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Studies on the impact of external fire on the lye of the shelter housing

A. Baryłka
Scientific Institute of Engineering of The Safety of Anthropogenic Objects, ul. Obozowa 82A/19, 01-434 Warszawa, Poland
Corresponding e-mail address: biuro@crb.com.pl
ORCID identifier: https://orcid.org/0000-0002-0181-6226

ABSTRACT

Purpose: The presented article presents a numerical analysis carried out to determine the impact of an external fire taking place on the surface of the ground on the level of stress of the trench shelter casing protected by a layer of soil.

Design/methodology/approach: Numerical analysis was carried out in two stages. In the first stage, a quasi-stationary distribution of the initial temperature in the centre of the ground and the shelter casing was sought. In the second stage of the analysis, the effect of the fire was considered according to the profile of time changes in the temperature of the shelter object.

Findings: We assume that the trench shelter is in an oblong shape, and the fire extends over a vast area. The area surrounding the shelter casing was treated as a material with average constant thermodynamic values.

Research limitations/implications: The process related to heating and cooling the enclosure was described on the basis of the Fourier equation on heat conduction in terms of the heterogeneous nature of the material, primer and concrete.

Practical implications: The use of the trench shelter model as a research element in the design of special objects.

Originality/value: The methods of non-stationary temperature flow through the ground and the shelter casing used, allows for a very realistic indication of how the housing will behave under the influence of high temperature caused by an external fire. The article can be useful for designers who design underground shelters.

Keywords: Excavation shelter, Part-time processes fire, Numerical analysis

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ANALYSIS AND MODELLING

1. Subject matter of analysis

Fire incidents in buildings are one of the most dangerous hazards when it comes to evacuation safety. In order to reduce the aftermath of fire in buildings, systems are designed to improve the fire evacuation safety. The design of fire protection systems in underground objects is a complex, multi-stage issue, which causes designers many problems. That is because of the complex nature of the physical phenomena that accompany the formation and development of a fire, against the effects of which the fire protection system should provide protection. This is a very important tool for performance assessment fire ventilation systems at the design stage is conducting thermal-flow analyses using the computational fluid mechanics CFD to recreate the conditions occurring in a building during a fire [1,2]. Of particular interest is the modelling of shelter-type objects. In this case it is difficult to talk about fire ventilation and escape route. Air conditioning systems are limited to ensuring the right temperature, humidity and air velocity in spaces. In modern shelters there is no ventilation, the air composition is prepared by removing harmful gases on the principle of adsorption, while oxygen is supplied from cylinders. Consequently, the appearance of a fire outside a shelter comes down to an analysis of the temperature distribution inside the structure of the object [3,4].

Subject to analysis was the shelter housing strain due to external fire on the ground surface [5-7]. The numerical projection was carried out for a separated area covering the longitudinal, dug shelter together with the surrounding land. It was assumed that the fire covered an extensive area which allowed to adopt a geometric model in the analysis in the form of a flat, heterogeneous shield with the width equal to the size of the shelter increased on both sides by ΔL. The shield structure covers the shelter filled with air, monolithic, reinforced concrete housing and an adjacent land limited in the part above the ceiling level with a specified thickness of the covering layer equal to Δh. During the shelter construction, main and structural reinforcement was neglected due to the assumed approach assuming that heat conduction is determined by the thermodynamic properties of concrete. At the edge of the top shield we assumed the environment temperature. Bottom edge of the shield was situated below the foundation slab level. It was positioned at the depth ensuring low sensitivity of the numeric analysis to is location. The analysed shield model was presented in Figure 1.

