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FIRE ENGINEERING, ARCHITECTURE & SUSTAINABILITY

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ABSTRACT

It may appear to be an impossible challenge to try to bridge fire engineering to architecture and further on to sustainability. Nevertheless this is being done as new and credible developments in fire engineering permit the architect to get rid of really now old fashioned fire resistance requirements. This means however that structural components may now remain visible and unprotected, which not only represents a quantum leap for good architecture, but constitutes also a real advantage in favor of solid sustainability.

Keywords: Active fire safety measures, architecture for current social necessities, economic construction, rational use of resources, realistic fire design, recycling of materials, simple and true architecture

INTRODUCTION

Starting in the 1980's up to the year 2000 an incredible number of research projects related to fire engineering took place worldwide, but which above all in Europe were orientated to general calculation procedures and to realistic and natural fire scenarios (Schleich *et al.* 1987a, 1991, 1993, 1997a, 1997b, 2002, 2003). At the same time the elaboration of the full set of Eurocodes was performed, dealing with all structural materials from concrete to masonry and for normal service conditions as well as for accidental situations like fires or earthquakes.

Hence the opportunity was given to incorporate into those Eurocodes also the principles of general or simplified calculation procedures for the fire situation, as well as the allowance to assume realistic i.e. natural fires instead of the previously imposed conventional fires like the ISO-fire.

Consequently we may now design structures according to realistic and so generally much more economic fire conditions. The main advantage however lies in the fact that the architect, if fire aspects are considered right at the beginning of the structural conception, is practically liberated from any constraints regarding insulating & hiding structural bearing components like floors, beams, bracings or columns.

Of course as these components as well as their welded or bolted connections may now also remain visible, structural detailing should be well proportioned, which in itself constitutes a further challenge for the architect and the engineer. If structural detailing is poorly done it would obviously be better to hide those mishaps. So one has to take care of detailing, which is quite feasible and brings even added value to architecture as shown in the buildings given hereafter, for which fire engineering was performed by the author (Schleich 2006a, 2006b, 2007, 2008, 2009, 2010).

Modern steel architecture following previous guidelines also contributes to a realistic sustainability. Indeed insulation materials, formerly needed to protect against fire, can now be eliminated, hence facilitating by far any later transformation of the building and even allowing a much easier dismantling or re-use of structural construction elements. Furthermore as the importance of active fire safety measures is recognized, this will have a direct favorable effect as well on the occurrence probability of severe fires and their subsequent disastrous environmental impact as on the number of injured people or fatalities.

FIRE ENGINEERING

Fire engineering comprises an impressive number of engineering fields, which have all to be operational in order to get satisfying results. First of all the **resistance** and the thermal properties of the various materials, used to guarantee the stability of structural components, have to be known in function of high temperatures. This concerns concrete, steel, timber, masonry and aluminium and refers to their stress-strain relationships and also to thermal elongation, thermal conductivity and specific heat, all of which shall finally be known for temperatures varying up to 1000°C. This is a "conditio sine qua non" if one wants to be able to simulate the behaviour of slabs, beams, columns or frames in the fire situation. A further condition of course was to elaborate consistent thermo-mechanical softwares (Dotreppe 1980, Franssen 1987) permitting also to analyse the global behavior of complete structures under f.i. a fire restricted to a compartment (Scheich *et al.* 1988a, 1990). It was however clear from the beginning, that these developments have to be confronted and checked against fire tests on loaded beams, columns and even frames (Kordina *et al*. 1985a and b, Minne *et al*. 1985). Hence more or less sixty fire tests were planed and commissioned by the author and performed throughout Europe in the well known Fire Stations in Gent (B), Braunschweig (G), Maizières-lès-Metz (F) and Boremwood (UK). Such a scientific procedure allowed finally to get a design tool permitting since then to analyse the structural resistance without being obliged to proceed to expensive and time consuming fire tests before starting any construction.

