THERMAL DEGRADATION OF A NPP REINFORCED CONCRETE ROOF STRUCTURE DUE TO AN AVIATION FUEL FIRE

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ABSTRACT

Thermal loading influences the material properties of construction materials (such as concrete and steel) used in Nuclear Power Plants,(NPP). The structural integrity of buildings can be lost not only from dynamic loading but also from thermal loading generated by burning aviation fuel from an aircraft crash. The Twin Towers in New York were destroyed due to thermal loading caused by burning aviation fuel inside of the buildings. Therefore, the evaluation of the thermal degradation of NPP building structures should be performed for the case of aircraft crash.

The evaluation of thermal degradation of the structural strength of an Ignalina NPP building structure due to thermal loading caused by burning aviation fuel on the roof is presented in this paper. A Boeing 737-300 airplane traveling at a velocity of 94.5 m/s and carrying 20,104 liters of aircraft fuel was assumed to crash on the roof. The crash was assumed to be a “pancake” type of crash in which the impact caused no structural damage to the roof. Specifically, the thermal degradation of the structural strength of the Ignalina NPP Accident Localization System (ALS) building structure due to thermal loading caused by burning aviation fuel on the roof was carried out using the numerical methods embedded in the TEMP-STRESS and NEPTUNE computer codes.

INTRODUCTION

The evaluation of mobile external events is important for the safety assessment of nuclear power plants. An aircraft crash or other flying objects in the vicinity of a NPP represents a very large threat to the plant, including the reactor. Aircraft traveling at high speed has the potential to cause a lot of destruction due not only to aircraft impact onto NPP structures but also due to the release of aircraft fuel and the resulting fire. Therefore it is very important to evaluate the thermal degradation of structural strength due to thermal loading in case a fire caused by burning aviation fuel.

This paper presents the thermal degradation of the structural strength of an Ignalina NPP building structure due to thermal loading caused by burning aviation fuel on the roof. The structure analyzed was a portion of the Accident Localization System described in [1]. The Ignalina NPP is a twin-Unit of the multi-channel graphite-moderated water-cooled reactors, called by a Russian acronym RBMK [1]. This is the most advanced version of the RBMK reactor design series (in fact, only two reactors of this type have ever been built). The Ignalina NPP Unit 1 was shutdown at the end of 2004 and Unit 2 at end of 2009. Those dates mark the beginning of the nuclear utilization process since the fuel will be located at the shutdown reactor for several years at spent fuel pools of reactor unit building. The building of the reactor should satisfy the safety requirements in order to guarantee the performance of fuel transportation path for the entire utilization period.

In this analysis, the thermal degradation of the structural strength of the Ignalina NPP ALS building structure due to thermal loading caused by burning aviation fuel on the roof was carried out using the computer codes TEMP-STRESS and NEPTUNE. NEPTUNE [2] does not have the capability to do the heat conduction analysis needed to determine the transient temperature distribution through the wall/roof. The TEMP-STRESS code was specifically developed at Argonne National Laboratory to model reinforced concrete structures stressed to their material limits under mechanical loadings and high temperatures [3, 4, and 5]. The computer code TEMP-STRESS is a finite element program that has a weakly coupled thermo-mechanical formulation. It can handle transient and steady state problems through the use of explicit time integration and dynamic relaxation. Thermal and mechanical loading can be handled by TEMP-STRESS with a possibility of variable material properties as a function of temperature. The NEPTUNE code can evaluate thermal stresses due to known temperature distributions. Therefore, TEMP-STRESS was used to determine the temperature distribution through a representative concrete slab. This temperature distribution was inputted into NEPTUNE for subsequent 3D stress analysis.

FINITE ELEMENT MODELING OF A TYPICAL IGNALINA NPP BUILDING

A typical Ignalina NPP building is selected for external loading event analysis. Deterministic and probabilistic analyses of the structural integrity of the Ignalina NPP building show that a Boeing 737 traveling at the approach speed of 94.5m/s will damage the impacted wall of an Ignalina NPP building [6, 7]. However, the extent of damage will be through-the-wall cracks, and no penetration by the aircraft should occur. Consequently, in those analyses the fuel should not get inside the ALS. Accordingly, the roof, as a representative part of the Ignalina building, is selected for the analysis of the effect from fire.

