Structural Fire Design and Optimisation of a Building

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Abstract

The "Maison de la Paix" building will be built for the Graduate Institute of International and Development Studies in Geneva (IHEID). At its heart will be a library, numerous auditoriums and seminar rooms and a cafeteria. A complete fire analysis has been performed to optimise the steel structures.

Keywords: fire; structures; building; CFD; FEM analysis; performance-based design.

Fig. 1: Virtual image of the four "petals" comprising the building

Introduction

Project

A new, complex-shaped, fully transparent, concrete and steel building will be inaugurated in Geneva in 2013 (*Figs. 1 and 2*). This high-quality work of architecture, the "Maison de la Paix" building, was designed by the Swiss architects IPAS in Neuchâtel and SANCHA, an engineering office in Yverdon-Les-Bains, to be the long-term home for the Graduate Institute of International and Development Studies (IHEID). The building will have an auditorium for 600 people, 15 classrooms, ten seminar and workrooms, a library with a surface of 4500 m^2 on two levels, a cafeteria and a terrace.

As requested by the authors of the project, while the slabs will be in prestressed reinforced concrete, in all vertical structures, the facades and the truss over the conference room, steel hollow structural sections (HSSs) will be used. As the first step, the whole building has been designed for the normal "cold" ultimate limit state (ULS); however, this design process is not described here.

Once the new building is complete, the structural steel will be visible. It was determined that passive fire protection for the steel would be very expensive and could be problematic in terms of durability and costs of application and maintenance.

Since the steel structure that will be used in the new building is sensitive to elevations in temperature as in case of a fire, it was necessary to analyse each sub-structure in terms of thermal action and structural behaviour. The results of these analyses are discussed in the following sections.

Description of Structure

Vertical Structures

All the vertical loads will be supported by HSS columns. The circular 323,9 mm tubes, with a steel grade of S355, have wall thicknesses varying from 10 to 40 mm. It is important to note that even if an HSS column is 40 mm thick, its temperature will also attain an untenable level (as the yield strength drops), even if it takes more time than for a tube with thinner walls to reach that level. Although oversizing (overdesign) could have been an option for a few members, in this project, it was deemed uneconomical. The chosen fire design strategy was thus to optimise the HSSs for the small loads, as well as the higher loads, to switch to composite columns, with or without steel rebar reinforcement.

Truss Girder

The other steel structure that required analysis was the three-dimensional (3D) truss girder (*Fig. 2* left side and *Fig. 3*), which is also made of HSSs that can support the loads from six floors above it. The upper members of the truss react with the concrete slab as a composite section, while the other truss members are normal steel sections. A 3D structural analysis was performed to analyse the global behaviour in a fire situation and to optimise the welding thickness.

Fire Analysis

Thermal Actions

As the building must achieve 60 min of fire resistance (R60), the standard approach, using the ISO fire curve as the temperature input for thermal calculations, quickly showed that this target time cannot be reached with the relatively thin walls used in the hollow sections. Therefore, to check whether the steel structures could stay unprotected, it was necessary to use a performance-based approach. Several natural fire scenarios (with zone models), localised fires and simplified computational fluid (CFD) simulation using the Fire Dynamics Simulator (FDS) software[1] were used to heat the sections (*Fig. 4*).

Natural Fires

The natural fire scenarios have been calculated according to EN 1991-1-2, Annex E[2] and the Natural Fire Safety Concept (NFSC).[3] Owing to the low thermal loads (quantity of combustible matter) present in the building that are estimated to a medium level, $q_{f,k} \cong 500$ MJ/m^2, and the active protection measures taken in the project (detection, sprinkler, smoke management, etc.), the expected gas temperature should

