Journal of Engineering Science and Technology
Vol. 11, No. 9 (2016) 1333 - 1343
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INVESTIGATION OF THERMAL BEHAVIOR OF MULTILAYERED FIRE RESISTANT STRUCTURE

R. GUOBYS, V. VEKTERIS, V. MOKSHIN*

Vilnius Gediminas Technical University, Department of Mechanical Engineering
J. Basanavičiaus str. 28, LT-03224, Vilnius, Lithuania
*Corresponding Author: vadim.moksin@vgtu.lt

Abstract

This paper presents experimental and numerical investigations of thermal behavior under real fire conditions of new generation multilayered fire resistant structure (fire door, dimensions $H \times W \times D$: 2090 × 980 × 52 mm) combining high strength and fire safety. This fire door consists of two steel sheets (thickness 1.5 and 0.7 mm) with stone wool (ρ = 33 kg/m^3, k = 0.037 W/mK, E = 5000 N/m^2, υ = 0.2) insulating layer in between. One surface of the structure was heated in fire furnace for specified period of time of 60 min. Temperature and deformation of opposite surface were measured from outside at selected measuring points during fire resistance test. Results are presented as temperature-time and thermal deformation-time graphs. Experimental results were compared with numerical temperature field simulation results obtained from SolidWorks® Simulation software. Numerical results were found to be in good agreement with experimental data. The percent differences between door temperatures from simulation and fire resistance test don't exceed 8%. This shows that thermal behaviour of such multilayered structures can be investigated numerically, thus avoiding costly and time-consuming fire resistance tests. It is established that investigated structure should be installed in a way that places thicker steel sheet closer to the potential heat source than thinner one. It is also obtained that stone wool layer of higher density should be used to improve fire resistance of the structure.

Keywords: Fire resistant multilayered structure, Fire resistance test, Temperature, Thermal deformations, Numerical model.

1. Introduction

Multilayered or sandwich structures are composite constructions of alloys, plastics, wood or other materials consisting of a core placed between two hard

Nomenclatures

D	Depth, mm
E	Young's modulus, N/m^2
H	Height, mm
k	Thermal conductivity, W/mK
p	Pressure, Pa
T	Temperature, ºC
t	Time, min
W	Width, mm

Greek Symbols

Δ	Deformation, mm
ρ	Density, kg/m^3
υ	Poisson's ratio

Abbreviations

CEN	Comité Européen de Normalisation (European Committee for Standardization)
DoF	Degree of Freedom
FE	Finite Element

outer sheets (skins). The core is usually made of lightweight foam. Solid, honeycomb, web, tubular or corrugated/truss cores are used in many engineering applications as well. Foams are usually made from plastics or ceramic materials, even from foamed metals. Honeycomb, web or corrugated cores are made from metal or glass-reinforced plastic. Synthetic organic adhesives are used to assembly sandwich components. Facing sheets are usually made from high-strength materials. In all loading cases primary loads are carried by outer sheets and transverse shear loads are carried by the core [1].

Multilayered structures are not only used as load carrying structures. In order to protect escape routes and people from fire modern civil engineering constructions often contain multilayered mechanical structures which can withstand high temperatures (up to 360ºC) for long period of time [2, 3]. Such fire resistant structures are widely used in residential, commercial and industrial buildings [4], thermal and nuclear power stations, space stations, ships [5, 6] and airplanes. They also are used as fixed or mobile partitions to protect premises and people from fire.

The most important component of fire resistant multilayered structures is core layer. In some cases gas and polymer fillers are used in structures [7], but these structures are expensive and complicated. The wood exhibits good thermal insulation properties, but its fire resistance time is limited due to high combustion rate (approx. 2 mm/min) [8, 9]. The gypsum and stone wool have good thermal insulation properties and can resist the spread of fire [10, 11].

Door resistance to the fire is very important for fire safety of the whole building. The main disadvantage of conventional fire doors is that they are deformed at high temperatures. Metal sheet located on the heated side expands, however opposite sheet which is not affected by high temperature doesn't change its dimensions. The structure deforms forming the clearance at the middle, bottom or top of the jamb. The air is allowed to reach the fire; heat and smoke penetrate into the neighbor rooms. Multilayered fire doors can provide suitable fire isolation and meet growing strength and fire safety requirements [2].

