A posteriori modelling of a fire spreading in selected types of industrial halls

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Abstract. Two different scenarios of fire development identified for two industrial halls are considered and discussed in detail. In both cases an attempt is made, using the appropriate numerical models, to describe a posteriori the spread of a fire that has already occurred in the past. The numerical model is implemented in a Fire Dynamic Simulator (i.e. FDS) computer program and used for simulation. The first considered hall is an one-storey two-aisled steel structure with an incomplete covering of its side walls. Recyclable materials were stored inside, mainly the plastic waste. The fire observed in this hall developed slowly, being repeatedly partly suppressed and then subjected to flashover again. The other building described in this contribution is an one-bay steel hall located in a transhipment terminal, in which the crude oil was stored in railroad tank cars. In this case, a fire initiated by the ignition of oil leaking from the damaged tank car and quickly intensified by the collapse of a part of the hall roof proceeded rapidly until the fuel supply ran out. The basic parameters of both models developed by the authors were calibrated on the basis of available material data as well as of the reports received from meteorological stations located in the vicinity of the destroyed halls.

1. Introduction

An inventory of the observed damage, i.e. deformations of structural components as well as their joints, plays an important role during the evaluation of the technical condition of steel bearing structure specified after fire. In general, simple visual observation combined with appropriately formulated material analysis program is insufficient to make an informed decision on possible extended service of selected structural components subjected to the episodes of at first monotonous heating due to the direct fire action of increasing intensity followed by intensive cooling during the firefighting period. In order to properly interpret and assess the state of damage after the fire it is advised to a posteriori replay the fire, which inflicted the observed damage [1]. It is not just about finding the values and distributions of internal forces actually generated in the structural members during the fire, which affected the considered structure. Thus, it is also important to verify, whether the a posteriori inventoried deformation state is formally in agreement with the a priori modelled fire plume temperature field in the nearest vicinity of structural members and the changes of basic parameters describing this field during the fire. In addition, a posteriori identification of possible local very intense heating or abrupt and nonuniform cooling episodes of the structural steel may give rise to suspicion, that adverse effects probably may have occurred in the microstructure of the steel, resulting in increased susceptibility to brittle failure during further service [2]. Changes of this type are extremely difficult to detect by direct approach, without anticipation due to the prior analysis. In this paper we intend to present two applications of the classical computer code – the Fire Dynamic Simulator (FDS) [3] to a posteriori model the development of two fires, which have occurred in real life and resulted in partial destruction of industrial steel halls [4]. Those two fires were completely qualitatively different, with different genesis, intensity and affected zone, though in both cases the obtained results proved to be useful not only in confirmation and justification of the conclusions drawn in appropriate expert appraisals but also in preparation of repair programs dedicated to both halls considered in this paper [5].
2. A fire in the steel hall of recycled materials warehouse

2.1. Description of the hall and the course of fire recreated based on eyewitness testimony

The considered hall was a single storey structure without basement, with incomplete sheathing of side walls (Figure 1). Its surface area was equal to 1314m² while the enclosed volume was 12337m³. The basic dimensions of the hall within the system axes were 36.1m x 60.0m, the maximum height at the ridge 12.2m and the distance between the system frames 10.0m. The columns have been made of rolled steel, wall beams of rectangular hollow sections while purlins have been designed and made of multi span hot rolled I beams. The sheathing has been made of profiled trapezoidal sheet metal. The structure had been designed to store recyclable materials, mostly scraps of man-made materials (plastics) [4, 5].

![Figure 1. Statical scheme of the hall described in the text](image)

The fire occurred during winter, while roof was free of snow cover, but the winds were strong. The eyewitness testimony indicated, that the fire lasted intermittently for approximately three days. The slowly burning recyclable materials faded for several times and after each fading flashed over again (Figure 2). The hall survived the fire, but the fire affected mostly the wall beams, braces and frames located at both ends of the hall. The columns of these frames sustained permanent damage in the form of bending (Figure 3). The remaining bearing elements, i.e. the roof purlins and the intermediate transverse frames have been deformed only locally or did not sustain any thermal deflections visible by naked eye. After the fire the hall has been reconstructed [4]. The a posteriori inventory indicated, that the average volumetric density of the materials stored in the hall at the time of fire was equal to 250kg/m³, while the stacking height did not exceed 3.00m.
2.2. Parameters of the numerical model applied to a posteriori simulate the fire

