fire design of external elements is on the safe side but not too conservative either. Regarding to this matter, for example, Wald et al. (2009) presented an experimental programme to investigate the global structural behaviour of a compartment in the three-storey steel frame building in a plant of the Mittal Steel Ostrava exposed to fire before demolition. Hence this research project was focussed on the examination of the temperature development within the various unprotected structural elements (beams and columns) and its connections during the natural fire. They concluded that (i) the methods for calculating the compartment temperature by the parametric fire curve given in Annex A of EN1991-1-2 compared well with the measured data. (ii) The incremental analytical models allowed presumption of temperatures of the unprotected beams with a good accuracy. (iii) Calculating the temperature of the beam-to-column connection from the measured gas temperature in the fire compartment based on the mass of the connection parts according to Annex D of EN 1993-1-2, was conservative during the heating phase. (iv) A calculation based on the bottom flange temperature of the supported beam was less conservative. (v) And finally, the prediction of the temperature of the beam-to-beam connections using the measured gas temperature in the fire compartment, based on the mass of the connection parts, was also conservative during the heating phase. The authors still proposed that the calculation based on the bottom flange temperature of the supported beam may be improved by factor 1.0 instead of 0.88. Abecassis-Empis et al. (2008) also carried out natural fire tests, which were conducted in a real high-rise building. The use of these experiments contributed towards extending the current understanding of the complex dynamics of fire and the inherent difficulties of predicting its evolution. They highlighted the strengths and limitations of fire safety tools and practices in real fires. These tests served as a validation tool for certain faculties of CFD models as well as emphasising some of the current limitations of their use. In what concerns to experimental tests focused on the temperature development along the facade of a building between openings, it is observed they are still fairly rare and are mostly of numerical nature. One example, it is the preliminary study published by Weinert and Poh (2006) on the performance of horizontal projections (balcony) in vertical separation of openings in external walls. Three fires were examined with different peak heat release rates. They found that a horizontal projection between about 0.3 m and 0.6 m is equivalent to a 1 m spandrel.

1 EXPERIMENTAL TESTS

The compartment fire was 5.30 m long, 2.03 m wide and 2.10 m tall. The compartment had two openings, one window of 1.23 m width and 0.92 m height, one door of 1.74 m height and 0.73 m width which correspond to an opening factor about0.30. The façade was 3.30 m long and 3.80 m tall. The distance between the openings in the successive floors was, in the three tests,1.10 meters. The test 1 was carried out without any balcony above the opening. Tests 2, 3 had a balcony of 0.55 m span and its length was 1.23 m (the same length of window), and 3.23 m(the length of balcony plus 1m away from each side of the opening), respectively, in tests 2 and 3. The internal walls and ceiling of the compartment were insulated by sandwich panels made of fire resistant gypsum boards and rock wool (40kg/m^3 for walls and 150kg/m^3 for ceiling). The fire load used in the experimental tests was materialized by means of wood cribs and was obtained by the simplified calculation methods established in EN1991-1-2 (2010). The heat release rate (HRR) used was 4.15 MW, distributed by three piles of wood cribs in the middle of compartment with 1384 kW each one of HRR (Heat Release Rate). For all tests, it was checked the air temperature and the wind speed before the test starts. So, during these tests, practically no wind was detected for all tests, the air temperature was around 30, 15 and 20ºC and the relative humidity was 36, 60 and 41% for tests 1, 2 and 3, respectively.

1.1 Test 1, 2 and 3

In test 1 the ignition of wood cribs was a little bit slowly. The time to reach the maximum temperature of 912.5 ºC inside the compartment (thermocouple localized in the ceiling) was 26 minutes. The maximum temperature outside, in the middle of the opening of the window of upper compartment, was 260 ºC, reached at 15 minutes and 30 seconds. The projection of flame and the plume of smoke in this test were slightly visible. The height of flame above the lintel of window was 0.28 m, the length of flame was 0.10 m and the horizontal projection was 0.88 m (Fig. 1).In test 2 the maximum temperature inside the compartment was 1080.9 ºC in ceiling thermocouple reached after 17 minutes and 30 seconds. Outside, below the balcony, was 501.4 ºC at 23 minutes and 30 seconds. The flame and the plume of smoke were very visible in this test. The height of flame in projection through the window was 2 m, the horizontal projection was 2.90 m and the lateral projection was 0.20 m (Fig. 2).In test 3 the temperature inside was 1088 ºC, obtained in the ceiling at 18 minutes. In the outside, the maximum temperature obtained below the balcony, was 659.8 ºC, at 22 minutes. The flame and smoke plume were very visible. The vertical and the horizontal projections of flame obtained were 2 m and the lateral projection was 0.20 m (Fig. 3).