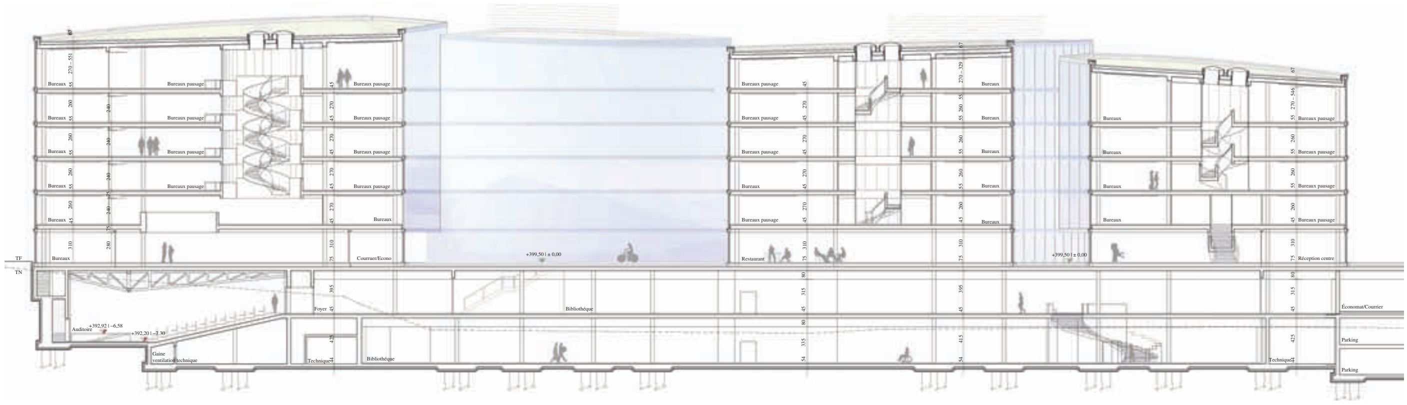

Fig. 2: Longitudinal view

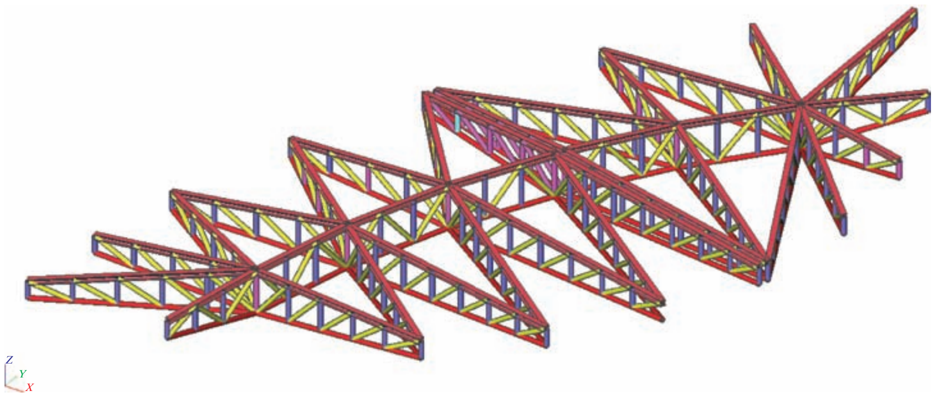

Fig. 3: Three-dimensional structural model of the truss over the conference room (SCIA Engineer model)

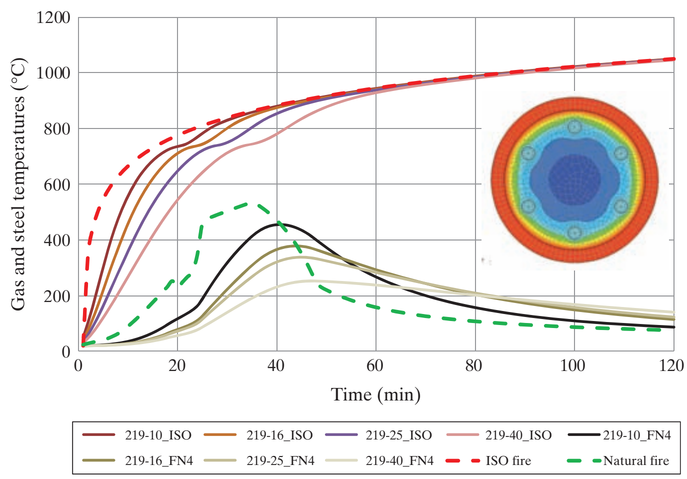

Fig. 4: Heating of the steel ring of the column sections in the conference room using ISO and natural fires (plain lines indicate diameter and thickness of the tubes)

be lower than that in the ISO fire curve. This means that the maximum temperature expected in the steel sections will stay relatively low.

Figure 4 shows the significant temperature difference in the conference room when using the natural fire scenario as opposed to the ISO fire curve. For example, the external steel ring heats up to 800°C after 30 min of exposure to ISO fire. With the natural fire, the HSSs only heat up to 450°C: the steel resistance is still 100% of the original (cold) value. At 400°C, the E-modulus decreases (the decrease starts at 200°C), thus making deformation the main concern, a topic that is discussed later.

