EXPERIMENTAL EVALUATION OF PROPOSED MULTI-LAYERED STRUCTURE FIRE TEST METHODOLOGY

by

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The paper presents results of numerical simulation and fire tests of multi-layered structures carried out under real fire conditions. It has been shown that fire test carried out according to ISO 834 standard differs from fire test conducted under real fire conditions. A new fire test methodology has been proposed. It is suggested to use real fire temperatures during fire tests to avoid accidents and allow occupants to evacuate the building safely. The ISO fire test standard should be improved visibly. Structural solutions to reduce temperatures and temperature deformations of multi-layered structures during fire are also reviewed. It was established that the gypsum layer should be placed in the middle of multi-layered structure in order to cool the structure more efficiently during fire.

Key words: *fire test, fire curve, multi-layered structure, temperature, thermal deformations*

Introduction

Fire resistance requirements for buildings are designed with the aim to slow down the spread of fire and to ensure the structural stability of elements of buildings for a period of time sufficient for the occupants to evacuate and for firefighters to intervene [1]. However, in most cases, these requirements are created based on standardized fire test procedure. It is known that periods of time 120, 60, and 30 minutes, during which separating element must stop the spread of the fire and which are widely used (in fire resistance requirements for building elements) for decades, are determined by standard ISO fire test. Such method, where products are judged by their behavior under specific fire conditions, is still used in many countries [1].

In the majority of cases, the thermal effect obtained in real fire conditions differs from effect obtained in fire test according to ISO 834-1 standard [2]. Fire tests according ISO temperature-time curve comparing with fire tests according temperature-time curves obtained from simulation utilize lowered temperatures and can cause distorted results in real fire conditions [3]. Therefore, in order to carry out a consistent and full fire safety engineering analysis of the buildings, new knowledge of the behavior of refractory elements under real fire conditions is needed [1].

Thus, in the work [1] two fire tests were performed to investigate the spread of fire from one room to another. Two types of refractory doors were installed into drywall partition wall separating rooms. First door was made of 1 mm thick steel sheets insulated with 40 mm

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thick mineral wool layer and second door was wooden covered with wood fiber boards. Each of these doors was already tested in accordance with ISO recommended fire test.

A fire was set near the bed. After 13 minutes, the flashover was reached. The temperature of the gas was gauged by sixteen insulated thermocouples which diameter was 0.8 mm. During the first ten minutes, the gas was stratified with temperature of 40 °C in the hot zone and 20 °C in the lower zone. Then the temperature in the hot zone continued to rise to 80 °C in twelve minutes and the temperature in the lower zone rose to 30 °C. After twelve minutes, the temperature rose to 900 °C uniformly. The temperature of the unexposed to fire door surface was also measured. Thermocouples were positioned in the same way and in the same places as recommended for the standard fire test (according ISO 834).

A comparison between temperatures of the door frame and the center of the sheet measured in ISO and real fire test was performed. Temperatures changed differently in these two types of tests. Only temperatures of the door sheet increased similarly up to 80 °C in the real and standard fire tests [1]. Temperature stabilization observed in fire tests at 90 °C temperature was, however, very short in the case of real fire test.

The large deformation of steel sheet was observed rapidly. Hot gas leakage sufficient to ignite cotton pad (as used to test integrity in fire resistance tests) occurred after less than twenty minutes. The deformation took place on the top of the sheet and it led to the rapid increase of the temperature of the frame. Locally, temperature of the door frame and edges increased rapidly to 250-350 °C [1]. So, the isolation criterion of the local temperature increase to 180 °C was obtained after twenty minutes. Meanwhile, average temperature of the door sheet was less than 140 °C. To clarify the higher deformation values obtained in real fire conditions in comparison with values obtained in ISO fire test, a temperature gradient (temperature difference) which exists between exposed to fire surface of the door and unexposed surface was calculated. It was determined taking into account the average measured temperature of unexposed metal sheet [1].

In the standard fire test, loss of integrity due to the deformation determined by ignition of cotton pad was observed after seventy minutes. At that point in time, the difference in temperatures of exposed and unexposed surfaces was 793 °C [1]. The peak value of 824 °C was recorded five minutes ago. These values were achieved after seventeen (793 °C) and eighteen (824 °C) minutes in real fire conditions [1]. It was obtained that the difference in temperatures of exposed and unexposed to fire door surfaces can be used as control parameter describing the behavior of steel doors under fire conditions.

