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“Experimental assessment of separation distances of a load-bearing straw-bale construction”

Petr HEJTMÁNEK, Hana NAJMANOVÁ and Tomáš VÁCHAL

1 Department of Building Structures, Faculty of Civil Engineering, Czech Technical University in Prague, Czech Republic
2 University Centre of Energy Efficient Buildings, Czech Technical University in Prague, Czech Republic
3 Department of Construction Technology, Faculty of Civil Engineering, Czech Technical University in Prague, Czech Republic

petr.hejtmanek@fsv.cvut.cz

ABSTRACT

With an increasingly dense urban structure and wider use of energy efficient and combustible materials, the requirements on fire separation distances are becoming an actual topic. In the Czech Republic, separation distances are determined according to “fire openness” categorisation of external walls. In line with the Czech Fire Standards, combustible external walls must be considered as unprotected areas (fire opened areas) until the opposite is proven. This classification might be a crucial element in building design and for location of an object on a plot. This paper introduces a project on fire safety evaluation of a load-bearing straw-bale construction and focuses on experimental determination of fire openness of combustible external walls with incombustible surface (A1/A2 reaction to fire class). To assess fire risk and a contribution to fire growth and flame spread of the walls, a full-scale fire test of an experimental straw-bale house was carried out in September 2017. The experimental object was designed as a mock-up of a residential house, single-storey, stand-alone building with ground floor dimensions of 4.0 × 6.0 m and a height of 3.5 m with two symmetrical connected rooms. The observations and measurements showed that the experimental wall composition, even though it was not certified as a construction with a specific fire resistance, did not contribute to the fire propagation and could be assumed as a fire closed area, where as unprotected areas are considered only windows. In the case of the evaluated object, this classification leads to a reduction in separation distances of almost 4 meters. According to the results can be concluded that a different approach to evaluate fire openness could be desirable to establish.

KEYWORDS

Large-scale fire test; fire; separation distance; heat flux; temperature; straw-bale construction; clay plaster; compartment fire
INTRODUCTION

In line with a growing importance placed on sustainable building, renewable resources and natural construction materials are becoming an inherent part of modern building design. Offering a new approach on the manner of designing buildings, this perspective challenges also other fields which at the first sight seemed to be in conflict with it, including fire safety design [1–2]. Regarding their combustibility, use of environmentally friendly materials may be questionable and strictly limited in national fire codes and standards. In context with an increasingly dense urban structure and a frequent application of these materials both in and on external walls, above all, the requirements on fire separation distances become an especially actual issue.

Among many possibilities of external fire spread, the radiative heat transfer is assumed as one of the main risks [3]. Considering this criterion, calculation of a separation distance is bounded with a line of critical radiative heat flux varying from 12.5 kW/m² for piloted ignition to 30.0 kW/m² for self-ignition [4]; in the Czech Republic, the critical value is 18.5 kW/m² [5]. Methodologies for determination of separation distances are usually given at national level by local standards and vary from simplified limit values based on expected radiation up to performance-based evaluation considering variables such as configuration factor, heat release rate, emissivity, the thermal capacity of the affected structure, and others. A common aspect can be found in most of the methods: the amount of “unprotected areas” in the building enclosure. An unprotected area may be defined as any part of a wall which may contribute to radiation during the fire: parts without fire resistance (e.g. door, window) or parts that emit radiation energy; hence, combustible structures and structures with a combustible cladding must be also taken into account [6]. In the Czech Fire Standards, limit values for radiative heat flux released from a façade are laid down for estimation of “fire openness” of a structure: an external wall containing combustible materials is considered as a fire opened area (FOA) if the heat radiation flux at the outer face of the wall exceeds the value 60 kW/m², a range between 15 kW/m² and 60 kW/m² determines the wall as a partly fire opened area (PFOA), and an external wall is assessed as a fire closed area (FCA), only if the value of the radiation heat flux is less than 15 kW/m². Furthermore, regarding the Czech classification system for evaluation of structure’s fire behaviour, combustible external walls must be considered as unprotected areas (fire opened areas), until the opposite is proven [5]. Calculation of separation distances are directly affected by the magnitude of a fire opened area, i.e. by openness categorisation of an external wall (FOA, PFOA, or FCA); as will be seen later in Fig. 7. Consequently, use of environmentally friendly and energy efficient materials in buildings may be strictly limited due to the large separation distances arisen from this classification.

