

## CFD MODELLING OF THE BRACED BARREL VAULT Made from Rectangular Hollow Sections in Natural Fire

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### Abstract

In the paper the CFD modelling of the complicated braced barrel vault made from rectangular hollow sections in natural fire is presented. The barrel vault is covering a shopping arcade. The covered area of this shopping arcade is 40 m x 80 m. The shopping arcade has two levels. One of the levels is underground. The model is built in full 3D. Natural fire is simulated in FDS software for different fire scenarios. Fire load densities, fire growth rate and rate of heat release are determined from EN 1-1-2: General Actions - Actions on structures exposed to fire. Heat release rate per area is determined for  $t^2$  function. The analysis shows temperature of rectangular hollow sections, distribution of temperature in the shopping arcade, visibility and heat fluxes. The temperatures or heat fluxes can be transferred to the non-linear structural analysis in finite element code Abaqus.

**Keywords:** fire safety, CFD, FDS, natural fire, braced barrel vault

### INTRODUCTION

Nowadays, examples of the expressive use of steel is more and more. Barrel vault is architectural form, used since antiquity (Makowski et al, 1985). The example of braced barrel vault is the construction of the roof of the Atrium Promenada Shopping Center which is presented in Fig. 1. The another example of braced barrel vault is the shopping arcade of the Heart of Atlantis Shopping Centre. The construction of the shopping arcade was designed by Zdzislaw Kurzawa and Lukasz Polus and was presented in Fig. 2.



Fig. 1 Braced barrel vault in the Atrium Promenada Schopping Center

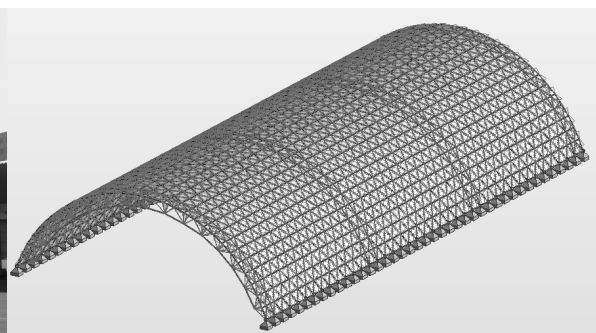


Fig. 2 Braced barrel vault of the shopping arcade in the Heart of Atlantis

Structural members of the construction presented in Fig. 2 are 75mm wide rectangular hollow sections which are 4mm thick. The roof of shopping arcade is a single layer grid structure with four 3D truss which improve the stability of the structure. The covered area is 40 m x 80 m and the shopping arcade has two levels. One of the levels is underground. A lot of people may go shopping and fire is the greatest danger. Design for fire is an important in the design process of the shopping arcade. In the paper, the natural fire in the shopping arcade is presented.

# 1 NATURAL FIRE MODEL IN SHOPPING ARCADE COVERED BY BRACED BARREL VAULT

The model of shopping arcade was created in PyroSim which is a graphical user interface for the Fire Dynamics Simulator and presented in Fig. 3. Model in Smokeview is presented in Fig. 4.

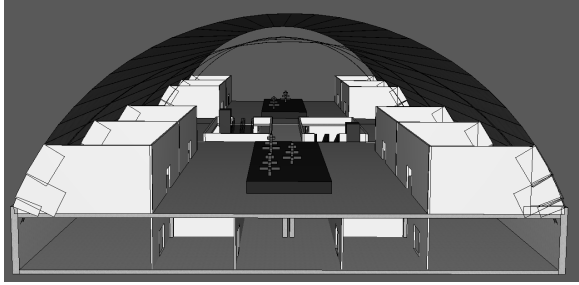


Fig. 3 The model of shopping arcade created in PyroSim

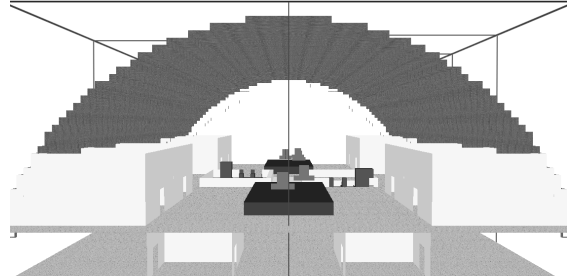


Fig. 4 The model of shopping arcade in Smokeview

The braced barrel vault was modeled as a cylindrical shell with a thickness of 4 mm. Design fire scenarios, characteristic fire load densities  $q_{f,k}$ , compartment floor areas  $A_f$ , fire growth rates, RHR densities, fire growth rates and powers released by the fire  $Q$  are presented in Tab. 1.