The message here consists in the obligation to proceed to new tests in the future, if new materials or new construction methods were to be used. Indeed we have to be aware that always, even with the most perfect software, we as engineers shall simulate physical reality and not any pious feelings.

As a consequence to the success obtained when performing such a vast set of practical fire tests, by the way still exclusively under ISO conditions following the heating curve given by

$$\theta_{furnace} = 20 + 345\log_{10}(8t + 1) \quad [\,°C] \qquad (1)$$

with t in minutes,

it became obvious that **composite construction elements** for beams, columns and slabs behaved astonishingly well in the fire situation. This was exhibited as well for temperatures inside the composite cross-sections which remained rather low over a long period of time, as for global deflections of beams which also increased quite slowly, as for elongations and lateral deformations of columns which grew in a rather slow and progressive manner. Moreover all these physical parameters like also the failure time became predictable as a credible thermo-mechanical software was available (Baus and Schleich 1986, Schleich 1987b and 1988b). That however allowed, quasi as a by-product, to develop new innovative construction elements, which from the architectural point of view became more expressive and more attractive.

The study of **real or natural fires**, instead of conventional fires like the ISO-fire conceived around the end of the nineteenth century, is the second most important engineering field. The idea to design on the basis of more realistic fires existed of course since 1958, when Kawagoe K. published in Tokyo his fires in rooms, but only by the ability to take account through calculation of a given heating curve was it possible to favor progressively design based on natural fire scenarios. However those so-called natural heating curves shall also correspond to the physical reality of a given compartment. This means nevertheless that all relevant parameters shall be considered i.e. the thermal properties of the surrounding surfaces, the quantity and the inflammability of the fire load, the ventilation conditions like the breaking of windows function of the air temperature etc.

Hence, after a first study of the effect of natural fires on structures (Schleich *et al*.1989, Wesche *et al*. 1989), a new set of research projects were undertaken starting in 1993 when studying heating conditions in large compartments and underground car parks (Schleich *et al*.1997a, 1997b), as well as the influence of water extinguishing means on the temperature evolution (Klaus, 1995). The breakthrough in this field on natural fires was however achieved on behalf of the work on the natural fire safety concept and on a set of 100 new tests on the evolution of temperatures in a compartment (Martin *et al*.1999, Schleich 2002 & 2003, Cadorin 2003). Indeed these research projects, starting in 1994, were actively supported by eleven European countries and led among others to the elaboration of the two zones software "OZONE", permitting to establish the natural heating curve in a compartment in function of the most relevant physical parameters.

Active fire safety measures constitute a further engineering field, which together with probabilistic considerations, allow finally to analyse the efficiency of these life safety means and to consider their indirect effect on the structural stability. Indeed active fire safety measures reduce the potential severity of a fire and even its probability of occurrence. **Life safety** considerations have been conducted using Bayesian Networks (Holicky and Schleich 2001, Schleich 2005), showing that f.i. sprinklers play the role of life saving through smoke reduction, but sprinklers simultaneously decrease the structural failure probability by reducing the probability of flashover. Further it may be assumed that smoke detectors connected to acoustic fire alarm favor the evacuation of people, but at the same time allow fire fighters an earlier intervention and hence a greater chance to properly stop the fire.