In the natural fire scenario parameters, the use of a double sprinkler system helped to reduce the impact of the fire, with one sprinkler directed towards the fire and the other directed upwards to cool the structure. The hypotheses that were discussed with and agreed on by the local fire authorities allowed considering the proposed active measures with a low factor $\delta_n = 0{,}44$ in the design fire load, $q_{f,d}$, calculation (according to Eq. (1) in Annex E.2):

$$q_{f,d} = q_{f,k} \cdot m \cdot \delta_{q1} \cdot \delta_{q1} \cdot \delta_n$$

Fire load density formula (MJ/m²)

Finally, as the glazing behaviour is still a big concern in fire engineering, several scenarios were calculated with a two zone model,[4,5] considering different room geometries, window-breaking scenarios (*Fig. 5*) and fire loads. It was observed that depending on the opening factor, the maximal gas temperature can easily raise to 800°C, with a δ of more than 200°C between the extreme values. Finally, as the glazing constructive solution was not decided at the time of this study, the worst reasonable case was chosen for the office fire scenarios.

Localised Fires

In the parts of Eurocode concerning fire, in particular, EN 1991-1-2[2] and EN 1993-1-2,[6] localised fire formulae are given for heat flux or air temperature evolution in the fire, as a function of the height or as a function of the horizontal distance from the fire. However, the Eurocodes lack methods that can be used for the analysis of a column situated near a fire, not in the flame itself, but sufficiently close to be affected by the radiation (*Fig. 6*). In order to take into account this fire scenario, an analytical model developed by Vassart–Zanon[7] was applied to the study described here.

The flame can be modelled by a geometrical surface emitting a flux. The intensity of the flux will vary with the temperature of the flame. The flux received at a certain distance of the flame will vary with the shape of the radiative surface, the intensity of the radiation and the view factor of the impacted element.

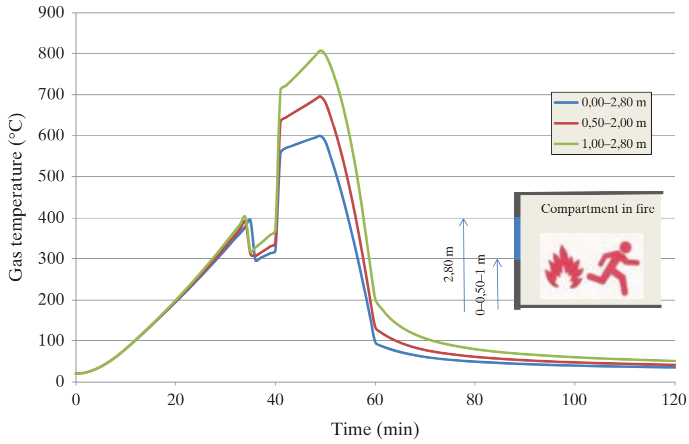

Fig. 5: Influence of the window breakage sequence on the gas temperatures in natural fire simulation (Ozone)

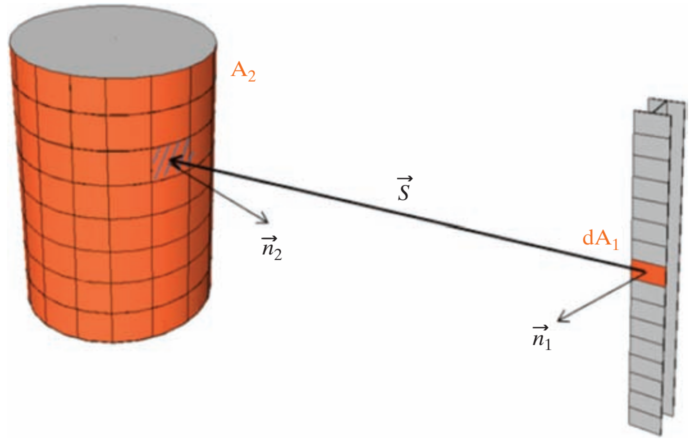

Fig. 6: Radiative flux from source to element

The shape of the flame can vary depending on the intensity of the fire and depending on the position of the ceiling (*Fig. 7*).

In this calculation, the fire scenario was a pallet of 500 kg of paper located at a distance of 300 mm from the column. This scenario is less conservative than the ISO curve that was applied to the whole building, but more severe and safer than when only the uniform temperature in the two zones of the zone model is considered (that is instead suitable for the whole compartment volume). The fluxes provided to the vertical elements were introduced in the Finite Element Model (FEM) Software SAFIR[8] to calculate the temperatures inside the tubular sections.