Tab. 1 Design fire scenarios

Design fire scenario	$q_{f,k}$ [MJ/m <sup>2</sup> ]	$A_f$ [m <sup>2</sup> ]	Fire grow rate [-]	RHR [kW/m <sup>2</sup> ]	$Q$ [MW]
Fire located to block primary means of escape Public space on the ground floor	122	184	Slow	250	17,64
Fire located to block primary means of escape Public space underground	122	184	Slow	250	17,64
Fire exposing braced barrel vault Shopping centre on the ground floor	730	88	Fast	250	22,00
Fire involving a large area Shopping centre underground	730	182	Fast	250	45,50

The most severe fire is in the shopping centre on the ground floor. Design value of the fire load  $q_{f,d}$  is given in Eq.(1).

$$q_{f,d} = \delta_{q1} \delta_{q2} \delta_n m q_{f,k} \quad (1)$$

where  $q_{f,k}$  characteristic fire load density  
 $m$  combustion factor  
 $\delta_{q1}$  factor for different floor areas  
 $\delta_{q2}$  factor for different types of occupancy  
 $\delta_{qn}$  factor which takes into account the effect of active fire fighting measures

The factor  $m$  is a combustion factor which value is between 0 and 1 (Franssen et al, 2010). The combustion factor is assumed as 0,8. The factor  $\delta_{q1}$  which takes into account the fire activation risk due to the size of the compartment, 88 m<sup>2</sup> is equal 1,212. The factor  $\delta_{q2}$  which takes into account the fire activation risk due to the type of occupancy, shopping centre, is equal 0,78. The factor  $\delta_{qn}$  takes into account the different active fire fighting measures:

- $\delta_{n1} = 1,0$ ; no automatic water extinguishing system
- $\delta_{n2} = 1,0$ ; no independent water supplies

- $\delta_{n3} = 1,0$ ; no automatic fire detection and alarm by heat
- $\delta_{n4} = 1,0$ ; no automatic fire detection and alarm by smoke
- $\delta_{n5} = 1,0$ ; no automatic alarm transmission to the fire brigade
- $\delta_{n6} = 1,0$ ; no fire brigade stationed in the building
- $\delta_{n7} = 0,78$ ; off site fire brigade
- $\delta_{n8} = 1,0$ ; safe access routes
- $\delta_{n9} = 1,0$ ; normal fire fighting devices
- $\delta_{n10} = 1,5$ ; no smoke exhaust system
- $\delta_{qn} = 0,78 \cdot 1,5 = 1,17$

Design value of the fire load is equal  $646,05 \text{ MJ/m}^2$ . The evolution of the RHR is presented in the Fig 5.