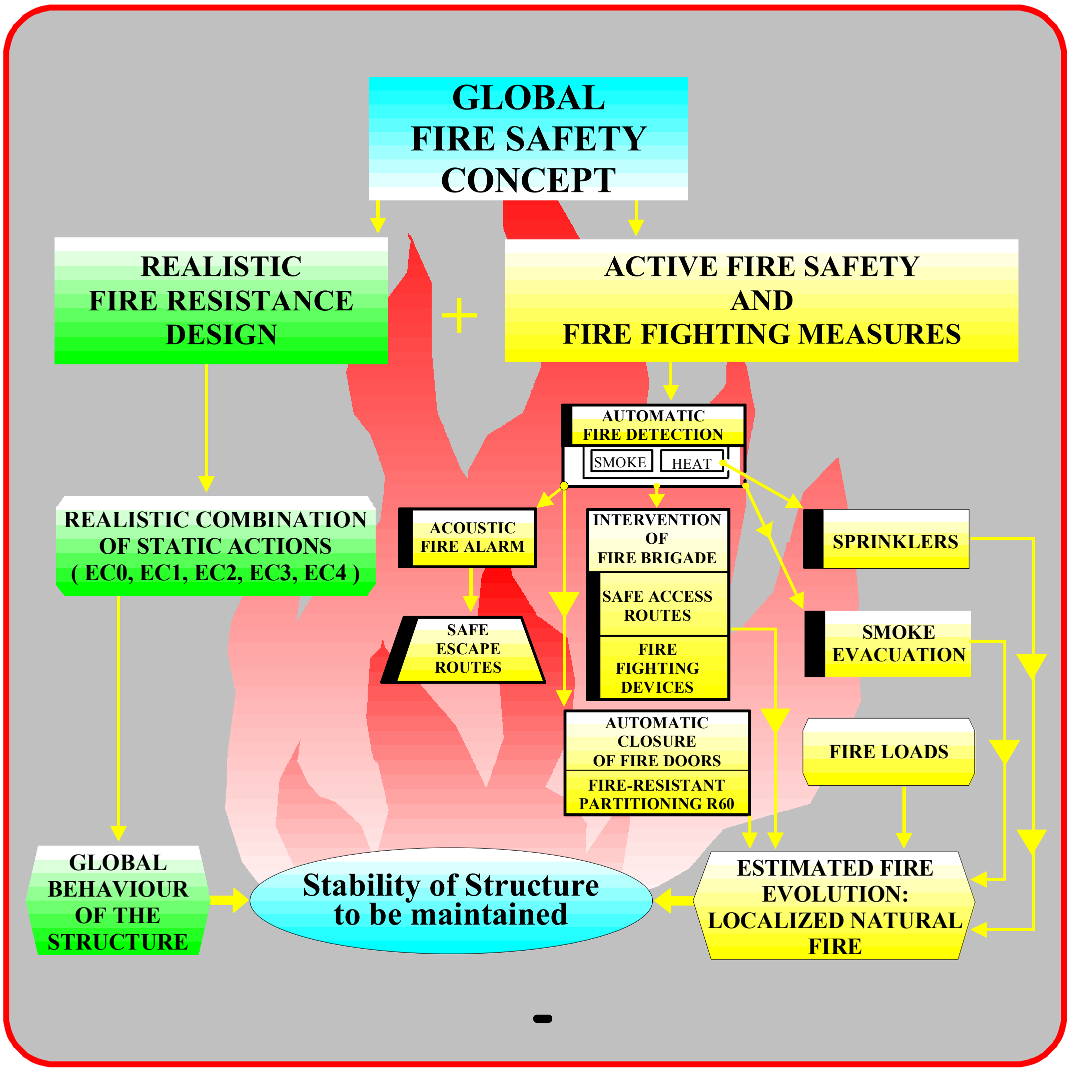


Figure 1. Global fire safety concept leading to the stability of the structure for the whole duration of the natural fire

Regarding the effect of active fire safety measures on the **structural stability**, a new procedure was elaborated which gives that correlation through the design fire load (Schleich 1998, EN1991-1-2 2002, Schleich *et al.* 2002 and 2003, Schleich 2005, DIN EN 1991-1-2/NA 2009).

A first step consists in proceeding to a global structural analysis in the fire situation (Schleich 1988a), in considering the accidental combination rule for actions during fire exposure (EN1990 2002) and in designing according to natural fire conditions. A second step consists finally in considering Performance Based Requirements i.e. the fire safety of occupants and firemen, the protection of property and environment, a realistic required fire resistance period, and a realistic structural fire design including active fire safety. The whole approach forms the so-called Global Fire Safety Concept, as shown in figure 1.