Material properties of building

The analysis of the building roof was performed using the experimental material properties data for the concrete and the reinforcement bars. The average of experimental data is presented in Table 1.

Table 1: Experimental data of Concrete

Material	Type (Russian brand)	Young's modulus, MPa	Poisson's ratio	Tensile strength (concrete)/ Yield stress (steel), MPa	Compressive strength (concrete)/ Ultimate strength (steel), MPa	Ultimate strain, %
Concrete	M300	1.95e4	0.184	3.8	51.6	0.47
Steel of reinforcement	AIII	22.25E4	-	443	697	-

The effect of temperature on the mechanical properties of the rebar steel and concrete was calculated using the coefficients presented in the reinforced concrete norms [8]. These coefficients are presented in Table 2 and Table 3.

Table 2: Coefficients at different temperatures for tension strength, compressive strength and Young's modulus of concrete [8]

	Coefficient at temperatures				
Degrees C	50	70	100	200	300
Compressive Strength	1.0/1.0	0.85/0.85	0.9/0.9	0.8/0.8	0.65/0.5
Tension Strength	1.0/1.0	0.7/0.7	0.7/0.7	0.6/0.5	0.4/0.2
Young's modulus	1.0/1.0	0.9/0.9	0.8/0.8	0.6/0.5	0.4/0.4

Table 3: Coefficients at different temperatures for strength and Young's modulus of reinforcement steel [8]

	Coefficient at temperatures				
Degrees C	50-100	200	300	400	450
Strength	1.0/1.0	0.95/0.85	0.9/0.65	0.85/0.35	0.75/0.15
Young's modulus	1.0/1.0	0.9/0.9	0.88/0.88	0.83/0.83	0.8/0.8

Remark – short-term/long duration

Finite element modeling of the roof of building for thermal analysis using TEMP-STRESS

The reinforced concrete structures of the roof of the INPP building were modeled using a plane beam element [3]. The cross section of the beam element is assumed to be homogeneous and the thickness is assumed to be constant in the entire cross section. This element is initially straight. The beam element is formulated in terms of the Bernoullii-Euler hypothesis, that normals to the midline are constrained to remain straight and normal [3]. In this element, the strain consequently varies linearly from end to end and linearly across the thickness. If the material response is nonlinear, the variation of the stresses through the elements can be quite complex, so that numerical integration is necessary to determine the nodal forces in the element. This integration is accomplished by using the trapezoidal rule through the thickness and along the length, with two points used in the integration along the length. The formulation of the elements is based on a modification of the co-rotational or rigid-convected formulation described by Belytscko and Hsieh [9]. The beam elements that represent concrete media have uniaxial reinforcement that has been superposed on the parent element [3]. The uniaxial reinforcement will be assumed to the embedded parallel to the respective neutral axis of the element. Axial and shear tie are the two types of reinforcement that can be specified at various layers in the beam element. The analytical model for thermal conduction of the Ignalina building roof is presented in Fig. 1.

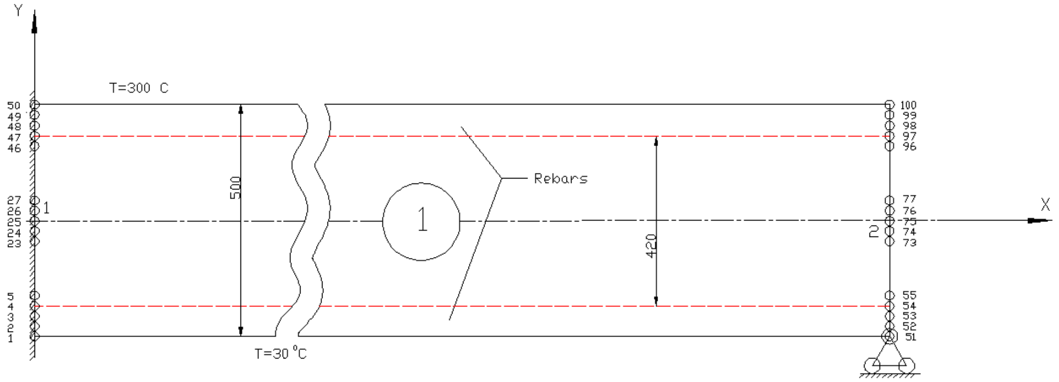
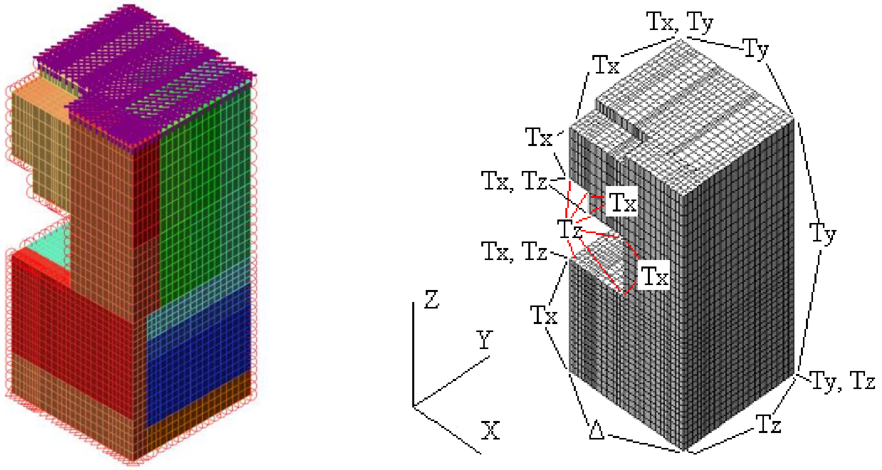