Fire resistant structures must satisfy certain requirements [12, 13] relating to their high-temperature stability. Experimental investigations of such structures (fire resistance tests) are carried out in accordance with special specifications [12] and provide the basis for much of the certification of fire protection systems [14]. Standard fire resistance tests are conducted in large fire furnaces. These investigations comprise measurements of temperatures and thermal deformations at certain points of the structure exposed to the fire [13]. Fire resistance of the test specimen is defined as time (expressed in minutes) of fire exposure during which corresponding fire resistance functions are maintained despite fire actions. According to the standard, three criteria are used to define the fire resistance: load-bearing capacity, thermal insulating function, and integrity separating function. In the test, the specimen is exposed in the furnace to the temperature rise which shall be controlled so as to vary with time within given limits according to the particular test being used [15].

Fire resistance tests are very expensive and consequently, the number of tests of each prototype of the structure ordinarily is limited to only one or two tests. Hence, there are no possibilities to evaluate test results statistically. Actual quality of structural materials in single fire resistance test can be considered as a random sample from a wide variety. Therefore, it can generally be higher than the quality guaranteed by manufacturer and consequently, mechanical properties of the material can be higher than standard [16]. The next disadvantage is that results of fire resistance tests are usually difficult to extrapolate to other scenarios [4].

Available simplified methods of calculation of temperature of fire exposed structures are, as a rule, based on assumption of uniformly distributed temperature over cross section and length of the structure at each time of fire exposure. These methods are suitable only for homogenous materials. However for certain types of steel structures, for example, beams with slab on the upper flange, significant temperature variation occurs over the cross section as well as in longitudinal direction during the fire resistance test. A simplified analytical method which neglects this influence gives an underestimation of the fire resistance in relation to the result obtained from the fire resistance test [16].

Numerical analysis involves a study of methods of computing numerical data. In many problems this implies producing a sequence of approximations by repeating the procedure again and again [17].

Numerical methods have one common characteristic: they invariably involve large numbers of tedious arithmetic calculations. With the development of fast, efficient digital computers, the role of numerical methods in engineering problem solving has increased dramatically in recent years [18].

Numerical simulation reduces the need to conduct fire tests and appears as a powerful tool to predict fire growth on composite (and other) structures at real scale. It can also be used to further understand the physical processes that occur. But, the main advantage of this approach is the flexibility and the possibility of a rapid and cost-effective assessment of the fire performance in various scenarios compared to experimental approach [5].

The main challenge to modeling the fire behavior of composite is the accurate analysis and representation of thermal, physical and failure processes, which control the thermal decomposition. It is further complicated because many processes are intertwined and are acting independently of one another [5]. Sandwich structures have specific structural composition and cannot be considered as homogeneous materials. Numerical modeling of thermomechanical response of sandwich structures requires detailed knowledge of thermal behavior and properties of all parts in contact – outer skins, core and interfaces [1]. The numerical model needs to be fed by a large amount of input data on the thermophysical properties of each element constituting the simulated material in the temperature range of interest [5].

Despite that many researchers have developed different models to predict heat and mass transfers, decomposition, softening and failure of sandwich structures, the robustness of the models is still stalled by a poor capability to model accurately the complex phenomena of the combustion and decomposition processes [5]. Furthermore, the interaction between the solid and gas phases is not analyzed. Instead, many models ignore the dynamics of the fire events and simply assume that the composite surface is uniformly heated under controlled heat flux or temperature conditions. Most of the past studies have been performed mainly at small scale. Therefore, the ability of current fire modeling tools to properly predict fire development (e.g. temperature spread) on composite material is questionable. The phenomena are more complex at large scale [5].

Real-scale computer simulation of thermal behavior of fire resistant multilayered structure with stone wool core layer was performed in this work. Simulation results were compared with experimental results obtained from the fire resistance test. Investigations were carried out on two fire doors that open into and away from the furnace; these are the only two types of configurations used in buildings.