The main objective is given by the acceptable safety level, which may be defined by comparison to the different existing risks in life including the structural collapse of a building in normal conditions of use. The target failure probability not to be exceeded in normal conditions is given by $7{,}23 \cdot 10^{-5}$ for the building life of ~55 years.

Hence the objective for the fire situation should be

$$p_{f,55}\,(\text{probability of failure}) \leq p_{t,55}\,(\text{target failure probability}) = 7{,}23 \cdot 10^{-5} \tag{2}$$

$$p_{f,55} = p_{fi,55}\,(\text{probability of severe fire}) \cdot p_{f\,fi}\,(\text{failure probability in case of fire}) \tag{3}$$

$$p_{f,55} = p_{fi,55} \cdot p_{f\,fi} \leq p_{t,55} = 7{,}23 \cdot 10^{-5} \tag{4}$$

This allows to extract the failure probability in case of fire as

$$p_{f\,fi} \leq (p_{t,55} / p_{fi,55}) = p_{fi,t} \tag{5}$$

which is the target failure probability in case of fire.

On the level of reliability indexes this means

$$\beta_{fi} \geq \beta_{fi,t} \tag{6}$$

It is assumed that p_{ffi} follows the Gaussian normal distribution and hence the corresponding reliability index β_{fi} is given by the inverse of the cumulative normal distribution.

Therefore in case of perfect design such as $p_{f\,fi} = p_{fi,t}$, we will get

$$\beta_{fi} = \beta_{fi,t} = -\Phi^{-1}(p_{fi,t}) = -\Phi^{-1}(\,7{,}23 \cdot 10^{-5} / p_{fi,55}) \tag{7}$$

This allows to establish the interesting relation between $p_{fi,55}$, $p_{fi,t}$, and $\beta_{fi,t} = \beta_{fi}$ as shown hereafter in figure 2.

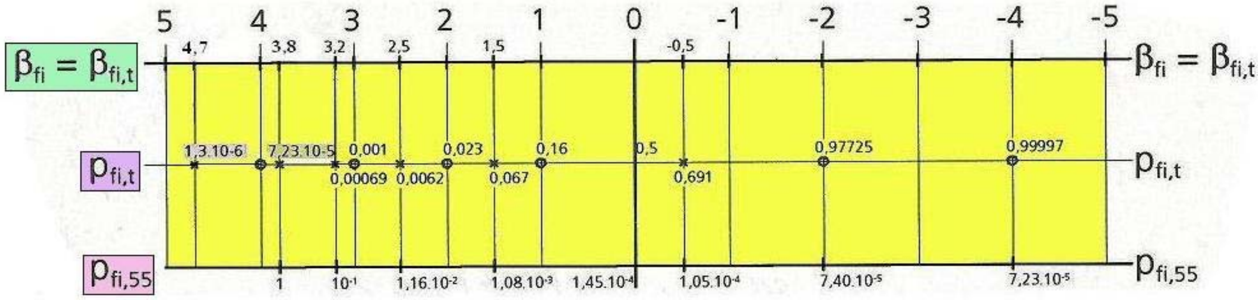


Figure 2. Connection between the reliability index β_{fi}, related to the probability of structural failure in case of fire $p_{f\,fi}$, and the probability $p_{fi,55}$ of getting a fully fire engulfed compartment during the life time of the building, which depends on the compartment size, the type of occupancy and the active fire safety measures

Reliability calculations have shown that the weighing factor for the main action at room temperature is strongly reduced in case of fire and may therefore be considered as a secondary action, whereas the fire load becomes the main action. This leads to a global factor γ_{qf} giving the design fire load:

$$q_{f,d} = \gamma_{qf} \cdot q_{f,k} \quad [MJ/m^2] \tag{8}$$

The design fire load as well as the characteristic value of the fire load may be represented through a Gumbel type distribution which permits to give the evolution of γ_{qf} as a function of β_{fi} as given by the following equation (Schleich 1998, 2005):

$$\gamma_{qf} = \frac{\gamma_{sd}\{1 - (V_{qf}(\sqrt{6})/\pi)\,(0{,}577216 + \ln[-\ln\Phi(-\alpha_{qf}\cdot\beta_{fi})])\}}{\{1 - (V_{qf}(\sqrt{6})/\pi)\,(0{,}577216 + \ln[-\ln\Phi(-\beta_k)])\}} \tag{9}$$