Fig.1: Location and numbering of Integration points for beam element

The roof of the NPP building is made of reinforced concrete. The geometrical data for the roof was obtained from construction drawings. The 0.5 m thick roof of the building selected for thermal degradation analysis has 26 mm diameter reinforcement bars with a pitch of 200 mm, 12 mm diameter bars with a pitch of 225 mm and 32 mm diameter bars with a pitch of 200 mm. The positions of the rebars are indicated in Fig. 1.

Finite element modeling of the roof for thermal loading analysis using NEPTUNE

The three-dimensional finite element model of the Ignalina NPP building roof for thermal stress analysis was the same model as used for transient analysis [6] and is presented in Fig. 2a. Reinforced concrete walls and slabs were modeled using four-node quadrilateral plate elements. Detailed description of these elements is presented in [6]. In some walls, metal frames made from different steel components were imbedded. These structures were modeled using separate beam elements and were added to walls and slabs in the locations of the frames [6]. The violet color in Fig. 2a shows the thermally loaded area for this analysis.



a) b)

Fig.2: a) Finite element model for the thermal stress analysis of the Ignalina NPP building and b) Boundary conditions applied to the model of a part of Ignalina NPP building.

Boundary conditions of the models

The portion of the ALS building used in the analysis is shown in Fig. 2, where adjacent parts of the ALS building are not shown. The portion not explicitly modeled was accounted for through constraints on the portion modeled. The outside constraints consist of walls, floor-ceiling slabs of the adjacent structure. Most of the outer nodes of the Ignalina NPP building model would be connected to the adjacent structures. Because these external constraints would be primarily resisting the Ignalina NPP building deformation in the tension-compression mode, their stiffness would be very large. For simplicity, therefore, the locations of the external nodes, which would be in fact connected to adjacent structures, are assumed to be completely fixed in translation. The model of the Ignalina NPP building is built in a rectangular (Cartesian) global coordinate system. The boundary conditions of these models are presented in Fig. 2b**Error! Reference source not found.**, where the symbol Δ means that the node is completely restrained; T refers to translation; and R to rotation. Tx, Ty, Tz mean that the nodes are restrained in translations along X, Y and Z axes, respectively.

Applied Loads

The thermal loads on the roof are determined by solving the relevant thermal problem, which depends on the distance from the fire location and fuel volume. Some simplifying assumptions can be made about the character of an occurring fire when carrying out estimations. If no destruction of construction structures takes place as a result of the plane impact, it can be accepted as the first approximation that the temperature on the surface of the construction structures makes up 300 ^{0}C, and the fire duration does not exceed 2.5 hours [10]. Accordingly, the requirements of [10] the temperature up 300 ^{0}C and the fire duration of 2.5 hours was used for thermal degradation analysis of the building in the case of fire.