2. Experimental and Simulation Technique

Multilayered fire resistant structure (fire door) consisting of two parallel steel sheets (ρ = 7870 kg/m^3, E = 2.05·10^{11} N/m^2, υ = 0.29) separated by stone wool (ρ = 33 kg/m^3, k = 0.037 W/mK, E = 5000 N/m^2, υ = 0.2) layer was chosen as object of investigation. Other temperature or time-dependent properties of materials of the structure are presented in work [19] as parameter versus temperature or time graphs. Cross section of the structure is shown in Fig. 1. First steel sheet had a thickness of 1.5 mm, second – 0.7 mm. The thickness of stone wool layer was 50 mm. Fire door was reinforced with 1.5 mm thick vertical inner steel stiffening rib located in the middle of the structure. Door dimensions $H \times W$ were 2090 × 980 mm.

Because of asymmetry of investigated structure, two fire doors (Fig. 2(a)) were installed into a brick wall (200 mm thick) as it is shown in Figs. 2(b) and 3. The wall with installed specimens was then hermetically fastened to the furnace as it is shown in Fig. 2(b).

The temperature inside the furnace was controlled using six thermocouples distributed evenly inside the furnace. Thermocouple signals were transmitted to computer which compares measured and programmed temperature values and controls fuel valve of the furnace. Initial temperature inside the furnace at beginning of the fire test was equal to 13ºC. Then it was increased according recommendations [12] (Fig. 4.). Pressure inside the furnace was kept constant ($p = 20$ Pa) throughout the whole fire test. The fire test was terminated after 60 min.

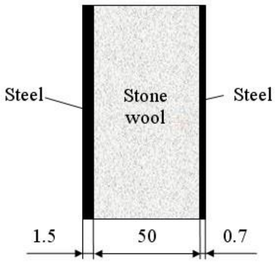
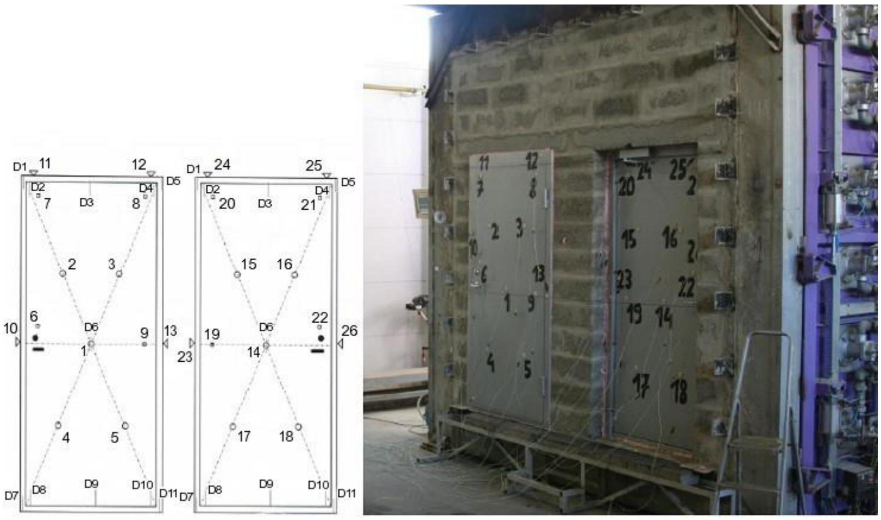


Fig. 1. Cross section of multilayered structure.

Door temperature outside the furnace during fire resistance test was measured by thermo elements attached to the door at measuring points 1–26 (Fig. 2) with 1 minute intervals. Thermal deformations of the structure were measured with respect to the wall at points D1–D11 shown in Fig. 2(a). For that purpose three horizontal steel strings were attached to the wall before investigated structure, these strings are seen in Fig. 2(b). Thermal deformations of the structure were measured with respect to these strings by means of caliper.



a) b)

Fig. 2. Scheme of investigated multilayered structure (a) (shown from both sides) and picture of the wall with doors fastened to the furnace (b): 1–26 – temperature measuring points, D1–D11 – deformation measuring points.