Fig. 1 Test 1 Fig. 2 Test 2 Fig. 3 Test 3

In test 1 the plume of smoke and the scanty flame up to the superior floor close to the façade (fig. 1). The flame in test 2 bended towards the superior window and surrounded the balcony (fig. 2). In test 2 the flame was projected to outside the façade after hit the balcony (fig. 3).

2 NUMERIC SIMULATIONS

In numerical simulations, the FDS program, version 5.5.3, was used. This program is a computational fluid dynamics (CFD) model of fire-driven flow. It is a large-eddy simulation code for low-speed flows with an emphasis on smoke and heat transport from fires(MacGrattan et al, 2010).For visualization of results was used the smokeview interface. The characteristics of fire compartment and façade were the same as in all experimental tests. A finite element mesh of 0.15x0.16x0.17 m was generated automatically by the program and used in all simulations. The time period of analysis was 1470 seconds, corresponding to time when the HRR started to decrease.

2.1 Numerical simulation 1, 2 and 3

In numerical simulation 1 (FDS1) the maximum temperature inside the compartment obtained was 947.2 ºC in the wall at 9 minutes approximately. The outside maximum temperature, below the window of upper floor, was 849.3 ºC at 10 minutes after begins fire. The height of flame obtained by simulations was 3.29 m upper the lintel of fire compartment window. The lateral and horizontal projection was 0.30 m and 1.20 m, respectively. The maximum temperature inside compartment in simulation 2 (FDS2) was 936.5 ºC at 8.74 minutes of fire. The maximum temperature outside the compartment was 1118.1 ºC, in the balcony thermocouple (end edge), at 10.34 minutes. The height of the projection of flame was 2.20 m and the lateral projection was 0.53 m. The horizontal projection was 1.20 m. In numerical simulation 3 (FDS3) the maximum temperature inside the compartment fire, was 936.1 ºC at 9.36 minutes. The outside maximum temperature was 1110.7 ºC at 11.34 minutes in front of balcony. The height of flame projection was 3.29 m, the lateral projection was 1 m maybe due to the balcony effect. The horizontal projection was 2 m.

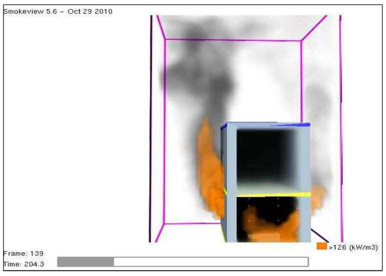


Fig. 4 Simulation 1

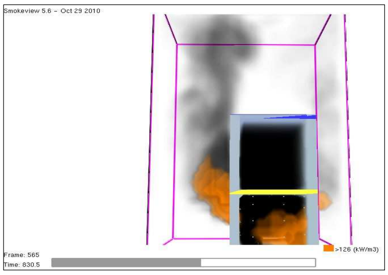


Fig. 5 Simulation 2

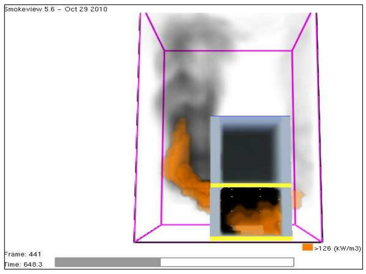


Fig. 6 Simulation 3

In numerical simulation 1 the flame rose up to the successive floor along the façade (Fig 4), but in the simulation 2 the flame surrounded the balcony and bended toward the window above (Fig. 5). The flame in the simulation 3 rose up parallel to the façade at a distance equal to the balcony span (Fig. 6).

3 ANALYTICAL SIMULATIONS

It was also carried out analytical simulations using the method of the parametric fire curves (annex A of EN 1991-1.2, 2010) and the simplified calculation method (annex B of EN 1991-1.2, 2010).The same compartment characteristics as the experimental tests were used in this analytical simulations. The method of parametric curves gave a maximum temperature (θg) of 989 ºC at 0.480 h inside the compartment (eq. (1).

$$\theta g = 20 + 1325\left(1 - 0{,}324\, e^{-0{,}2t^*} - 0{,}204\, e^{-1{,}7t^*} - 0{,}472\, e^{-19t^*}\right) \quad [ºC] \qquad (1)$$

where θg – gas temperature in fire compartment [°C]

t* –fictitious time

In the simplified calculation method used the equations of forced draught. The temperature (T_f) inside compartment was 775.4 ºC by (eq. (2)).

$$T_f = 1200\,(1 - e^{-0{,}0028\,.\,\Omega}) + T_0 \quad [K] \qquad (2)$$

where T_0, initial temperature [K]