The transient temperature distribution analysis through the thickness of the roof was performed for the ALS roof using TEMP-STRESS. The model used for this analysis is shown in Fig. 1. The results of the temperature distribution analysis are shown in Fig. 3. The temperatures are presented at different times of the analysis. The analysis was carried out through the time span of 2.5 hours. The positions of rebar location in the roof are shown by red lines in Fig. 3. At the time of 2.5 hrs it is seen that the temperature decreases from 300 ^{0}C at the outside surface to 50 ^{0}C at the mid-thickness of the roof, i.e. at the depth of 0.25 m of the slab thickness. The temperature decreases to 200 ^{0}C at the depth of 0.08 m from the outside surface. The concrete strength degradation due to 200 ^{0}C temperature will be about 20% according to the data presented by the Russian Norms (see Table 3). It was observed that the temperature will reach about 230 ^{0}C in the layer of rebars near the outside surface (0.04 m). The rebar strength degradation due to the 230 ^{0}C temperature will be about 15% according to the data presented by the Russian Norms (see Table 3).

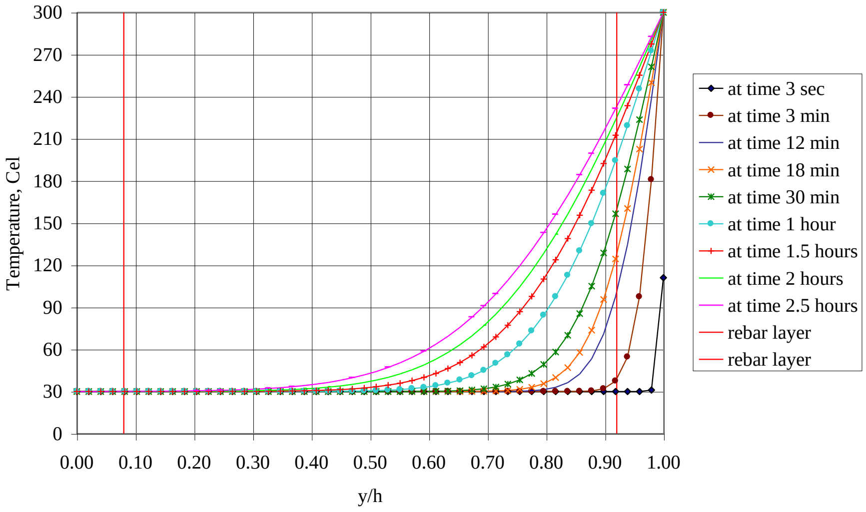


Fig.3: Transient temperature distribution through the roof

The NEPTUNE code [2] can only model linear temperature distributions through the thickness of the roof slab. Therefore, the assumed temperature distribution through the thickness of the roof slab is taken to be linear with an inside surface temperature of 30 ^{0}C and an outside surface temperature of 300 ^{0}C. Fig. 4 shows the difference between the true temperature distribution and the assumed linear temperature distribution. It is noted that the assumed temperature distribution is conservative in that it provides a thermal conditions where time approaches infinity. The implied thermal loading in NEPTUNE is significantly larger than the true thermal loading at 2.5 hrs; thus, the NEPTUNE results for the state of stress would also be significantly higher and, thus, conservative.

Because heat conducts very slowly through concrete, a static structural analysis was performed to determine the structural degradation of the ALS roof structure. The NEPTUNE code [11] does not have a static solver *per se* because it is based on explicit integration. However, static solutions can be obtained using explicit integration by applying “slow dynamic loading”. With this approach, the loading is applied as a ramp load whose rise time is long enough that no significant dynamic effects occur in the structure. To insure that the rise time of the ramp loading is long enough, an *a posteriori* examination of the results is performed to assure that dynamic effects are minimal. The results obtained below will show that the static solution of the structural response for the thermal loading occurring at 2.5 hours can be obtained with a ramp rise time of 2 sec. The results will show that the oscillation amplitudes about the static solution are not significant. Thus, a significant savings in computer time is gained by reducing the simulation time from 9,000 sec (2.5 hours) to 2 sec. It should be noted that “time“ in this type of solution method does not represent real time but represents an integration parameter. We will use the word “pseudo-time” to indicate that it is not real time. At time 0.0 sec the surface temperature is 30 ^{0}C and increases to 300 ^{0}C at 2 sec and is held at 300 ^{0}C up to 3 sec, at which time the analysis is terminated. Thus, the results during the 2.0-3.0 sec interval represent the static solution for the real thermal loading at 2.5 hrs, which theoretically should be constant over this interval.