Due to the nature of the stored material, the data corresponding to the properties of municipal waste have been used to simulate the fire load gathered in the hall, as it was recommended in [6]. It was a good approximation because these wastes consisted mainly of plastics intended for use as recyclable material. Based on the paper [6] the burning speed of such materials may be assumed in between 0.018–0.034 kg/(m²⋅s). The heat of combustion of municipal waste usually is in between 16.7–29.0 MJ/kg. In the experimental analysis of shredded waste, composed of 62% man-made materials and 23% biomass (timber and other organic waste) of low humidity, the heat of combustion has been proved to be at the level of approximately 20 MJ/kg, as reported in the paper [6]. Considering the condition of the waste at the moment of fire initiation, and especially the lack of processing and partial exposure to precipitation the maximum rate of heat release has been estimated based on the formula:

\[ RHR_f = Qν \]  

(1)

where the heat of combustion \( Q \) has been assumed conservatively at the level of 16.7 MJ/kg, and the combustion speed \( ν \) accordingly at the level of 0.018kg/(m²⋅s). The value of \( RHR_f=300\text{kJ/m}^3 \) estimated in this manner is close to the heat release rate assigned in the code [7] to offices and buildings of collective residence. The fire development scenario in this structure, according to the recommendations contained in [7], has been modelled as a \( t \)-square fire with subsequent phases described by the following equations (Figure 4):

\[ Q(t) = \begin{cases} 
10^3 t/t_α & \text{when } 0 \leq t < 328 \text{ s} \\
300 & \text{when } 328 \leq t < 29400 \text{ s} \\
-0.012t + 652.8 & \text{when } 29400 \leq t < 54400 \text{ s}
\end{cases} \]  

(2)

In those equations the variable \( t \) represents the fire duration time measured in seconds, while the set value \( t_α \) stands for the time after which the heat release speed (in other words the fire intensity) reaches the threshold of 1MW.

The whole main bay area of the considered hall has been assumed as affected by the fire (burning fuel). As the information acquired from the eyewitnesses indicated that the fire burned for several days, the fire has been classified as a slow burning one in the sense of classification published in the code [7], this in turn means, that \( t_α=600\text{s} \). Based on this it was estimated, that the growth phase took 328s, the fully developed fire phase took approximately 8 hours, while the fire extinguishing phase took additional 7 hours (Figure 4) [8]. According to the conventional \( t \)-square fire model it was assumed in addition, that the beginning of the fire extinguishing phase started after 70% of the combustible material burned out. The chemical composition of the burning material, needed to
perform calculations, has been assumed in a simplified manner following the advice found in [3], with the values of functions responsible for generation of carbon monoxide and soot equal to: CO\_YIELD=0.63 and SOOT\_YIELD=0.163, respectively. Based on the archival meteorological data the weather conditions in the nearest vicinity of the fire have been recreated as well. A constant north-westerly wind has been modelled, with an average speed of 5.5m/s, and daily average air temperature at the beginning of numerical simulation has been assumed as equal to 0°C.

Figure 4. The course of a fire in the considered hall, simulated according to the t-square fire model in the coordinate system of: fire exposure time – released energy.

2.3. Discussion of the results obtained during numerical analysis
Results of the computer simulation performed by FDS [3] are shown in Figure 5. In this Figure the distribution of fire plume temperature recreated for the cross section located between the system axes 5 and 6 of the analyzed hall (Figure 1) is depicted after 30 minutes of the simulated fire. It is clearly visible, that the highest temperature has been reached along the longitudinal axis of the hall, directly under the ridge. This is, according to the Authors, a direct result of the hall shape, and precisely a ready and unlimited availability of combustion supporting oxygen from the surroundings due to the hall having incomplete sheathing of walls as well as stacking of the burning material into a more or less symmetrical prism with a ridge coinciding with the roof ridge axis. In Figure 6 the change of fire plume temperature during the simulated fire at the points located in the nearest vicinity of roof sheathing is depicted in detail. As one may easily observe, after reaching the fully developed fire stage, this temperature in both considered points climbed to reach the maximum value of approximately 400-450°C, which quickly stabilized and did not exhibit any significant growing trend in the following burning phase of the materials stockpiled in the hall. Similar value of the temperature observed at the same moments of fire at points located along the roof ridge and eaves indicates that the fire plume temperature evened out in the whole fire affected zone. However, in the simulation performed substantially different temperatures have been determined for the individual steel elements constituting components of the bearing structure. These differences are depicted in Figure 7, for the selected points on the main beam of the transverse frame and the adjacent wall beam, respectively. The differences in the heating speed of individual bearing components may be, therefore, attributed not only to the differences in the size of steel sections used to erect the hall but also to the differences in the location of measurement points, which directly affects the effective ventilation possible (the ridge well ventilated form the bottom versus badly ventilated eaves located in the corner between the wall and roof sheathing). The graphs juxtaposed in Figure 7 indicate, that in each of the compared points after 60 minutes of fire exposure the temperature did not exceed the level of 400°C. This in turn
means, that the yield limit of the steel of which the bearing structure has been made did not have to be reduced because of thermal action.