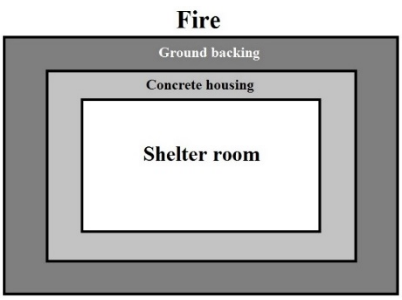

Fig. 1. Heterogeneous shield model

The computational analysis was carried out in two analysed stages. In the first stage, elements of the quasi-stationary distribution of the initial temperature in the ground and the casing of the trench shelter were sought. It was assumed that this condition is determined by two factors: proper air temperature in the summer time as well as thermal effect of the protected resources and shelter crew, which after filling will be in the condition of complete hermitization. It has been assumed that air temperature in the summer time is t_0=22°C. The initial temperature in the ground centre, housing and shelter room was assumed to be t_{schr}=12°C. At the same time, a function of temperature increase was assumed in the shelter room. Temperature increase is due to heat generated by shelter users. It is assumed that the shelter room temperature after one day reaches the stationary distribution in the form of a linear function at the room's height. This function spans across the ordinates at the floor and ceiling level, ($t_{podł}$, t_{sufit}). The edge values of these temperatures were assumed, t_{sufit}=28°C and $t_{podł}$=0.8 t_{sufit}. Further stationary nature of this distribution is ensured by shelter's air conditioning system. After 4.5 days, quasi stationary temperatures were reached in the analysed shield – the housing and the surrounding land.

In the second stage of the analysis, the impact of an external fire was assumed according to the temporal profile of temperature changes as per [3,8,9]. This profile covers the change of higher fire temperatures over the period. We will define this period as the pre-heating, after the elapse of which the period of external air cooling will commence. In the cooling period, we will assume that the external temperature will be described by the adequate equation of Gauss curve falling branch.

$$t_P(\tau) = \begin{Bmatrix} t_{max}\left[1 - 0.325 \cdot e^{-0.167(\tau-\tau_{iP})} - 0.675 \cdot e^{-0.675(\tau-\tau_{iP})}\right] + t_0 \\ t(\tau_{kP}) \cdot e^{b(\tau-\tau_{kP})+c(\tau-\tau_{kP})^2} + t_{asympt} \end{Bmatrix} \quad (1)$$

In formula (1), the initial air temperature prior to the fire equals t_0, and t_{asympt} becomes the temperature of the post-fire extinction. t_{asympt} =300°C was assumed for numeric analysis.

2. Basic equations

A non-stationary heat condition process was considered based on Fourier equation with the constant, average temperature adjustment in individual shield areas.

$$\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial z^2} = \frac{1}{a} \cdot \frac{\partial t}{\partial \tau}, \quad (2)$$

where: $a = \frac{\lambda}{\rho \cdot c_w}$ – average temperature balancing factor dependent upon λ heat conduction factor, proper heat cw and volume density ρ of the ground or concrete.

The equation (2) is solved using a differentiation method combined with an open integration scheme and assumed temperature distributions – in the first stage of initial conditions determination in the shield according to item 1 and in the second stage of fire interaction (1) on the surface level subject to temperature continuity in the shield at $\tau = \tau_{iP}$.

The spatial division of Δx and Δz was introduced and time step of Δt, which ensure stability of numeric procedure and consistency of differentiation solution. The evolution formulas of the grid temperature were derived using the energy balance method of A.P. Waniczew [5,7,10], for convenient analysis of areas with thermodynamically heterogeneous properties. Presented below are evolution formulas in the characteristic grid points.

Surface grid nod in the ground surface level (I, J=2).

A system of nods included in the elementary energy balance for nod (I, J = 2) is presented in Figure 2. We assumed that temperature assumption factor from the fire air area into the ground is $\alpha_{PO-GR} = 2.4\frac{W}{m^2K}$.

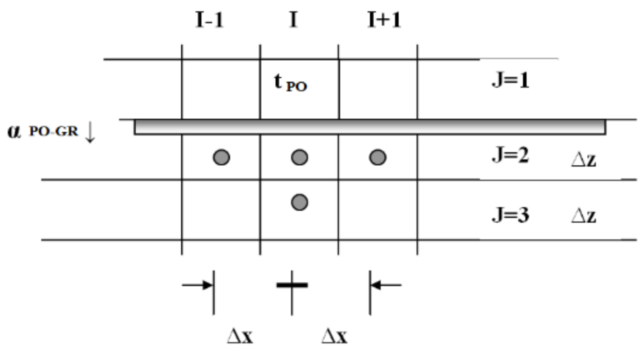

Fig. 2. The system of nods participating in the elementary energy balance for nod (I, J = 2)