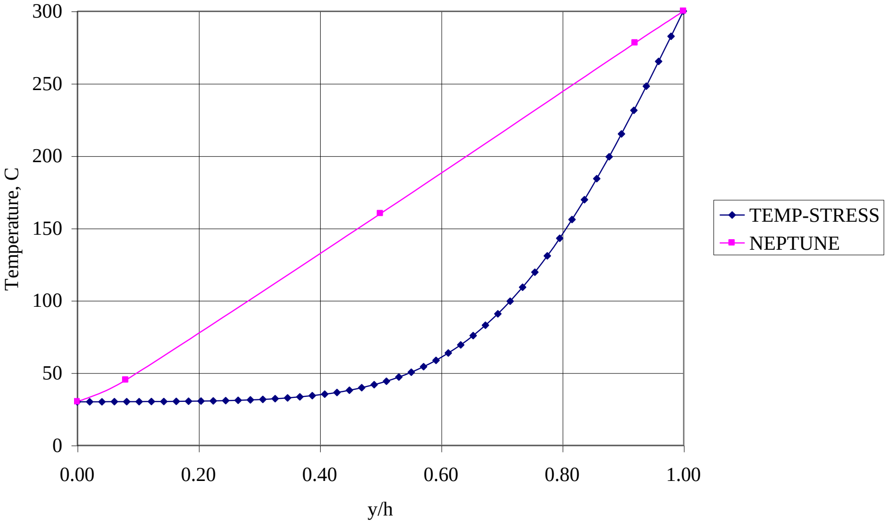


Fig. 4: True temperature distribution computed by TEMP-STRESS and assumed linear temperature distribution modelled in NEPTUNE.

For this problem it was determined that gravity loading would be important in determining the final deformed configuration of the structure; therefore gravity loading was taken into account. The gravity loading was applied in the same manner that the thermal loading was applied. At time 0.0 sec the value of gravity was 0.0 m/sec^2 and at 2.0 sec the value was 9.8 m/sec^2 and held at that value for the remainder of the analysis. The analysis was performed using first combined gravity and thermal loading and then gravity loading only and thermal loading only.

ANALYSIS RESULTS OF THE THERMAL DEGRADATION ANALYSIS OF STRUCTURAL STRENGTH IN CASE FIRE

The results from the thermal stress analysis of the Ignalina NPP building for the case of a 2.5 hour duration fire are depicted in Fig. 5 to Fig. 6. The von Mises stress snapshots are presented for the entire building. The maximum stresses are in the building roof with a value of 392 MPa in rebar layers 2 and 3 (see Fig. 5). These stresses are in the rebar layer near outside surface of the roof and correspond to the yield stress of the steel rebar. The maximum normal stress in concrete is 0.99 MPa (tension, Fig. 6, b) at integration point 5 and 0.064 MPa (compression Fig. 6, a) at integration point 1.

The location of the element and node numbers at which the NEPTUNE results for stress and temperature temporal histories are plotted are presented in Fig. 7. The final normal stresses in the X and Y-directions in concrete element 8623 in layer 1 (outside surface of the roof) and layer 5 (inside surface of roof) are presented in Fig. 8. The results show that the normal stress σ_{xx} at layer 5 is the largest with a value of 0.486 MPa in tension. The other stresses are smaller. It was determined that this element responds in tension. The applied temperature in the concrete element 8623 in layer 3 (middle of the roof) is presented in Fig. 9. The results show that the temperature of layer 3 has a value of 160 ^{0}C. However, the temperature reaches about 40 ^{0}C at the midsurface of the roof using the code TEMP-STRESS (see Fig. 3). The linear temperature profile through the thickness of the roof slab was used by NEPTUNE while the parabolic temperature profile through the thickness of the roof slab was obtained by TEMP-STRESS (Fig. 4). The NEPTUNE stress analysis results assuming linear temperature distribution through the roof is quite conservative.