To minimize separation distances of combustible external walls, i.e. to achieve other classification than FOA, “the opposite” must be proven. Regarding this aim, however, several problems are occurring. Firstly, although the limits of FOA, PFOA, and FCA are set down, no methodology how this characteristic can be obtained in practice is available. Since the set limits assess a contribution to fire of the surface, there is no simply way to measure the heat release without outer sources that may influence the results when it is tested physically. Furthermore, to comply current requirements when experimentally tested, both fire resistance tests from outside and inside must be conducted to get the knowledge about the external surface behaviour and to estimate surface temperatures on the unexposed side of the structure. Subsequently, from the maximum surface temperature on both sides, the heat flux is calculated using the Stefan-Boltzmann Law:

\[
I = \varepsilon \cdot (T_{\text{max}} + 273)^4 \cdot 5.67 \cdot 10^{-11}
\]

where \(I\) is heat flux [kW/m²]; \(\varepsilon\) is emissivity [-], for fire \(\varepsilon = 1\); \(T_{\text{max}}\) is the highest temperature on the unexposed side from both interior and exterior fire tests [°C]. Regarding this method is arguable, why surface temperature in the interior must be set and considered when an outer surface is assessed. Another way to estimate the value of heat radiation flux of a combustible wall is a summation of total heat release of all combustible layers of the structure; however, since an eventual incombustible surface (covering) layer and heat release of layers in time have no effect in the calculation, the real behaviour of the construction is neglected and may cause conservative results when using this method. This paper introduces a project on fire safety evaluation of a load-bearing straw-bale construction. With respect to the current scarcity of data describing fire characteristics and fire performance of straw as structural elements, the main goal of the project was to enhance the knowledge of fire behaviour of this material by acquiring new data in full-scale fire test of an experimental straw-bale house. This contribution focuses on experimental determination of fire openness of combustible external walls with incombustible surface and aims to assess their fire risk and contribution to fire growth and flame spread.
EXPERIMENTAL STRAW-BALE HOUSE

The experimental object was planned, constructed, tested, and burned during one-year period; besides the fire testing, other issues such as labour time dependency or thermal stability were investigated. It was designed as a single-storey, stand-alone building with ground floor dimensions of 4.0 × 6.0 m and a height of 3.5 m with two symmetrical connected rooms. Each room had two openings: a wooden door (0.7 × 2.0 m) on the shorter side of the building (western and eastern façade) and a plastic, double-glazed, window (0.8 × 1.4 m) on the southern façade. To compare influence of the openings, the northern façade was left without any opening, see Fig. 1.

To prevent moisture adsorption, the building was founded on concrete blocks. The walls were made of compressed straw bales having approximate dimensions of 0.60 × 0.40 × 0.35 m with initial density estimated of 130 kg/m³. The straw bales were placed between a lower and upper wooden frame, where every row of bales was connected with the previous one with several reinforcement bars. Doors and windows were installed in wooden frames (cases). To provide structural stability, the whole construction was tied up with steel stripes. On the upper frame, wooden beams covered with OSB boards from both sides and water-proof insulation were laid as a roof construction, thermally insulated with mineral wool between the beams. The roof composition was designed according to Eurocode with REI 60, this evaluation was addressed in a parallel research. The straw bales were covered with an inner and outer plaster (approximately 50 mm in thickness), which due to research purposes varied in mixtures of clay (in-situ quarried clay, prefab clay mixture, or prefab lime-based clay), in reinforcement of the plaster (an inner plaster with reinforcement wire-mesh was used in one of the rooms), as well as in a way of its application: the plasters were cast either by professional worker, by trained students, or by amateurs under supervision of a professional. The window and door frames were left exposed.

The object was designed as a mock-up of a residential house. According to the Czech Fire Standards, load bearing external constructions must fulfil R 15 fire resistance in this case. Nevertheless, despite complying this requirement, an external wall is assumed as FOA, unless the contrary is approved by a certification.