Ω, $(A_f.q_{f,d})/(A_v.A_t)^{1/2}$

A_f, floor area of the fire compartment [m]

A_v, total area of vertical openings on all walls

A_t, total area of enclosure (walls, ceiling and floor, including openings)

$q_{,f,d}$, design fire load density related to the surface area A_f

The height of flame (L_L) projected through the window was 0.58 m given by Eq. (3).

$$L_L = \left(1{,}366\,\left(\frac{1}{u}\right)^{0{,}43} \frac{Q}{A_v^{\frac{1}{2}}}\right) - h_{eq} \quad [m] \qquad (3)$$

where Q, rate of heat release of the fire

h_{eq}, weighted average of window heights on all walls

u, 6 m/s

The horizontal projection (L_H) obtained was 2.17 m given by eq. (4).

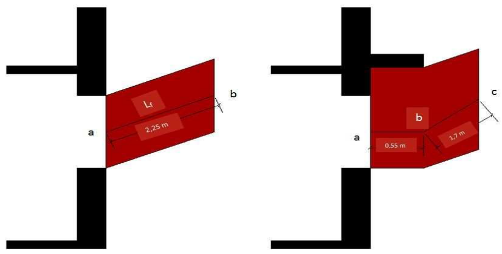
$$L_H = 0,605 \left(\frac{u^2}{h_{eq}}\right)^{0,22} (L_L + h_{eq}) \quad [m] \tag{4}$$

The width of flame (lateral projection) (W_f) was 2.62 m given by eq. (5).

$$w_f = w_t + 0,4\, L_H \ldots\ldots [m] \tag{5}$$

where W_t, sum of window widths on all walls

The temperature of flame at the window was 746.9 ºC and the flame temperature along the axis of one meter was 737.7 ºC. In the forced draught the trajectory of the flame may be directed horizontally if there are balconies. The flame is deflected outwardly at a distance equal to the width of the balcony, but the length not change. The L_f is the same and equal to 2.25 m.



a) b)

Fig. 4 Flame deflection: a) without balcony; b) with balcony

4 COMPARISON AND VALIDATION OF RESULTS

The maximum temperatures inside compartment were obtained in the ceiling on experimental tests and in the two smaller walls in the numerical simulations. The time to reach the maximum temperature was 9 minutes (FDS 1), 8.70 minutes (FDS 2) and 9.36 minutes (FDS 3) for the numerical simulations and 26 minutes (Test 1), 17.5 minutes (Test 2) and 18 minutes (Test 3) for experimental tests and 29 minutes (Parametric curve) for analytical simulations (Fig. 5).

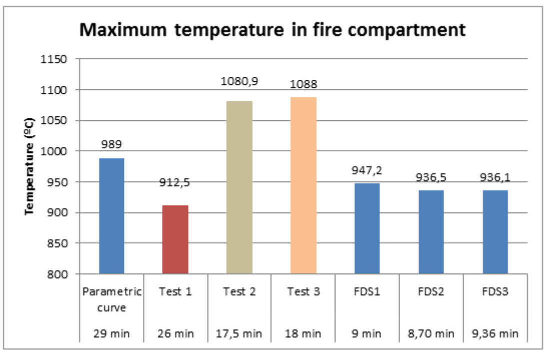
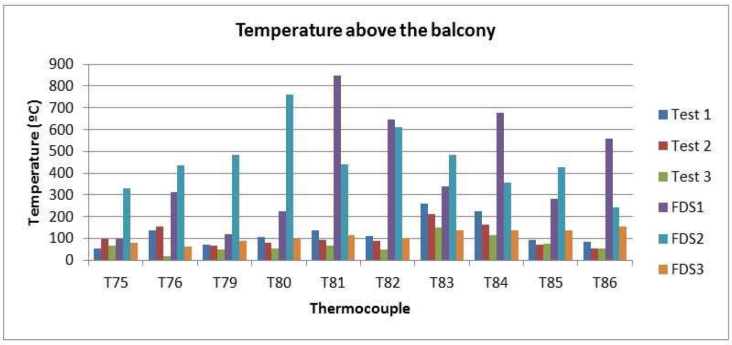


Fig. 5 Maximum temperature in fire compartment

In experimental tests the temperatures inside compartment were higher than outside. In the numerical simulations the temperatures outside were higher than inside compartment. It was noted that the time was not the same when the maximum temperature was reached outside and inside the compartment both in the experimental tests and in the numerical simulations. The existence of a balcony larger than the window (Test 3 and FDS3) led to that the temperatures above it are smaller than in the case of the balcony ending on the border of the window (Test 2 and FDS2) and much smaller than comparing with the case of inexistence of balcony (Test 1 and FDS1). The results showed that temperatures along the façade do not decrease as a function of height. At different points above the balcony and below the window of the upper compartment were registered temperatures below the ones in the centre of the window of that compartment. It can also be seen clearly in Fig. 6 e 7 that the numerical temperatures at points corresponding to thermocouples T80, T81 and T82 (above the balcony) of the experimental tests, were lower than the ones at pointes located below it.