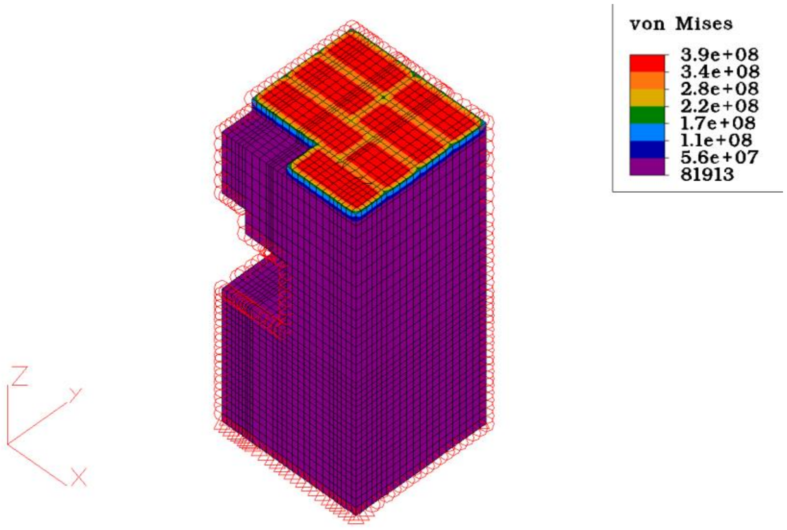
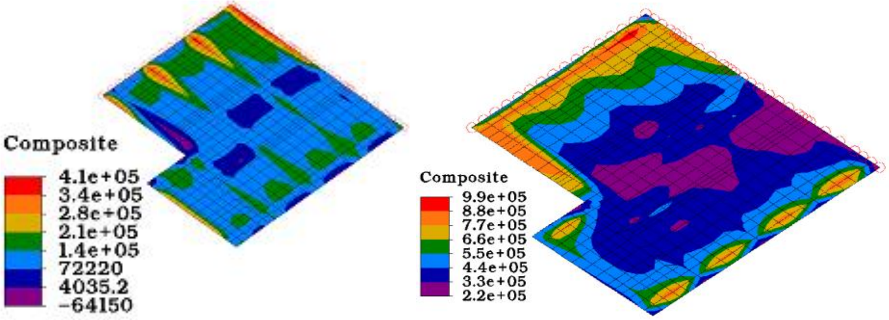


Fig.5: von Mises stress distribution on the INPP building.



a) b)

Fig.6: Normal stress (Pa) distribution in the concrete roof, a) Integration point 1 - X-direction, b) Integration point 5 - Y-direction.

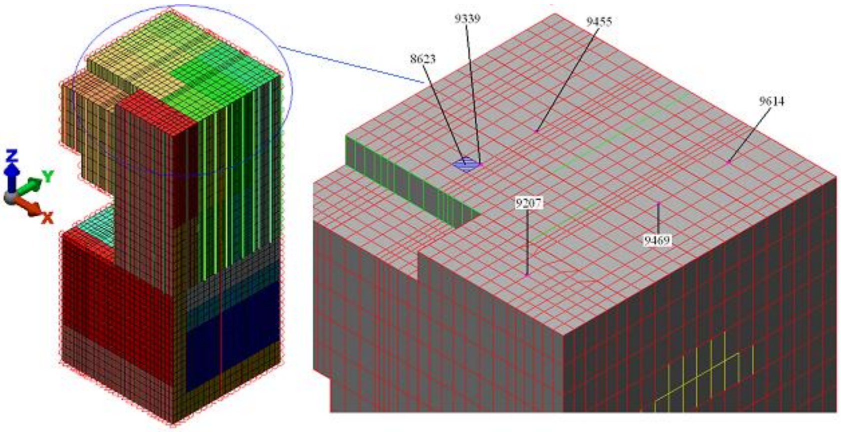


Fig. 7: Identification of referenced node and element numbers of the model.

The axial stresses in the reinforcement bar (element number 8623) at all three layers of the roof are shown in Fig. 10, which show that the stress is the largest with a value of 392 MPa in layers 1 and 2. The positions of these layers are near the outside surface of the roof. The stresses have a value of 36.7 MPa in layer 3. The position of layer 3 is near the inside surface of the roof.

According to these results, the influence of thermal loading is small on the overall concrete state of stress for the case of a burning aviation fuel. The influence of this loading is considerable on the reinforcement bar layers near to the outside surface of the roof. The influence of thermal loading is small on the reinforcement bar layers near to the inside surface of the roof state of stress.