Steel doors with fire-resistance ratings E60 (integrity) and EI45 (integrity and insulation) obtained in the standard (ISO) fire test, have reached fire resistance limit in real fire after less than twenty minutes [3].

In the case of wooden door, standard fire tests carried out according to ISO standard also ensure lower temperatures compared to temperatures obtained under real fire conditions. As it is presented in [4], wood burning rate corresponding to the temperature-time curve for ISO fire test is equal to 0.5 mm per minute for hard wood and 1 mm per minute for wood panels. In the case of wooden fire doors discussed in the work [1], the wood is similar to the wood panel and its burning rate is considered as 1 mm per minute. In standard fire test, a hole in wooden door was observed 27 minutes later after fire starting. The door thickness was 40 mm. Thus, the average burning rate was equal to 1.1 mm per minute, which is close to the value given in [4]. However, in real fire tests, the hole appeared after sixteen minutes only. In this case calculated rate was 2.5 mm per minute, so the difference is obvious. Sometimes the wood is impregnated with ammonium salt to protect against heat, but this causes other undesirable effects [5].

Analysis of steel structures subjected to the fire has shown that their deformations depend on the insulating material used [6]. So, in the work [7] steel door with adjustable steel frame inserted into brick wall was exposed to fire in accordance with ISO 834-1 standard [2]. In addition thermocouples located on unexposed surface (according ISO), twelve additional thermocouples were inserted inside the door frame at various distances from heat source. To reduce the effect of thermal gradients on signals from thermocouples, they were arranged along isothermal plane. The evolution of temperatures measured by thermocouples was later used to validate the results of 2-D transient thermal analysis which was also carried out. Created numerical model was used to determine the influence of boundary conditions and filler materials on temperature evolution. For calculation of two- and 3-D temperature distribution inside the door frame Physibel VOLTRA software was used. The model consisted of massive brick wall and adjustable door frame. The door itself was not included into the model, but its intersection with door frame was taken into account as surface with adiabatic boundary conditions. The assumption was made that there was no heat flow perpendicular to this surface.

Obtained results showed that suitable model was chosen for numerical simulation. It ensures reliable results only if during the test no openings occur at the door clearance to allow the hot gases to escape into the room. This assumption is equivalent to integrity criterion satisfaction. Assuming that integrity criterion is satisfied, it can be stated that protection of unexposed side of the steel frame from radiant heat can be achieved by partially filling of the space between door frame and brick wall. Complete filling of this space with insulating material or material with high thermal mass (for instance, gypsum) has little influence on temperature evolution of unexposed side of the frame [7].

In keeping with the assumption that integrity criterion is satisfied, the case of the door *opening away from* the fire meets stricter fire resistance requirements than in the case of door *opening into* the fire [7]. This happens due to the surface of the door frame facing the fire, which is much larger in the first case [7]. In the case of steel door and steel frame, fire tests and numerical analysis for *opening away fr*om the fire configuration at the same time would suffice to assess the *opening into* the fire configuration [7].

In accordance with EN 1634-1 standard [8], the integrity criterion is met for the *opening into* the fire assembly as long as this criterion is satisfied for the *opening away from* the fire assembly. However, the situation differs for wooden door due to the burning of wood. In the case of butted frame, the situation is also different [7].

The flame stabilization mechanism was shown in work [9], in which two-layered structures were analyzed. However, it was only laboratory testing. Other authors [10, 11] experimentally and numerically investigated temperatures of the gas stream and its impact on indoor structures.

Proposed fire test methodology

Using the graph of temperature change obtained during real fire instead of provided in standard, fire test algorithm was formulated that differs from ISO algorithm [2] in that the furnace temperature control is performed according to the graph shown in fig. 1. Initially, the temperature is quickly raised to 1180 °C, fig. 1, after ten minutes from the start of the test it reaches 1200 °C value, then it is gradually lowered to 1000 °C per one-hour period during which evacuation of people from a building can be carried out.