The structure was also investigated numerically using SolidWorks® Simulation software. Real scale 3D model of investigated structure was created for this aim. It was divided into 3D 4-node tetrahedral FE 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 245 554, number of DoF – 7204, number of nodes – 54 143. The following boundary and initial conditions were used: initial temperature of structure – 13ºC, duration of heating – 3 600 s. Temperature of heated wall of the fire door was gradually increased to 950ºC according the graph, presented in Fig. 4. Structure was analyzed using a transient type of analysis and bonded type of contacts. Door frame was rigidly fixed at 8 points as in case of fire test. Calculation interval was 600 s. FFEPlus iterative solver which is the most efficient for models with great number of DoF was used for computer simulation.

Fig. 3. View of the furnace during the fire test.

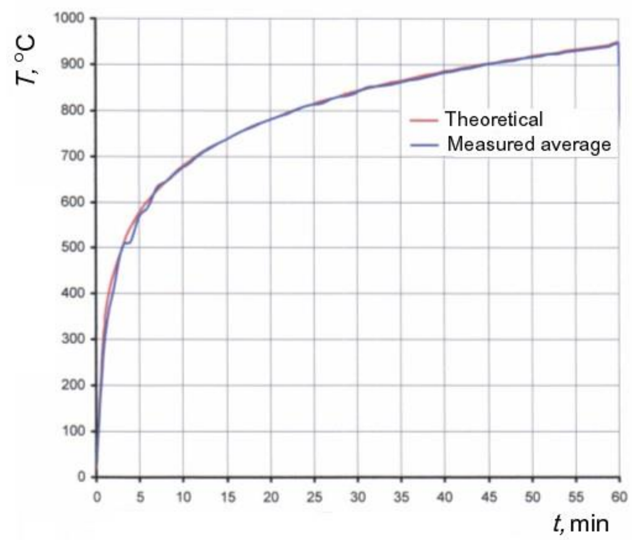
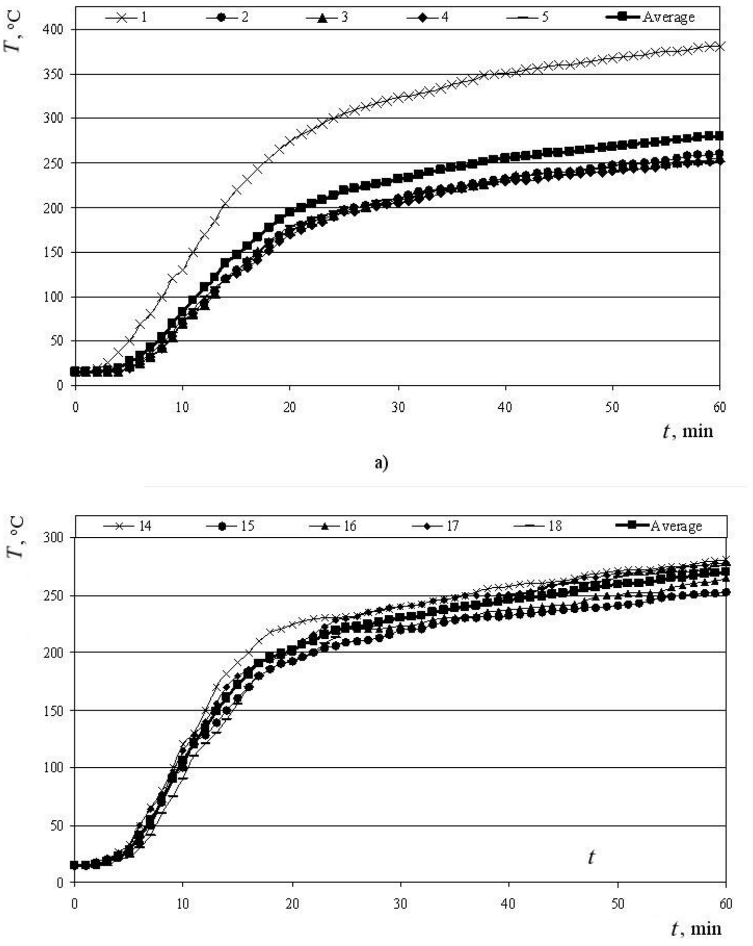


Fig. 4. Temperature inside the furnace versus time curve.