![Figure 5. Distribution of fire plume temperature obtained in the considered hall after 30 minutes of the numerically simulated fire exposure.](image)

![Figure 6. Development of the fire plume temperature in the numerically simulated fire exposure determined under the ceiling of the considered hall in the direct vicinity of the eaves and the ridge of the girder located at axis 6 (Figure 1).](image)

The above presented results of performed a posteriori numerical simulation of the fire seem to be formally in agreement with prior provisional conclusions, formulated ad hoc during taking the inventory of the deformation state of the structure after fire. These deformations, relatively limited with respect to both the number and the measured deviations from the initial shape (Figure 3), could be justified simply by the restrained thermal expansion capability of structural members during the fire, without the need to take into account the additional phenomenon of weakening the strength of material.
Figure 7. Changes in the steel temperature recorded during the numerically simulated fire exposure at the ridge and eaves of the main frame located at the axis 6 juxtaposed with corresponding changes in the temperature of the top steel beam located along the axis E in between the axes 5 and 6 (Figure 1).

3. Fire of the steel structure of a railway transhipment terminal

3.1. The cause and course of the fire
The fire described in this chapter occurred during summer in a hall of railway transhipment terminal, where the goods transported in railway cars conforming to gauge standard in European Union countries are transferred to the railway cars operating on wide gauge prevalent in the countries of Eastern Europe. This fire was initiated by the ignition of fuel spilled over a large area inside the terminal. This fuel leaked unnoticed for a long time from a depressurised railway tank car. The tank car contained raw oil, an easily inflammable material burning in a violent manner. The high intensity fire, according to eyewitness testimony, lasted for many hours, until the fuel burned completely. The bearing structure of the transhipment terminal consisted of a steel hall. The scheme of the hall is depicted in Figure 8. In the same picture the inventoried state of the deformed bearing members after the fire is presented in a simplified manner using exaggerated displacements [4]. The hall was one storey high, without basement, having the floor area of 770 m² and enclosed volume estimated at 5780 m³ (Figure 9). During the fire the roof of the hall was destroyed, falling in into the zone of intensive fire exposure while all the girders of the frames neighbouring with this zone sustained significant thermal deformations (Figure 10). Large part of the hall sheathing, including the supporting horizontal beams has been completely destroyed. Thus the sheathing ceased to function as a barrier between the inside of the hall and outside world and allowed for unlimited availability of combustion supporting oxygen. The main columns of transverse frames located outside the zone delimited by the destroyed roof survived the fire relatively intact, with only local deformations due to the thermal actions. As the fire occurred during summer, when the roof was loaded only by the covering material made of trapezoidal sheet metal panels, the 3D displacements depicted in Figure 8 could be attributed to the thermal loads only.
Figure 8. Scheme of the railway transhipment terminal hall described in this paper. The heat induced deformations of the bars inventoried after the fire are shown exaggerated.

3.2. The purpose and parameters of the a posteriori fire development simulation

During the post factum recreation of the considered fire it has been assumed, that because of the fuel initiating combustion, it followed the scenario of hydrocarbon fire [7]. The observation of this type leads to the conclusion, that if only the unlimited availability of oxygen from the outside to the fire area is ensured, the fire would almost immediately, in general during the first minute of fire exposure transform into the stage of fully developed fire, and the temperature of fire plume very quickly would reach the level exceeding 1000°С and remain more or less stable at this level until the fuel is completely exhausted. Such fire development scenario should in general result in complete destruction of the analysed structure, but this has not been observed on site after the inventory has been taken. The independently conducted a posteriori numerical fire development simulation precisely correlated with the real conditions determined for the terminal hall considered in this example should be able to dispel the doubts formulated in such a manner. This simulation has been performed using FDS code [3]. For the purpose of this analysis the heat release rate in the numerically simulated fire exposure has been assumed as equal to $RHR_f=500\text{KW/m}^2$, while the combustion speed $\nu=0.018\text{kg/(m}^2\cdot\text{s})$. 