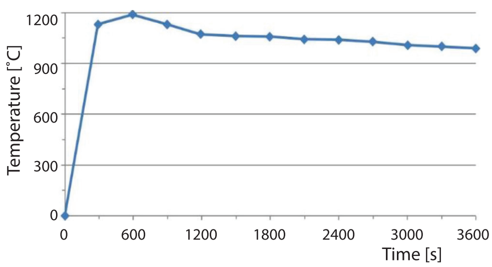

Figure 1. Temperature *vs.* time curve

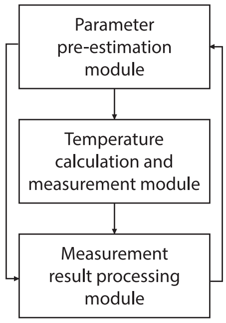

Figure 2. Modules of proposed fire test system

Studies have shown that door fire tests are standardized in most cases. Technique proposed by ISO 834-1 standard [2] is currently used. When taking into account real fire conditions, fire test system must combine the following main modules, fig. 2: module of pre-estimation of parameters of multi-layered structure, temperature calculation and measurement module and temperature measurement result processing module. Parameter pre-estimation module allows to estimate a-priori parameters of the structure which are later used to establish initial parameters of temperature measurement subsystem. Then measurements of temperature variations at predetermined points of the structure are performed. The aim of feedback system of temperature measurement result processing module is to adjust a-priori set of parameters of thermodynamic model of the structure.

In detail, fire test technique can be divided into structural blocks shown in fig. 3.

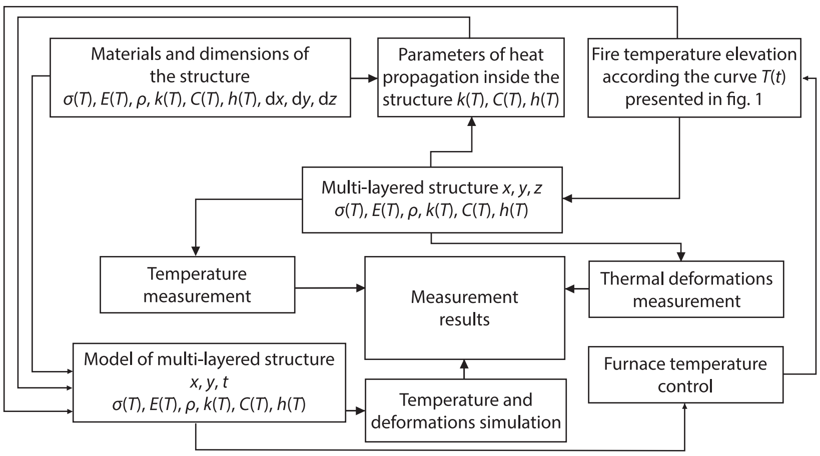

Figure 3. Detailed scheme of proposed fire test technique

Initial parameters of insulating layers of the structure (ρ, $E(T)$, $\sigma(T)$, $k(T)$, $C(T)$, $h(T)$, dx, dy, and dz) should be considered as a-priori parameters of multi-layered structure. These parameters are known in advance and are taken from tables or graphs. Temperature evolution graph inside the fire test furnace is determined next, fig. 1.

A numerical thermodynamic model of the structure and fire test model are also developed, fig. 3, in accordance with initial parameters of the structure.

Obtained temperature measurement results are compared with numerical simulation results. After comparison of experimental results with those obtained from numerical analysis, the procedure of adjustment of initial parameters of the model is carried out.

After combining parameters of measurement system, thermal deformations are measured in the next stage, structural degradation is identified if it occurs and its parameters are established. According to results, the design of the structure is improved and further tests confirm or reject the assumption of its effectiveness under fire conditions.