CFD Simulations

In addition to the simplified zone model or localised fires, several CFD simulations were performed with the FDS software (*Fig. 8*) to verify the hypotheses used in the previous calculations. The first simulations were performed for the conference room, the others to validate the window-breaking scenarios and their influence on the maximal gas temperature inside the office compartments.

These simulations also showed that

- the gas temperature reached by the Ozone software was of the same magnitude (within ±100°C);
- the hypothesis formulated for the window breakage sequence had the same effect on the FDS simulation and the Ozone models;
- a highly resistant windows system (many layers) that can resist fires without complete damage could stay in place even when the glass is broken, thereby modifying the air movement.

(a) *(b)* *(c)*

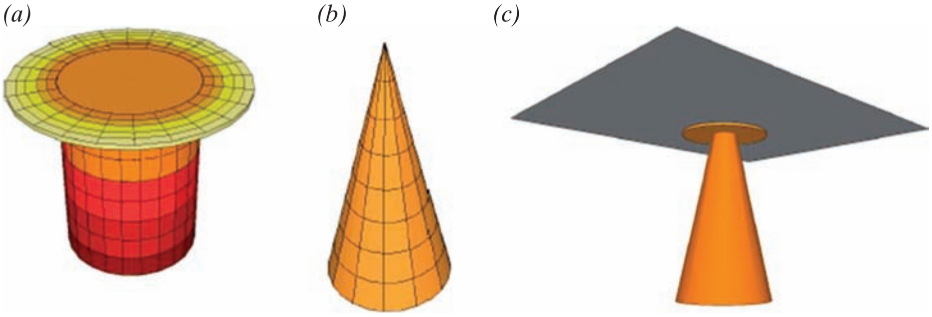

Fig. 7: Different shapes of the flame: (a) cylinder of flame impacting the ceiling, (b) cone of flame not impacting the ceiling and (c) cone of flame impacting the ceiling

Structural Analysis

Conference Room

The truss girder over the conference room supporting several storeys was modelled and verified with a 3D SAFIR[8] beam and shell model. *Figure 9* shows the evolution of the deflection in the middle of the truss girder. The first deflection is due to the loading of the structure, then the heating begins and the thermal elongations together with the E-modulus drop cause the deflection to increase. When the fire is controlled, the temperature gets cooler and the thermal elongations are recovered, while permanent deformations stay. In a natural fire scenario, the deflections after the fire is controlled are relatively low and the structure will not fail within the first 60 min of the fire.

It has been then showed that even if a fire occurs, the heating of the tubes is very limited, as well as the deflections, that could cause great collateral and expensive damage.

Facades

The tubular truss facades (*Fig. 10*) were also modelled and checked with natural fire scenarios.

As the facade structure was overdesigned to deflect very little in the normal serviceability limit state (SLS) design situation, there is a great level of inherent safety: the resistance is thus not a great concern even during fire. The deflection during fire was thus deemed reasonable and admitted as sufficient for the SLS. Again, the deformations were a concern in this part of the building, but as the active fire protection measures (sprinklers) will be installed (a 98% effectiveness probability is considered for sprinklers in Switzerland), the residual risk is very low, and accepted.

Columns

Finally, the whole vertical steel column system was designed and optimised in the fire situation, using hypotheses from natural fires and localised fire scenarios described in the section *Description of Structure*. First, verifications were conducted using the NRCC method,[9] which is mainly based on laboratory full-scale tests. These calculations showed that with a reasonable load ratio (2000–4000 kN), the unreinforced concrete-filled HSS columns could withstand high loads (up to 8000 kN). This was confirmed by further FEM non-linear calculations using SAFIR.