3.3 Analysis of obtained results

In the numerical simulation performed a special emphasis has been laid upon a posteriori replication of the first 15 minutes of fire development, counted from the moment of initiation. According to the conventional hydrocarbon fire model after such fire exposure time the temperature of exhaust gases, uniform in the whole fire compartment, should have reached the level of:

$$\Theta_g = 1080 \left( 1 - 0.325 e^{-0.167 t} - 0.675 e^{-2.515 t} \right) + 20 = 1071 \, ^\circ C$$

(3)

Correlating this result with the results obtained via the numerically simulated for the considered hall fire plume temperature curve $\Theta_g(t)$ specified for the nearest vicinity of the eaves in the most intensely heated cross section of the bearing structure, depicted in Figure 11, one may confirm the thesis, that the so high level of the fire plume temperature has been actually reached in the structure. The significant difference with respect to the classical curve describing the hydrocarbon fire lies in the fact, that the level of the temperature $\Theta_g$ exceeding the value of 900°C has been obtained in the numerical model only after approximately 20 minutes of intensive burning of the spilled oil, instead of almost immediately as the standard model predicts. The temperature of the exhaust gases after 15 minutes (i.e. 900 seconds) of simulated fire exposure reached only about 500°C, i.e. much less than forecast by the formula (3). This in turn means, that in the case considered here the hydrocarbon fire model proved to be overly conservative. This conclusion seems to be corroborated by the curve depicting the evolution of the maximum steel temperature $\Theta_a$ determined at the eaves of the most intensely heated transverse frame in the considered hall. This curve, for the comparative purposes, has been shown in Figure 11. As one may see there, the temperature of the considered beam stabilizes at the level of approximately 900°C after more or less 22 minutes of interaction with hotter and hotter exhaust gases.

The temperature $\Theta_a$ distribution map shown in Figure 12, determined after 30 minutes of numerically simulated fire exposure for the sheathing panels on the roof, and the steel transverse bearing frames of the hall justifies the selection of the eaves cross section as authoritative for analysis. It is visible there, that the highest steel temperature values have been reached in the zones adjacent to the eaves. This may be attributable to the somewhat restricted ventilation in this zone, and thus limited cooling capability of the heated structural members. Air circulation in the nooks and crannies of this type is effectively restricted and its outflow limited on both sides by the sheathing of the hall. Of course in a real fire such temperature level will most probably never be recorded in steel sheathing panels, as
these panels will sooner fall to the ground, as happened in reality during the fire analyzed here. Additionally, the map presented in Figure 12 confirms the limited reach of the intensive fire exposure zone. As it is visible there, this zone in general did not reach to the outermost transverse frames, and this is formally in agreement with the a posteriori inventoried structural member deformation state depicted in Figure 8.

![Figure 11. Development of the exhaust gas temperature $\Theta_g$ and maximum steel temperature $\Theta_a$ determined at the eaves of the most intensely heated beam of the transverse frame under the conditions of numerically simulated fire exposure for the transshipment terminal hall.](image)

![Figure 12. Temperature distribution map on the steel roof sheathing and steel bearing beams of the terminal hall obtained after 30 minutes of simulated fire exposure.](image)
4. Concluding remarks
In this paper, based on the two selected examples related to a priori occurring fire development scenarios, we have tried to prove the usefulness of numerical simulation performed a posteriori and replicating the real conditions of fire exposure. According to our opinion the data obtained during such simulations, in both considered cases, significantly expanded the initial knowledge base of the evaluating expert, gathered in the conventional manner by visual identification and accompanied by additional supplementary material analyses. The results presented in this paper seem to prove, that the simple schemes and models of analysis applied initially have been often overly pessimistic with too wide margin of safety. The numerical analysis allowed for identification of weak spots in the structure, often difficult to discover when only the conventional methods of evaluation are applied, but never the less very important from the point of view of safety guaranteed to the user, should the decision be made to continue the use of the structure in its current state. The proposed approach, extended by numerical simulations yields the life of an expert making the decision on possible rebuilding works much easier, should those works be deemed necessary and possible. Of course, the reliability of the evidences obtained this way is limited by the diligence of the person conducting the numerical experiments and replicating the real conditions existing a priori within the considered structure at the moment of fire initiation. Of these conditions the parameters describing the potential combustible material, and especially its characteristics determining the burning speed and efficiency, as well as the conditions of ventilation prevalent in the fire affected area seem to play the most important role, as these conditions determine whether the fire will remain at the stage of localized fire with limited affected zone or will flare up and proceed into the stage of fully developed fire. The considerations presented in this paper are based on simulations performed using the computer code of the FDS type. Though commonly used in the engineering practice because of availability and ease of use this is only one of the programs, which may be applied for this purpose by the contemporary engineer.

5. References
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