Summarized steps of proposed fire test algorithm under real fire conditions are following:
– identification of initial a-priori parameters of multi-layered structure,
– determination of parameters of thermodynamic model,

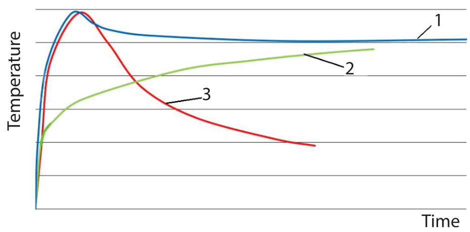

Figure 4. Temperature-time curves:
1 – proposed furnace temperature-time curve, 2 – the standard furnace temperature-time curve according ISO 834-1 [2], and 3 – temperature-time curve obtained under real fire conditions

- comparison and adjustment of parameters of multi-layered structure and model,
- control of temperature evolution in the furnace according to real fire temperatures,
- measurement of temperatures and thermal de formations,
- determination of limit values of thermal deformations, and
- confirmation of the efficiency of the structure or improvement of its design and further investigations.

The comparison of temperature-time curves is shown in fig. 4.

Results and discussion

It has been observed that some multi-layered structures are deformed sufficiently under real fire conditions. Therefore, large gaps are formed near joining elements through which the fire penetrates. Such large deformations due to the sudden rise in temperature are formed very rapidly, which means that not all products tested according to EN 1634-1 standard [8] ensure fire resistance for a specified time interval.

Multi-layered structure consisting of solid steel sheets, fig. 5, is most likely to deform and if such structure tested according to EN 1634-1 [8] standardized fire test fully satisfies fire resistance requirements, the duration of fire resistance of such structure in the case of real fire is reduced by about half.

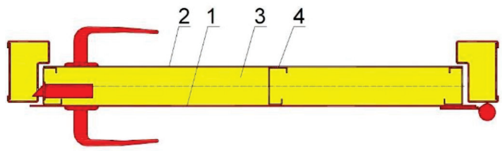

Figure 5. Deformed multi-layered structure (cross-section is shown on the right) consisting of solid steel sheets separated by stone wool insulating layer: *1 – steel sheet (1.5 mm thickness), 2 – steel sheet (0.8 mm thickness), 3 – stone wool insulation layer (37 kg/m^3, 50 mm thickness), and 4 – stiffness profile*

Thermal deformations of the structure were studied numerically using SolidWorks® Simulation software [12]. Real scale 3-D model of multi-layered structure was created for this aim. As shown in previous work [13], the percent differences between temperatures of the structure obtained in numerical simulation by similar model and measured in fire test do not exceed 8%. Model was divided into 3-D 4-node tetrahedral finite elements of different sizes. The largest element (stone wool layer) was divided into 44.5015 mm size elements. Hinges and latch were divided into 4.34324 mm size elements. Total number of FE used was 217268, number of DoF – 6474, number of nodes – 47857. The following boundary and initial conditions were used: initial temperature of structure – 13 ºC, duration of heating – 3600 seconds. Temperature of heated wall of the fire door was increased according the graph, presented in fig. 1. Structure was analyzed using a transient type of analysis and bonded type of contacts. Door frame was rigidly fixed at 8

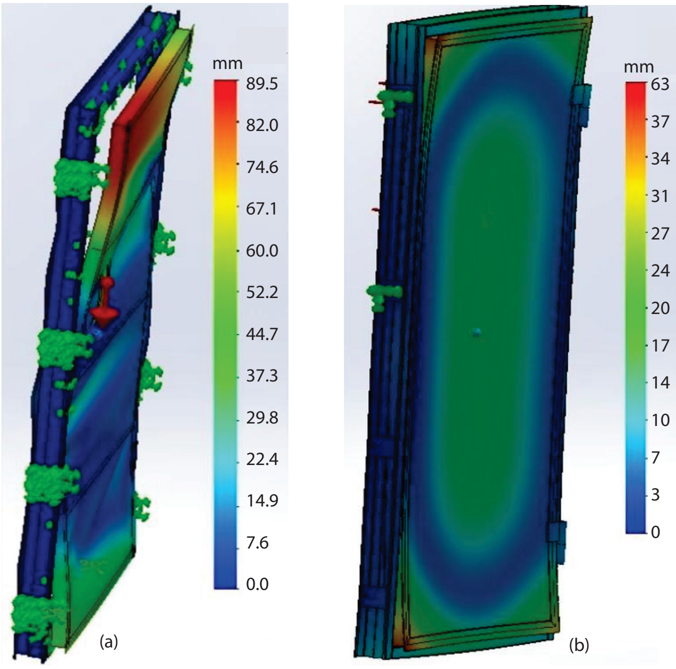

Figure 6. Deformations of multi-layered structure after fire test according to temperature-time curve, fig. 1, (a) and ISO curve (b) (numerical simulation results)

points as in case of fire test. Calculation interval was 600 seconds. FFEPlus iterative solver which is the most efficient for models with great number of DoF was used for computer simulation.