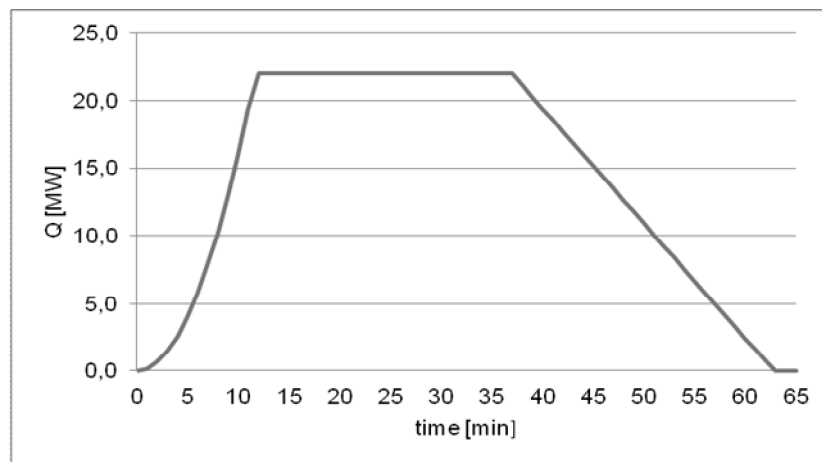


Fig. 5 The evolution of the rate of heat release

## 2 SIMULATION RESULTS

Smokeview 5.6 - Oct 29 2010

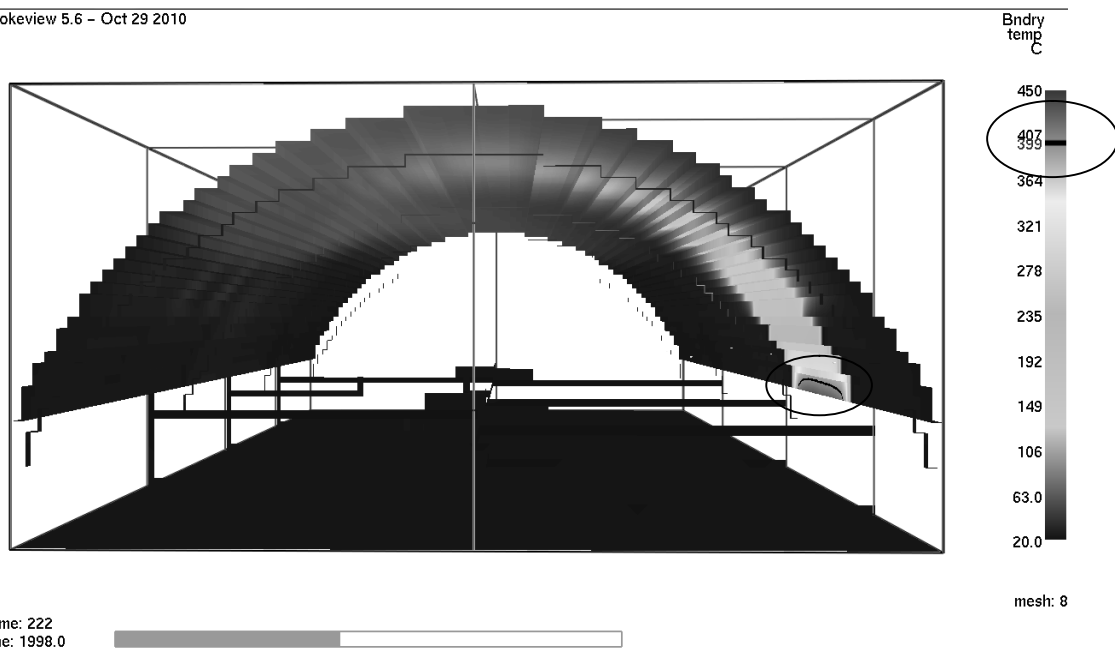


Fig. 6 The wall temperature, mesh  $0,5 \text{ m} \times 0,5 \text{ m} \times 0,5 \text{ m}$  1998 s

The wall temperature and the adiabatic surface temperature were obtained as an output from a fire model. The wall temperature shows the temperature of construction. The adiabatic surface

temperature, which considers a surface as a perfect insulator exposed to heating conditions, should be used to calculate heat transfer to fire-exposed structures (Wickstrom et al, 2007). The adiabatic surface temperature is the solution to problems with heat flux boundary conditions like: „the net heat flux to a surface computed by the fire model is dependent on the corresponding surface computed by the same fire model” (Wickstrom et al, 2007). The wall temperature is presented in Fig. 6 and Fig. 7. The maximum wall temperature is equal to 433°C.