The balance of elementary energies is expressed by the following equation (3) which takes into account tn(I-1,2) = tn(I,2) = tn(I+1,2), as a consequence of the assumption of the extensive fire area.

$$\Delta x \cdot \frac{t^n(I,3)-t^n(I,2)}{\frac{\Delta z}{\lambda_{GR}}} \cdot \Delta\tau - \Delta x \cdot \frac{t^n(I,2)-t(I,1)}{\frac{1}{\alpha_{PO-GR}}+\frac{\Delta z}{2\lambda_{GR}}} \cdot \Delta\tau = \rho_{GR} \cdot c_{wGR} \cdot \Delta x \cdot \Delta z \cdot [t^{n+1}(I,2) - t^n(I,2)] \quad (3)$$

Heat penetration factors from the fire into the ground and back were varied. The thermal energy balance equation after the insertion in $t^n(I,1) = t^n_{PO}$, is as follows:

$$t^{n+1}(I,2) = [1 - \frac{1}{M_{z,GR}} \cdot \left(1 + \frac{1}{N_{z,PO-GR}}\right)] \cdot t^n(I,2) + \frac{1}{M_{z,GR}} \cdot \left[\frac{t^n{}_{PO}}{N_{z,PO-GR}} + t^n(I,3)\right] \quad (4)$$

where: $M_{z,GR} = \frac{\Delta z^2}{a_{GR}\cdot\Delta\tau}$, $N_{z,PO-GR} = \frac{1}{2} + \frac{1}{\Delta Bi_{z,GR}}$ (5)

In (5) $N_{z,PO-GR}$ is defined using the Biot number,

$$\Delta Bi_{z,GR} = \frac{\alpha_{PO-GR} \cdot \Delta z}{\lambda_{GR}} \quad (6)$$

Grid nod in homogeneous areas (I,J).

The case where the nod and its surrounding areas remain in a homogeneous area, for example in the ground.

Based on the energy balance equation (Fig. 3), we will be able to calculate the following:

$$t^{n+1}(I,J) = [1 - 2 \cdot (\frac{1}{M_{z,GR}} + \frac{1}{M_{xGR}})] \cdot t^n(I,J) + \frac{1}{M_{x,GR}}[t^n \cdot (I-1,J) + t^n \cdot (I+1,J)] + \frac{1}{M_{z,GR}} \cdot [t^n \cdot (I,J-1) + t^n \cdot (I,J+1)] \quad (7)$$

where: $M_{x,GR} = \frac{\Delta x^2}{a_{GR}\cdot\Delta\tau}$, $M_{z,GR} = \frac{\Delta z^2}{a_{GR}\cdot\Delta\tau}$, $a_{GR} = \frac{\lambda_{GR}}{\rho_{GR}\cdot c_{w,GR}}$.

Nod within the external land cover directly adjacent to concrete (I, J=JOB).

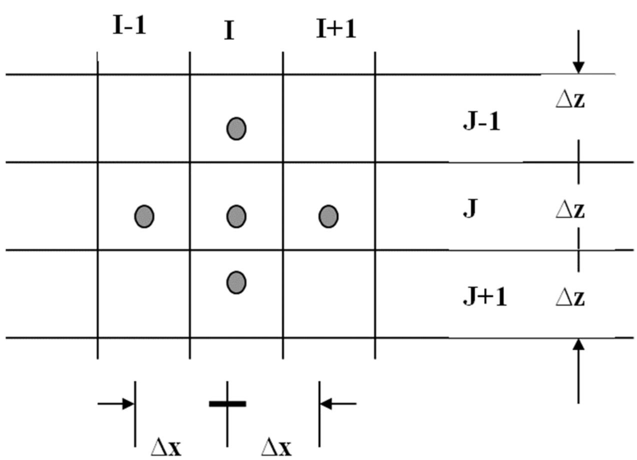

Fig. 3. A system of nods participating in the elementary energy balance

Separate analysis is required with respect to nod situated directly in the neighbourhood of the ground and concrete housing borders area. The formula presented below allows to calculate the evolution of temperature in the nod situated in the ground cover in the J=JOB layer adjacent to the concrete housing. We will use the geometric model given below (Fig. 4).