Numerical simulation results, fig. 6(a), show that deformation of the structure, fig. 5, makes up 90 mm on the left side and 65 mm on the right side, that is, the deformations increased by about 40% compared to the case when the ISO curve was used, fig. 6(b). Such increase in deformation often become critical and multi-layered structure (previously tested according with EN 1634-1 standard [8]) in the case of real fire will not satisfy fire resistance criteria determined in its fire test carried out in accordance with mentioned standard.

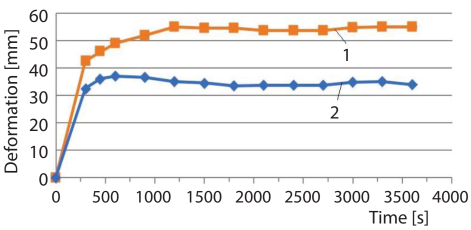

Figure 7. Structure, figs. 5 and 6, central point deformation *vs.* time graphs obtained under ISO (2) and real fire conditions (1)

Simulation results showed that multi-layered structure would degrade earlier and stronger compared to fire test of the same structure carried out in accordance with EN 1634-1 standard [8]. Structure deformation *vs.* time graphs which were obtained using ISO curve and real fire temperature values, fig. 1, are presented in fig. 7.

Graphs shown in fig. 7 confirm that the same product in the event of real fire will not meet fire resistance requirements obtained according standard fire test, and the proposed technique assesses the effect of real fire temperature.

Figure 8. Multi-layered structure consisting of narrow steel elements after fire test

Multi-layered mechanical structures consisting of smaller area steel elements deform less under real fire conditions, fig. 8. Each element is deformed in different directions, so there are no large total deformations that could strongly bend the entire structure. Such multi-layered structures exhibit significantly better fire resistance. In the case of real fire, the temperature is higher, fig. 1, than given in standard, but it does not significantly affect fire resistance of the structure, since no large gaps are formed between joining elements. Having multi-layered steel carcass of this type it is enough to select inner and outer insulating layers to satisfy the requirements.

Figure 9. Deformation restriction mechanism with changed geometric dimensions after fire test

Another effective way to reduce deformations and stop gap propagation between connecting elements is to improve the design of multi-layered structure. For example, special mechanism can be installed into the structure which, depending on variation in ambient temperature, changes its geometric dimensions and at the same time form connection with another adjacent structural element. Such mechanism can be installed into one of inner layers of multi-layered structure and this will allow to keep the same aesthetic appearance of the product. One of the mechanisms developed to limit thermal deformations is shown in fig. 9.

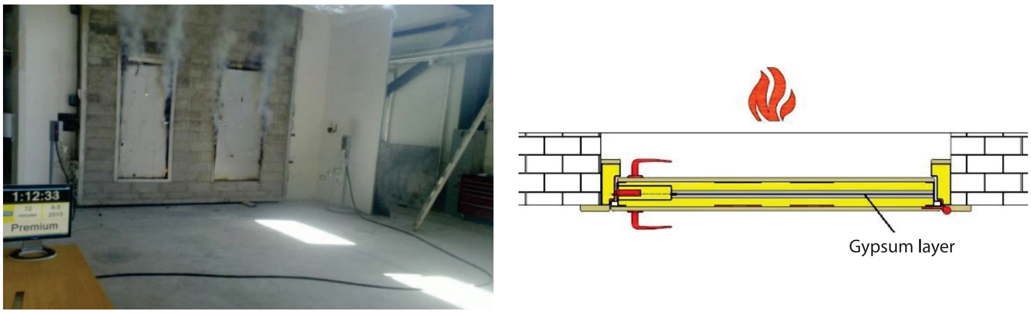

Figure 10. Deformed multi-layered structure (cross-section is shown one the right) consisting of steel strips separated by stone wool and gypsum insulating layer located in the middle of the structure

This specially designed device perfectly reduced deformations during fire tests. Elements of the structure remain connected to each other throughout the test, so the flame and hot gases from the furnace could not enter the environment.