3. Simulation and Experimental Results

Experimental results (from fire resistance test) are presented in Fig. 5. Temperature of the right door (Fig. 2(b), its 1.5 mm thick steel (Fig. 1) sheet was exposed directly to fire) measured at points 14–18 increased rapidly to 200ºC during the period of 20 min then increased more slowly to 270ºC approximately at 1.75ºC/min rate (Fig. 5(b)). Temperature of the left door (Fig. 2(b), its 0.7 mm thick steel (Fig. 1) sheet was exposed to fire) measured at the points 2–5 increased similarly, however temperature of the point 1 increased to 370ºC in the end of fire resistance test (Fig. 5(a)). This rise of temperature increases the risk of fire penetration through the structure, therefore case shown in the left of Fig. 2(b) was chosen for numerical analysis. Temperature field computer simulation results are presented in Figs. 6 and 7. It is evident from that temperature graph (shown in Fig. 7) obtained from the simulation tends to coincide with experimental one (Fig. 5(a)).



a)

b)

Fig. 5. Temperature of investigated structure as function of fire test time: (a) – left (from viewer‘s perspective) door (Fig. 2(b), Fig. 3), points 1–5 (Fig. 2(a)), (b) – right door (Fig. 2(b), Fig. 3), points 14–18 (Fig. 2(a)). Results of direct measurements.

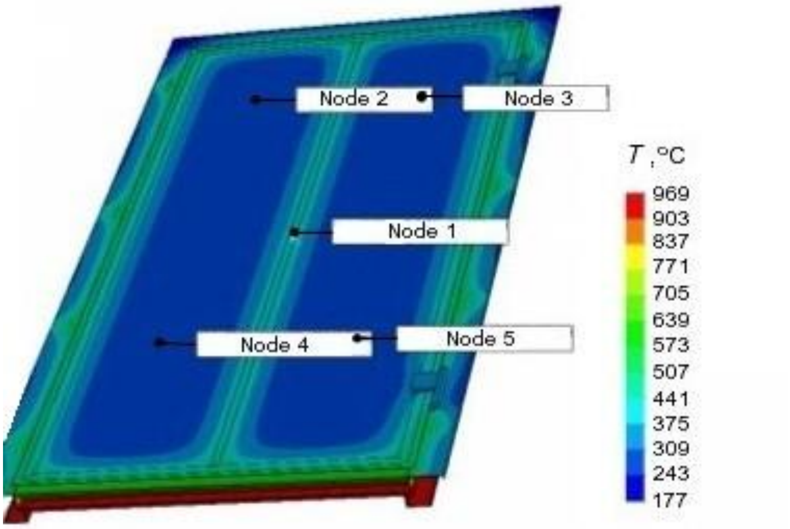


Fig. 6. Temperature distribution in investigated structure (left from the viewer‘s perspective, Fig. 2(b), Fig. 3) after the 60 min fire test (nodes 1–5 correspond to measuring points 1–5 shown in Fig. 2). Results obtained from SolidWorks® Simulation software.

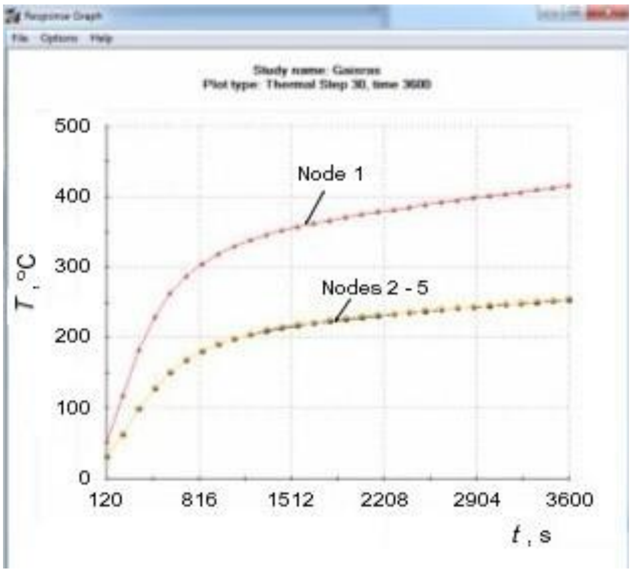


Fig. 7. Temperature at nodes 1–5 (correspond to measuring points 1–5 shown in Fig. 2) versus fire test time graph. Results obtained from SolidWorks® Simulation software.