This allows to establish figure 3 when adopting (1,05) for the model uncertainty factor γ_{sd}, (0,3) for the variation coefficient V_{qf}, (-0,9) for the weighing factor α_{qf} and the 80% fractile for the characteristic value of the fire load $q_{f,k}$, which means that $\Phi(-\beta_k) = 0{,}8$.

Knowing the effect of the compartment size, of the type of occupancy and of the active fire fighting measures on the probability $p_{fi,55}$ of getting a fully fire engulfed compartment (Fontana *et al.* 1999, Schleich *et al.* 2002, 2003), that probability may be given for an office building by the relation

$$p_{fi,55} = (p_{fi,55}^{IGNITION}) \cdot (p_f^{OC} \cdot p_f^{PS} \cdot p_f^{SP}), \text{ with} \tag{10}$$

$p_{fi,55}^{IGNITION} = (10 \cdot 10^{-6} /m^2 \cdot year)\ (55\ years) = 0{,}00055$ *per* m^2

$p_f^{OC} = 0{,}40$ *the probability of failure of occupants in stopping the fire,*

$p_f^{PS} = 0{,}10$ *the probability of failure of public safety services in stopping the fire,*

$p_f^{SP} = 0{,}02$ *the probability of failure of sprinklers in stopping the fire, which leads to*

$p_{fi,55} = 4{,}4 \cdot 10^{-7}$ *per* m^2 *of the compartment area in an office building.*

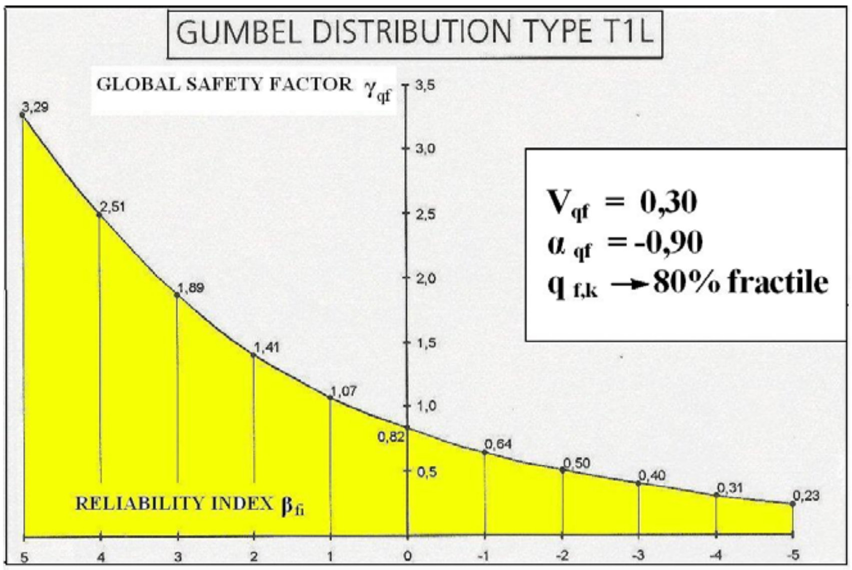


Figure 3. This figure, together with figure 2, allows to create the connection between the probability $p_{fi,55}$ of getting a fully fire engulfed compartment during the life time of the building and the global factor γ_{qf} affecting the characteristic value $q_{f,k}$ of the fire load