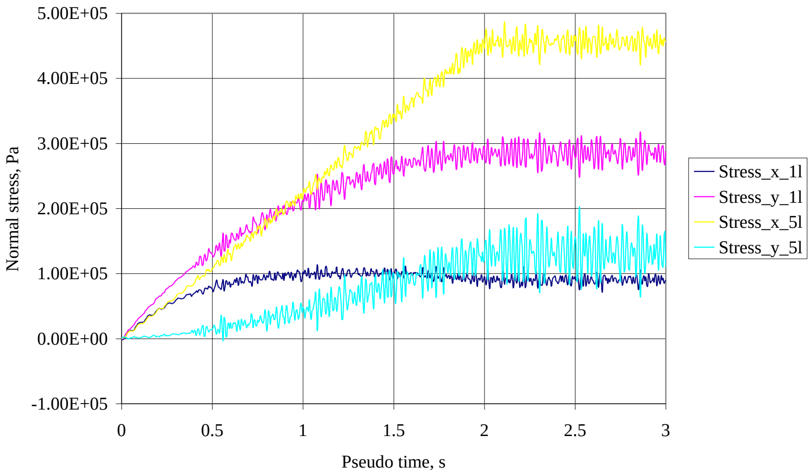


Fig.9: Normal stresses in concrete element 8623 (integration points 1 and 5).

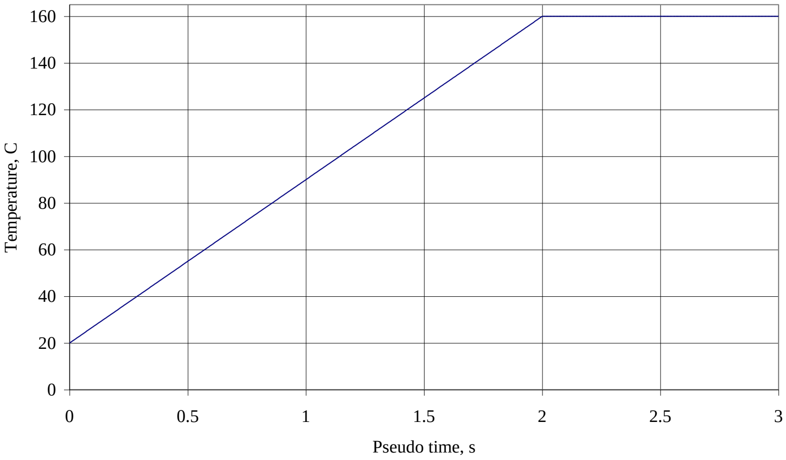


Fig.9: Temperature in concrete element 8623.

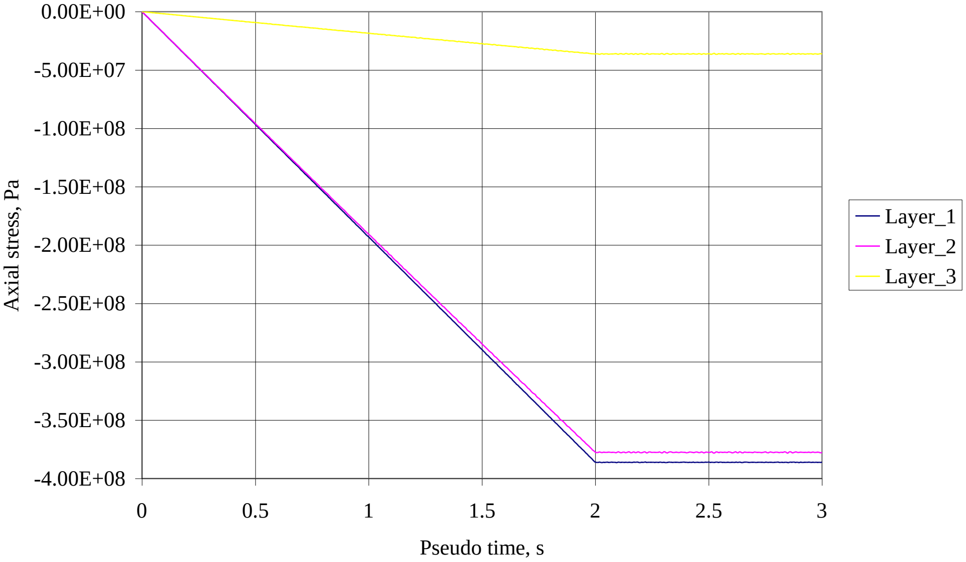


Fig.10: Axial stresses of reinforcement bars in element 8623.