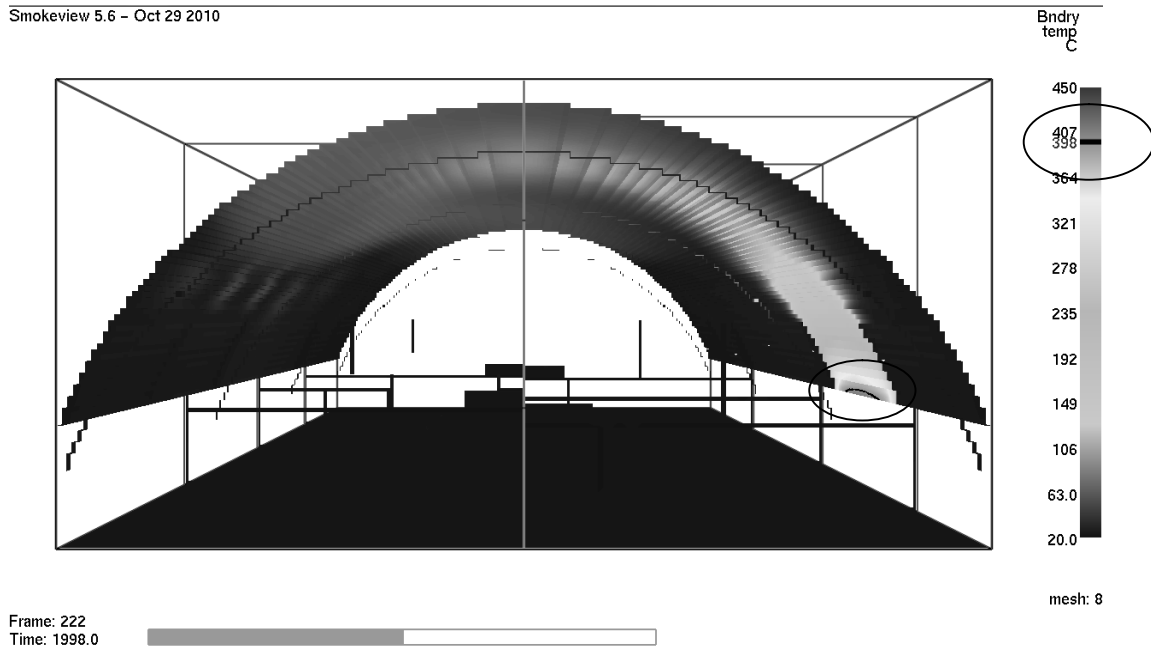


Fig. 7 The wall temperature, mesh 0,25 m x 0,25 m x 0,25 m 1998 s

The adiabatic temperature is presented in Fig. 8.