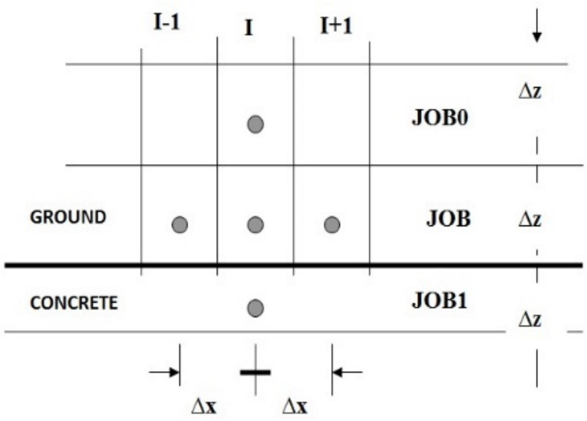

Fig. 4. The system of nods participating in the elementary energy balance

Based on the energy balance (4), we obtain a formula representing the temperature evolution in the nod (I, JOB)

$$t^{n+1}(I,JOB) = [1 - (\frac{2}{1+\frac{\lambda_{GR}}{\lambda_C}} + 1) \cdot \frac{1}{M_{z,GR}} - \frac{2}{M_{x,GR}}] \cdot t^n(I,JOB) + \frac{1}{M_{z,GR}} \cdot \left[\left(\frac{2}{1+\frac{\lambda_{GR}}{\lambda_C}}\right) \cdot t^n(I,JOB1) + t^n(I,JOB0)\right] + \frac{t^n(I1,JOB)+t^n(I0,JOB)}{M_{x,GR}} \quad (8)$$

We determine the temperature evolution formulas in remaining areas of the shield.

3. Numeric result analysis

The shield of the thickness equal to Δh=0.4 m and axial dimensions of the elements constituting the housing L= 6.00 m and H=2.80 m was considered. In the numeric analysis, it was established that the thermal interactions included, in principle, the near surface strip of the total thickness equal to the thickness of the cover and the housing ceiling, i.e.: Δh + 0.40 m. This observation was used to determine the thermal effect on the housing. It was therefore justified to burden with the temperature changes only the housing ceiling – the main upper frame rafter.

Two cases we considered. In the first, the fire with the following parameters was considered: t_{max}=650°C, $\tau_m = \tau_{kP} - \tau_{iP} = 2h$. It was assumed that the thickness of the ground cover was Δh1=0.40 m. The numeric results including analysis stage whose aim was to determine the initial conditions of the shield at the break of the fire and the stage of pre-heating and cooling of fire temperatures are given in Figure 5. Individual temperature variation curves represented selected layers: sub-ceiling and five internal ceiling layers. The black line represents the extreme, external ceiling layer.

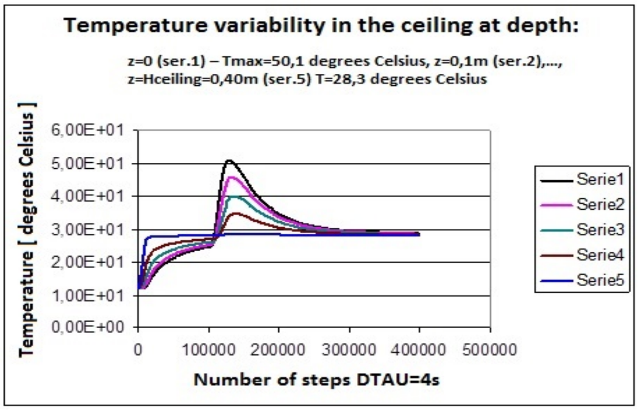

Fig. 5. Temperature variability in the sub-ceiling and five internal layers in the stage of determining the initial conditions of the analysis and the stadium of influence of fire (650°C, 2h)

The system of curves in the initial stage is reflected by the temperature distribution in the shield aiming to stabilise. We assumed that these temperatures constitute long-term effect on the shelter housing and the results of such influence are subject to relaxation. For this reason, we do not consider them when predicting the initial shelter strain. We look for strain increase due to the occurrence of fire [11,12].