LARGE-SCALE FIRE TEST

The fire experiment was carried out at the University Centre of Energy Efficient Buildings, Czech Technical University in Prague, in September 2017. Inside the building, wooden cribs, representing a residential house fire load of 40 kg/m², were deployed equally. Every crib consisted of wooden planks. To achieve the temperature development according to ISO 834 curve, every 4th row of the planks was replaced by OSB boards to slow down the burning rate. In total, there were 423 kg of wooden planks and 191 kg of OSB boards used in 12 cribs (6 cribs placed in each room). Windows were closed, doors were partly opened in 45° angle.

For this fire test, the façade with windows (southern) and the façade without openings (northern) were observed. On the southern façade, 28 surface thermocouples were arranged into the matrix 7 × 4 on the upper part of the wall, additional 2 thermocouples were put in the middle of the window overhead. On the northern façade, 12 surface thermocouples were installed (see Fig. 2). All thermocouples were K-type of 0.5 mm diameter ended with a copper disc sheet of 10 mm diameter, mechanically mounted to surface with a screw right next to the disc. Overall surface temperatures were also monitored with set of thermographic cameras. Heat flux meters (Schmidt-Boelter gauges, ranged up to 100 kW/m²) were installed in the distance of the calculated separation distance only for windows. Unfortunately, the connection with the gauges was lost in the early minutes of the test and data describing heat flux were unavailable.
The fire test started at 10:50, two minutes after, all wooden cribs were simultaneously ignited with petrol channels. After 4 minutes, the first window broke and fire started to affect the southern façade. The second window broke after 8 minutes. 11 minutes after ignition, fire spread through openings onto the roof. In the 20th minute, the straw bales themselves were exposed to fire, when unprotected OSB frames of doors and windows fell off. The unexposed surface stood intact until the 25th minute, when the first small cracks emerged; since the 40th minute, the external plaster started to spall off. In the 55th minute, one of the window frames came down and since that moment, the straw bales located above were getting loosed. Eventually, the whole construction collapsed 64 minutes after the ignition.

![Fig. 2. Positions of thermocouples arranged on the northern (left) and southern façade (right).](image)

During the fire test, the temperature rate in the object, monitored by one shielded thermocouple placed in the geometry centre of each room at a height of 2.0 m (2/3 of the room height), copied ISO 834 curve quite well; although the real values were higher: in the 30th minute, approximately 20% difference between ISO 834 and real temperatures was identified. Maximum temperatures reaching 1.100 °C were observed from the 25th to the 48th minute, followed by a gradual decline (see Fig. 3).

![Fig. 3. Wooden cribs simulating residential house fire load (left). Development of temperature inside the tested object (right).](image)

**RESULTS**

The observations showed that the straw-bale construction with an incombustible plaster resisted in fire conditions successfully. Even when exposed due to a fallen-off plaster or due to a burnt-away casing and when caught by fire on the surface, the straw showed satisfactory behaviour: thanks to a char layer formed on the surface, almost no contribution to the fire propagation was observed in the duration of the fire test. The good behaviour in fire can be illustrated in Fig. 4 comparing the southern and the northern façade just before the object’s collapse. While the southern façade is damaged, the window overheads are completely fallen off and the straw bales are exposed to fire due to a plaster deflection, the northern façade without any opening seemed to be intact. During the fire test, the lime-based plaster started to drop off earlier – the first shard spalled in the 40th minute, whereas the clay plaster remained solid until the 63rd minute.

Since it was not intended to separate the heat flux of the fire and the eventual heat flux caused by the construction, a different approach was used to evaluate fire openness of the external walls. According to Eq. 1, the limit values for heat flux (15 kW/m² and 60 kW/m²) were transformed into limits given by temperature, i.e. maximum temperature of 444 °C for classification as FCA and 741 °C for classification as PFOA (higher temperatures represent FOA). Using the thermocouple matrix, temperatures in defined points on the surface were measured and were later compared with the thresholds.
Fig. 4. Northern (left) and southern (right) façade in the 65th minute (just before the collapse).