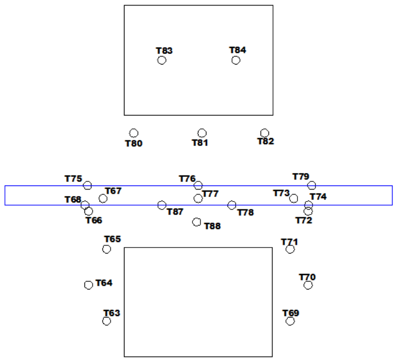


Fig. 6 Temperature above the balcony

Fig. 7 Measuring temperature points

In Eurocode 1 part 1-2 (EN 1991-1.2, 2010) for forced draught the flame occupies the entire window when occurs the flame projection. In experimental tests this situation didn't occur, (Fig. 7, 8 and 9).This can be observed by a dashed line in Figure 8, where the flame and the plume of smoke do not occupy the entire opening. From these figures it can be assessed that about 20% of the window was used by the fresh air to entry in the compartment while in numerical simulations the flame occupied practically the entire window. The height of flame projection in experimental tests 2 and 3 was 2 m being smaller than test 1 that was 0.28 m. In numerical simulations, it was verified that the height of flame in FDS 2 was (2.22 m) smaller than the ones obtained in FDS 1 and FDS 3 (3.29 m). Concerning the simplified calculation method the height of flame was 0.58m. The horizontal projection in experimental tests was higher in test 3where the flame was away from the façade. In the numerical simulations FDS 1 and 2,it was observed an equal horizontal projection of flame from the wall, which was 1.20m. In the simplified calculation method the horizontal projection of flames was 2.17m that is the highest value relating to the experimental and numerical tests, exception for test 2. The width of flame enlarged from each side of the window in all experimental and numerical tests, but in experimental test 2 the enlarging is higher than in the others. In the simplified calculation method the flame width was 0.70m that was smaller than in numerical simulation FDS3 (1.0m) and higher than in the other numerical and experimental tests (see Fig. 9).

Fig. 8 Flame projection in forced draught

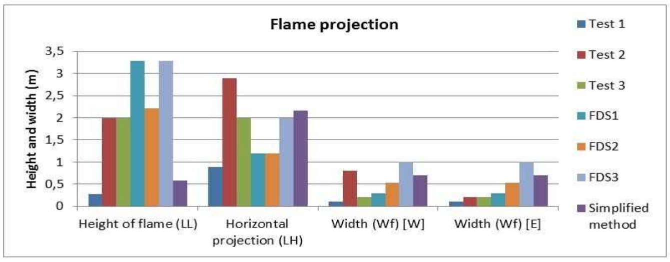


Fig. 9 Flame projection

The presence of a balcony with 1 meter to each side of window was the most viable option, since because of it the flame was kept away from the façade and so the temperatures in the wall above the balcony were lower than the ones recorded in other tests. Therefore, with a balcony between successive openings, the risk of fire propagation to the upper floors will be much smaller. In FDS 2 the height of flames is smaller than the other cases however the flame surrounded the balcony increasing lateral spread of the fire to the upper floors.

REFERENCES

Abecassiss, C., Reszka, P., Steinhaus, T., Cowlard, A., Biteau, H., Welch, S., Rein, G. and Torero, J.L., " Characterisation of Dalmarnock fire test one". Experimental Thermal and Fluid Science, Vol. 32, pp. 1334-1343, 2008.

EN 1991-1-2. "Eurocode 1 – Actions on structures Part 1-2: General actions – Actions on structures exposed to fire", 2010.

MacGranttan, K. et al. "Fire Dynamics Simulator (Version 5) - User's Guide and Technical Reference Guide". National Institute of Standards and Technology, 2010.

Decree-Law 220/2008, November 12, Legal Regime for Fire Safety in Buildings.

Law 1532/2008, December 29, Technical Regulations of Fire Safety in Buildings.

Wald, F., Chlouba, J., Uhlír, A., Kallerová, P. and Stujberová, M., "Temperatures during fire tests on structure and its prediction according to Eurocodes". Fire Safety Journal, vol. 44, pp. 135-146, 2009.

Weinert, D. and Poh, W., "Performance of horizontal projections in vertical separation of openings in external walls – comparison with BCA solutions". Proceedings of the International Conference on Fire Safety Engineering, Gold Coast, Australia, 2006, 15 p.