Location of insulating fire-resistant layers in the structure has a significant influence on temperature propagation over time. Experiments have shown that multi-layered structures with insulating gypsum layer located closer to the heat source provide more efficient cooling, but it lasts a shorter time than in structures in which insulating layer is located in the middle of the structure, fig. 10. Temperature *vs.* time graphs are presented in fig. 11.

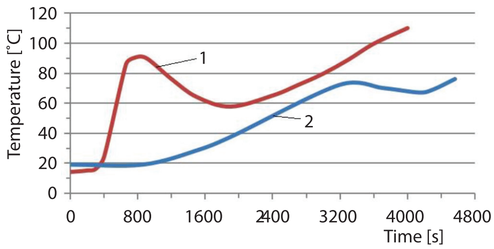

Figure 11. Average unheated surface temperature - time graphs obtained during tire tests of multi-layered structures (doors) consisting of steel strips separated by stone wool and gypsum layers: *1 – with insulating gypsum layer located closer to the heat source and 2 – with insulating gypsum layer located in the middle of the structure, fig. 10*

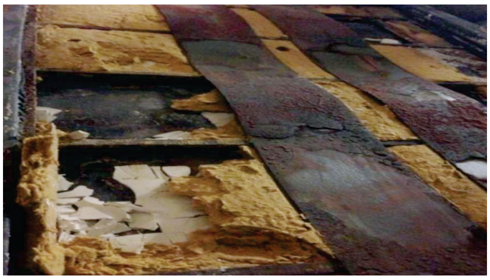

Figure 12. Gypsum layer after fire test of multi-layered structure

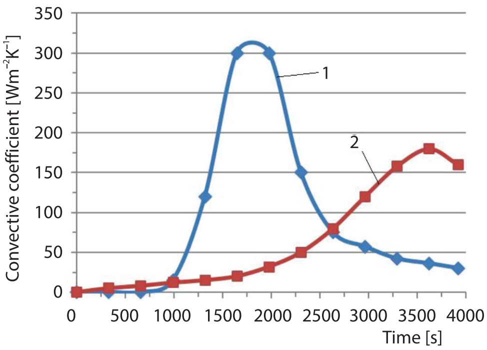

Figure 13. Convective coefficient of gypsum layer *vs.* time graphs obtained during fire tests of multi-layered structures: *1 – with insulating layer located closer to the heat source and 2 – with insulating layer located in the middle of the structure*

Results of fire test of multi-layered structure with insulating gypsum layer located closer to the heat source, fig. 11 and 1 curve, have shown that sudden rise in temperature destroys gypsum insulating layer which immediately turns into powder and falls to the bottom of the structure. Therefore, such multi-layered system cannot ensure uniform cooling process across entire area of the structure. The best results were obtained in fire test of multi-layered structure with gypsum layer located in the middle of the structure. The highest gypsum convection level was achieved after almost an hour from the start of fire test, fig. 11 and 2 curve, and it lasted about 20 minutes until the wood finish was ignited. As can be seen from fig. 12, about 30% of gypsum layer was disintegrated only and it would have cooled down the structure if finishing materials would be of higher fire resistance level.

According to obtained graph of temperature changes during fire test, value of convective coefficient of gypsum layer was calculated as well as its variation over time. Convective coefficient *vs.* time curves presented in fig. 13 accurately reflect observed degradation changes of the structure.

Conclusions

Proposed fire test technique evaluates real fire temperatures and therefore, allows the structure to resist fire for much longer period of time, which is sufficient for people to evacuate.

It has been found that thermal deformations of multi-layered structure tested according proposed fire curve increased by about 40% compared to the deformation values obtained in ISO fire test. Results confirm that fire tests conducted according to ISO standard do not satisfy requirements of modern multi-layered structures because of lowered temperature values compared to obtained under real fire conditions.

To ensure more efficient cooling of multi-layered structure during a fire, it is better to place the gypsum cooling layer in the middle of the structure rather than closer to the fire source.

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