The northern façade (without openings)

Thermocouples and thermal images on the northern façade had shown a very limited growth of temperature. In general, temperature did not exceed 150 °C, except sporadic peaks which lasted at most for minutes. Based on the observation and experience may be assumed that a measurement mistake occurred at those points, caused mainly by the wiring affected by high temperature. Even if the peaks corresponded to the real temperatures, because they lasted a very limited time, the heat released during these sequences would be negligible. Leaving out those peaks, the highest temperature was observed in the upper part of the wall (namely thermocouple E4 on the lime-based façade and W5 on the clay façade), see black dots in Fig. 5.

Fig. 5 The highest temperatures on the northern façade (left). Development of unexposed surface temperatures in selected points (right).

The southern façade (with windows)

As can be seen in Fig. 6, in time of the maximal fire intensity (around the 30th minute), temperatures exceeding the criterion of 444 °C can be found only around the windows and near the roof (dashed-line rim). The temperatures over 741 °C occurred only at one point just below the roof and at one point near the window (namely D2 and B2; solid-line rim). According to the visual observation, there was no crack or gap in the plaster at these points, elevated temperatures on the surface were caused by the flame only, either coming from the window or from the uncovered roof. On the remaining part of the wall only lower temperatures than 444 °C were measured. The highest temperature in each line of the thermocouple matrix was observed around the western window (namely A2, B2, C3, and D2), reaching almost 800 °C (indicated as black dots in Fig. 6).

Fig. 6. The highest temperatures on the southern façade. Dashed-line rim: over 444 °C, solid-line rim: over 741 °C (left). Development of unexposed surface temperatures in selected points (right).
Separation distances evaluation

Since the openness of the tested straw-bale construction is not approved by a certification, according to the Czech Fire Standards, it must be treated as FOA. In this case, the separation distance is determined for the whole façade as $d_{FOA} = 5.57$ m. However, the fire test has shown that temperatures did not exceed the criterion for FCA at any point on the northern façade. In the case of the southern façade, this criterion was exceeded only around the windows and near the roof, what corresponded to the impact of present radiation heat flux of the fire. Thus, it can be inferred that the external walls did not emit any significant amount of heat, did not contribute to fire propagation and could be therefore assumed as FCA. The separation distance determined just for windows is calculated as $d_{FOA} = 1.64$ m, what is almost 4 meters less (for a comparison see Fig. 7). For further refinement, an FDS6 mathematical model with given heat flux in the openings corresponding the fire intensity equalling inside temperatures was used. Radiation heat flux was measured on a plane in the middle of windows, where the maximum separation distance defined by the Standard’s critical value 18.5 kW/m² was determined as 1.81 m. Albeit slightly higher, this result is comparable with the value given by the Standard for FCA; however, a difference is observable on the edges of the area, where the Standard assumes broader radiation. Results for the southern façade are compared in Fig. 7. In case of the northern façade, the separation distance given by the Standard for FOA is the same 5.57 m; the wall assessed as FCA (with no openings) has no separation distance.

CONCLUSIONS

In view of the fire openness categorisation of façades, determination of separation distances in the Czech Republic is quite strict and it limits use of environmental efficient (and combustible) materials and constructions. In this paper, contribution to fire growth of external load-bearing straw-bale walls with an incombustible surface was evaluated. The observations and measured values confirmed that the tested wall composition, even though it was not certified as a construction with a specific fire resistance, did not contribute to the fire propagation. Higher temperatures on the unexposed surface measured on the southern façade were caused by the flames and heat radiation of fire going only from the openings. Based on these results, the external walls could be therefore assumed as FCA, where separation distances are calculated only for windows. In the case of the evaluated object, the decision between FOA and FCA causes the difference in separation distances of almost 4 meters. If the FDS model is used to determine separation distances, a refined shape would be obtained lowering down the corner values. According to the executed fire test it is thought that a different approach to evaluate fire openness could be established. It can be assumed that a construction with fire resistance and solid incombustible surface is fire closed area unless it has openings installed. With openings present, the impact of such wall to separation distances is significantly lower (or even insignificant) than stated by the Czech Fire Standard.

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