The “self-cooling” effect noticed for similar structure with stone wool layer and gypsum plate [2, 20, 21] was not observed for investigated structure with stone wool layer only.

Thermal deformation measurement results are presented in Fig. 8, Tables 1 and 2. It is seen from Fig. 8 that thermal deformations of the central point of the door reached their maximum after 10 min of the fire resistance test. The structure deformed up to approximately 35 mm towards the fire and then deformations remained at the same level during the rest 50 min of the fire resistance test.

It can be seen from Tables 1 and 2 that thermal deformations were larger in the case when 0.7 mm thick steel (Fig. 1) sheet of multilayered structure was exposed directly to fire (Fig. 2(b), left door from viewer‘s perspective). The largest deformations were obtained in points from which the steel stiffening rib is the most distant.

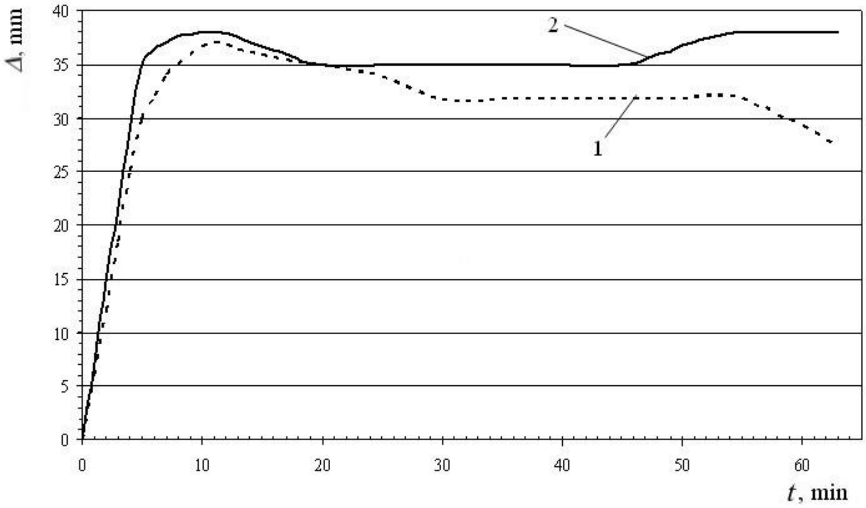


Fig. 8. Deformation of the centre point of the door (D6, Fig. 2(a)) as function of the fire test time: 1 – left (from viewer‘s perspective) door (Fig. 2(b), Fig. 3); 2 – right door (Fig. 2(b), Fig. 3). Results of direct measurements.

Table 1. Deformations of the left (from viewer‘s perspective) door (Fig. 2(b), Fig. 3) measured at deformation measuring points D1–D11 (Fig. 2(a)) at the end of the fire test.

Measuring point	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11
Δ, mm	-25	-19	3	1	8	27	-20	-18	4	3	16

Table 2. Deformations of the right (from viewer‘s perspective) door (Fig. 2(b), Fig. 3) measured at deformation measuring points D1–D11 (Fig. 2(a)) at the end of the fire test.

Measuring point	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11
Δ, mm	22	18	12	-1	0	38	12	11	10	-5	-3

4. Conclusions

Some concluding observations from numerical and experimental investigations are given below.

- In order to minimize risk of fire penetration through investigated multilayered structure, it is advisable to place thicker steel sheet closer to the heat source than thinner one.
- Temperature differences between numerical and experimental data are only about 2–8%.
- Obtained results show that thermal behavior of multilayered structure can be investigated numerically, thus avoiding costly and time-consuming fire resistance tests.
- Multilayered fire resistant structure that contains stone wool of low density (33 kg/m³) and steel sheets gets rapidly overheated. Therefore, it is necessary to use insulating layer of higher density.

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