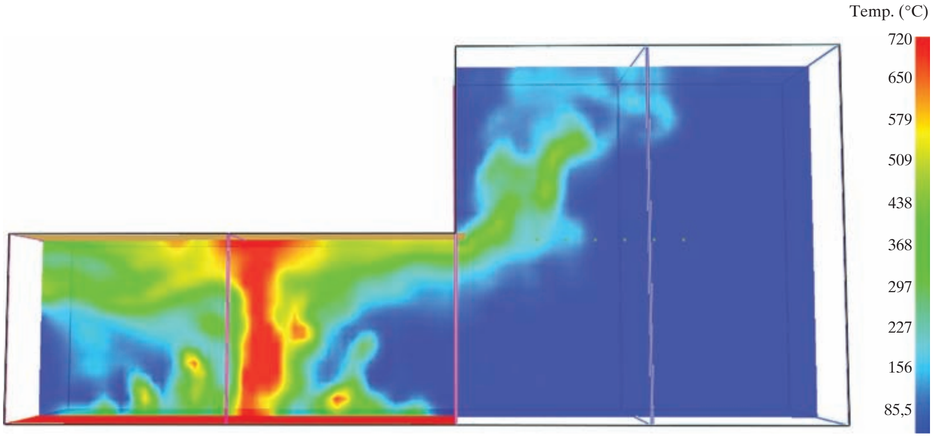

Fig. 8: FDS simulation for a typical simplified office compartment. Gas temperature visualisation with the windows open (glass broken)

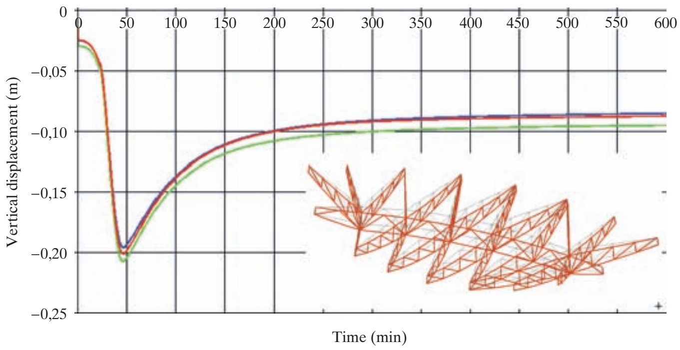

Fig 9: Maximal and residual deflections under a natural fire scenario

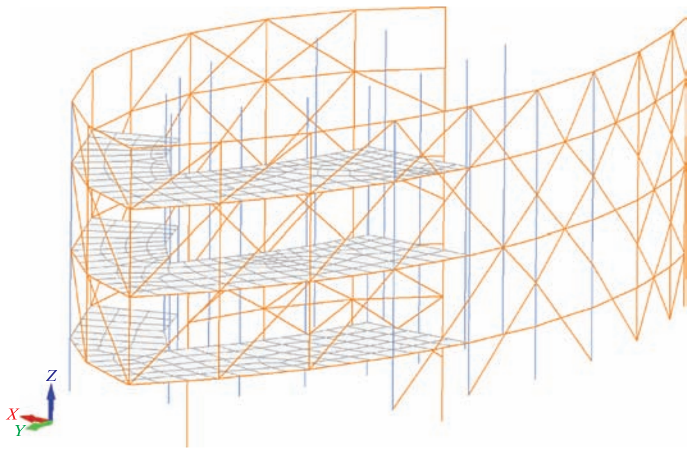

Fig. 10: SAFIR 3D structural model of the truss facade

However, using FEM together with the localised-fire-heated sections, it was possible to push the optimisation to its reasonable maximum (being not extreme as well as keeping safety in mind). An incremental procedure was used to find the critical load capacity under the natural and localised fire situations, knowing that this load is a function of the evolution of the section temperature that varies non-linearly with time. Many calculations were necessary to determine the critical load capacity, as every group of columns has a different load and buckling length. As a result of the procedure used, an optimisation of the section much closer to the effective critical temperature of each group of columns was achieved as compared to the values obtained with the much more conservative ISO fire approach.

Conclusions

The performance-based design approach used in this project has been a full success. The steel structure, as desired by the architect, remained unprotected and slender. The structural fire optimisation that was performed proves that the fire analysis and design process is really valuable and sustainable when achieved by a well-trained and experimented specialist. Thanks to the use of the new localised fire method proposed by Vassard and Zanon, the columns have been optimised within a conservative safety concept. The columns with lower load can stay unprotected, while the columns subjected to higher loads will be constructed as reinforced steel–concrete composite sections. The truss girder over the conference room and the façade structure will stay completely unprotected, thanks to the active fire protection measures and at the price of sophisticated design verifications.

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SEI Data Block

Owner:
IHEID

Contractor:
Steiner - Total Services Contractor

Steel (t):	1700
Concrete (m^3):	20 000
Rebars (t):	2000
Pre-stressing steel (t):	5400
Estimated cost (CHF million):	170
Service date:	June 2013