CONCLUSION

The thermal degradation of the structural strength of an Ignalina NPP building structure due to thermal loading caused by burning aviation fuel on the roof was carried out using the finite element method. The computer code TEMP-STRESS was used to determine the transient temperature distribution through the thickness of the roof subjected to an aircraft fuel fire that would burn for 2.5 hrs. The computer code NEPTUNE was used for the thermal stress analysis due to thermal and gravity loading for the case an aviation fuel fire. The "slow dynamic loading" method was used to obtain the solution of this static problem. An examination of the results validated the use of this method. The influence of thermal loading is small on the concrete stress condition in case a fire caused by burning aviation fuel. The results show that the largest normal stress σ_{xx} in concrete is 0.99 MPa in tension and a value of 0.064 MPa in compression.

The maximum axial stress in the reinforcement bar near the outside surface of the roof is about 392 MPa. The yield stress for rebar steel is 392 MPa (standard data). The axial stress in the reinforcement bars near the inside surface of the roof is about 36.7 MPa. According to these results, the influence of thermal loading is larger on reinforcement bars near the outside surface of the roof. The influence of thermal loading is small on the reinforcement bars near the inside surface of the roof.

Because the interface temperature between the outside surface of the roof and the inside surface of the burning fuel is only 300 ^{0}C, the structural strength of the concrete and reinforcing steel does not degrade much. Therefore, the structural degradation of the concrete and reinforcing steel roof of an Ignalina NPP building would be small.

ACKNOWLEDGMENTS

This research was funded by a grant (No. ATE-10/2010) from the Research Council of Lithuania. The authors also want to express gratitude to the administration and technical staff of the Ignalina NPP, for providing information regarding the operational procedures and operational data.

REFERENCES

[1] Almenas, K., Kaliatka, A., Uspuras, E. (1998). *Ignalina RBMK-1500. A Source Book, extended and updated version*, Ignalina Safety Analysis Group, Lithuanian Energy Institute.
[2] Kulak, R.F. and Fiala, C. (1988). Neptune a System of Finite Element Programs for Three Dimensional Nonlinear Analysis. *Nuclear Engineering and Design,* vol. 106, pp. 47-68.
[3] TEMP-STRESS, A Thermomechanical Finite Element Program for the Analysis of Plane and Axisymmetric Reinforced/Prestressed Concrete Structures, User's Manual by A.H. Marchertas and P.A. Pfeiffer, 1998.
[4] A. H. Marchertas and R. F. Kulak. "Numerical Modeling of Concrete Under Thermal Loads", Nuclear Engineering and Design, 68, pp. 225-236, 1981.
[5] R.F. Kulak and P.F. Pfeiffer, "Pretest Analyses of a 1;4-Scale Prestressed Concrete Containment Vessell," Transactions 16th International Conference on Structural Mechanics in Reactor Technology, Washington DC, USA, August 12-17, 2001, Paper # 1180 (H02/1).
[6] DUNDULIS G., KULAK R.F., MARCHERTAS A., UŠPURAS E. *Structural integrity analysis of an Ignalina nuclear power plant building subjected to an airplane crash //* Nuclear engineering and design. ISSN 0029-5493. 2007. Vol. 237, Iss. 14, p.1503-1512.
[7] Dundulis G., Kulak F. R., Alzbutas R., Ušpuras E. Integrated probabilistic analysis of nuclear power plant building damage due to an aircraft crash // International Journal of Crashworthiness. ISSN 1358-8265. 2011. Vol. 16, No. 1, p. 49-62
[8] Norms and Rules for Buildings SNiP 2.03. 04-84. (in Russian).
[9] T. Belytschko, and B.J. Hsieh, 1973, "Nonlinear Transient Finite Element Analysis with Convected Coordinates", International Journal for Numerical Methods in Engineering., Vol. 7 pp. 255-271.
[10] Taking into account external effects of natural and technological character on nuclear- and radiation-hazardous facilities. PNAE G-05-035-94, Moscow, 1995.
[11] Kulak, R. F., and Fiala, C. (1989). A Method for Three-Dimensional Structural Analysis of Reinforced Concrete Containments. *In: Shin, Y. S., Wang, C. Y., Colton, J. D. and Kulak, R. F. (Eds.), Shock and Wave Propagation, Fluid Structure-Interaction and Structural Response,* Vol. 159, pp. 115-123, ASME PVP Conf., Honolulu, Hawaii.