Based on the analysis, the temperature increases due to fire were evaluated: on the ceiling surface t_z = 25.5°C and on the internal surface t_w=3.7°C. The shape of the bending moments and longitudinal forces due to load: altogether, the load of the cover, side thrust onto the housing walls, own weight of the housing and temperature effect (t_z, t_w) on the frame rafter is given in Figure 6.

Characteristic ordinate values are as follows:

MP = -111.11 kNm/m,
MS = -30.11 kNm/m, (9)
NS = -38.18 kN/m,
NF = -10.51 kN/m.

Values due to temperature are equal:

MP = MS=-74.41 kNm/m,
NS = -NF = -31.92 kN/m. (10)

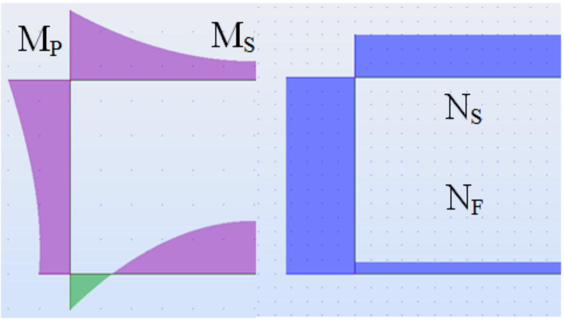

Fig. 6. The shape of the internal force diagram within the housing structure

Comparing the presented results of (9) and (10) we can draw a conclusion that the share of thermal influence in the strain of the critical cross-sections of the raft is considerable. This comment pertains in particular to critical cross-sections of the upper node of the frame. The occurrence of the compressive force in the main rafter is used due to tightness of the housing. In the other case, fire with the following parameters was considered: t_{max}=1600°C and $\tau_m = 1.5h$. It was necessary to assume the cover of increased thickness of Δh2=0.60 m. Analogous temperature variability in the housing ceiling layers us presented in Figure 7.

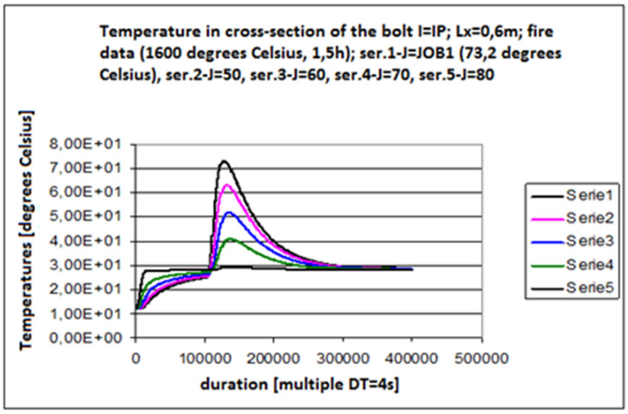

Fig. 7. Temperature variability in sub-ceiling and five internal ceiling layers in the stages of determining initial analysis conditions and fire influence stage (1600°C, 1.5h)

As in the preceding case, we look for temperature increases in the housing frame rafter due to fire. The can be estimated in the following way: t_z=47.7°C and t_w=4.6°C. The characteristic values of the internal force diagrams are shown below in (11) and (12) and are:

MP=-190.71 kNm/m,
MS=-91.71 kNm/m,
NS=-70.62 kN/m, (11)
NF=17.06 kN/m.

The values due to temperature are equal:

MP=MS =-145.47kNm/m,
NS=-NF =-61.93kN/m. (12)

4. Conclusions

The results of the numeric analyses show that the thickness of the ground covering should be determined depending on the fire parameters. The ceiling, which is the element most exposed to temperature, is positively compressed. The upward bending results on unloading of the central section due to bending and at the same time adversely loads the nod of the monolithic fixing of the ceiling in the wall.

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