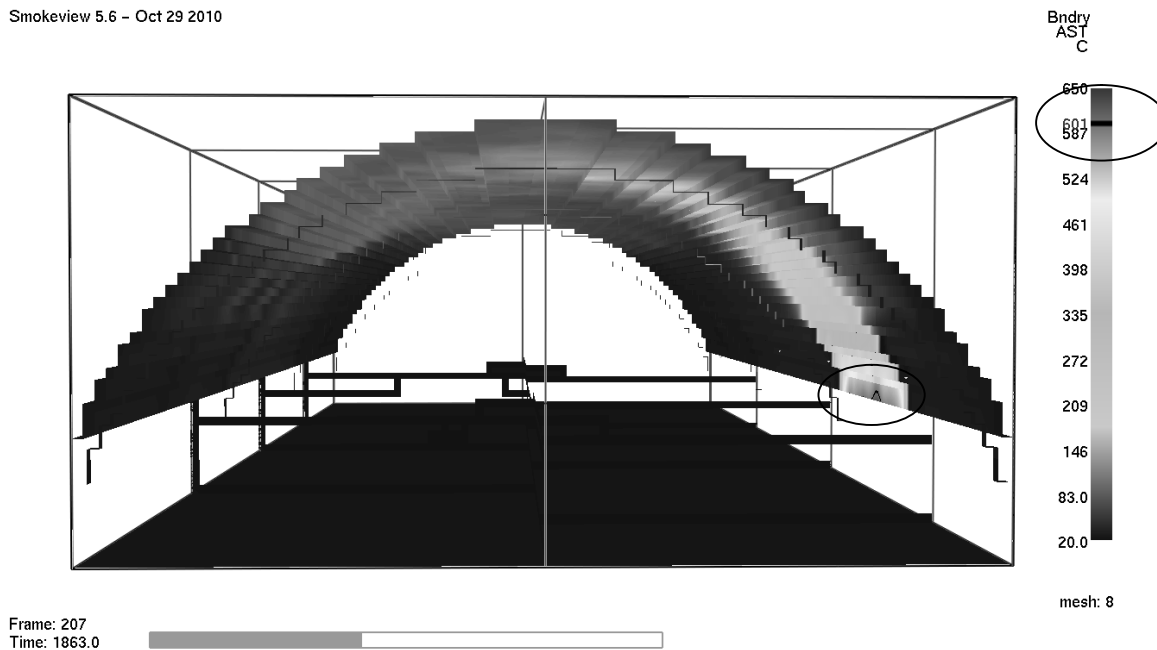


Fig. 8 The adiabatic surface temperature, mesh 0,5 m x 0,5 m x 0,5 m 1863 s

The maximum adiabatic temperature is equal to 623°C. The wall temperature and the adiabatic temperature in the other scenarios are lower.

### 3 CRITICAL TEMPERATURE

According to EN 1993-1-2 the critical steel temperature  $\Theta_{a,cr}$  at time  $t$  for a uniform temperature distribution may be determined for any degree of utilisation  $\mu_0$  at time  $t = 0$  using Eq. (2).

$$\Theta_{a,cr} = 39.19 \ln \left[ \frac{1}{0.9674 \mu_0^{3.833}} - 1 \right] + 482 \quad (2)$$

The degree of utilisation was obtained from Autodesk Robot Structural Analysis Professional software for the fire situation and presented in Fig.9. The combination of actions for accidental situation is given by Eq. (3) (EN 1990).

$$G_k + 0,2S + 0,2W \quad (3)$$

where  $G_k$  all permanent actions  
 $S$  snow loads  
 $W$  wind loads

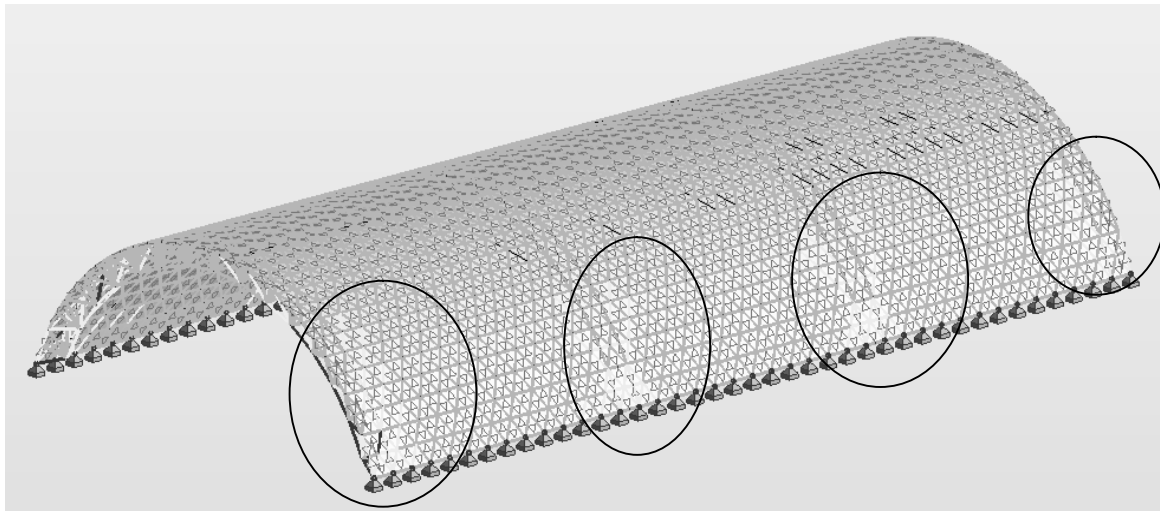


Fig. 9 The degree of utilisation, the most loaded structural members are marked

The critical temperature of the most loaded element,  $\mu_0 = 0.48$ , is equal to  $591,2^\circ\text{C}$ .

### 4 SUMMARY

The wall temperature is lower than the critical steel temperature of the most loaded element. The building is huge and hot smoke can easily propagate. The most severe fire is the fire in the shopping centre on the ground floor which has not the highest power of all fires but it exposes braced barrel vault. The adiabatic surface temperature should be used to calculate heat transfer to fire exposed braced barrel vault and can be transferred to the non-linear structural analysis in finite element code Abaqus.

### ACKNOWLEDGMENT

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