The design fire load may also for practical reasons be calculated by multiplying the characteristic fire load by the partial factors δ_{q1} and δ_{q2}, and the differentiation factor δ_n as follows

$$q_{f,d} = m \cdot \delta_{q1} \cdot \delta_{q2} \cdot \delta_n \cdot q_{f,k} \quad [MJ/m^2], \tag{11}$$

where m is the combustion factor, δ_{q1} is the partial factor considering the fire activation risk due to the compartment size, δ_{q2} is the partial factor considering the fire activation risk due to the type of occupancy, $\delta_n = \prod \delta_{ni}$ is the product of the differentiation factors δ_{ni} considering the different active fire fighting measures (sprinklers, detection, automatic alarm transmission, firemen..), and $q_{f,k}$ is the characteristic fire load density per unit floor area [MJ/m²].

This last procedure is of course an approximation which is however on the safe side. For that reason the global combustion factor m may be taken as 0,8. This method has the enormous advantage to be quite userfriendly, as all partial and differentiation factors may be taken directly from Annex E of EN1991-1-2 (2002). The previously described procedure was clearly developed during the years 1994 to 2000 by an European Research Group (Schleich 1998, Fontana *et al.*1999, Schleich *et al.* 2002, 2003) comprising various competent Research Institutes from eleven European countries.

Practical design performed in the fire situation, on the basis of the previously described procedure, leads to the conclusion that structures may get safer and even more economic. Indeed for all of the buildings highlighted in the next chapter on Architecture, the real fire, function among others of the ventilation conditions and the fire load, was considered by the author. Furthermore the effect of active fire safety measures on the design fire load was also taken into account. It follows that

▪ the design results clearly indicate that, under natural heating, no failure nor any critical deformation will occur. This is due to the fact that steel structures are in fact best protected by the active fire safety measures, as the potential severity of a fire and its probability of occurrence are cut down.

▪▪ all static calculations in the fire situation have been done through a two dimensional analysis, which is completely sufficient in connection to every day design as proposed in the global fire safety concept by Schleich (2006a, 2007, 2008, 2009, 2010).

▪▪▪ fire is to be considered as a load like wind or earthquake, which will lead to a robust structural design of buildings. Indeed the global behaviour of the structure has to be activated in the fire situation, as was underlined for the first time by Schleich (1988a). Of course this also highlights the fact that, in a two dimensional analysis, floor beams may move into catenary action, pulling columns back inwards etc. This means that a redistribution of internal load actions takes place in the fire situation and that among others connections may be submitted to much higher load effects than in normal conditions of use.

ARCHITECTURE

Chambre de Commerce, Luxembourg (2000-2004) / Arch. Claude Vasconi & Jean Petit / Engineer Schroeder & Associés

This building complex, with façades presented in figures 4 and 5, has a total occupied area of 52000 m^2 including underground parking levels. The relevant authorities imposed the ISO fire resistance requirement of R90 for all underground structural elements. This was encountered by performing on those levels composite columns and composite beams.

Figures 4 and 5. Glass façades with solar radiation deflectors

However the structure situated on the ground level and on the upper 5 floors could be designed according to natural fire models. In fact the use of natural fire models corresponds to the new European Standard EN1991-1-2 which, as an alternative to the ISO-fire, permits the use of natural fire models. That standard, dealing with actions on structures exposed to fire, contains in Annex E all numerical values allowing the estimation of the design fire load, and gives in Annex D the rules required to be fulfilled by any software program in order to calculate the real heating evolution.

In the specific situation of this building, safety aspects were addressed in the following way:

▪ the **danger of fire activation** has been limited on one side by the limitation of the size of compartments to a maximum of 750 m^2, and on the other side by the choice of a clear occupancy of offices respectively of education areas.

▪▪ **automatic fire suppression** is given through an automatic water extinguishing system of sprinkler heads installed all over the building, underground levels included; sprinkler redundancy is guaranteed among others by independent water supply.

▪▪▪ **automatic fire detection** is obtained by installation of smoke detectors all over the building, and by automatic alarm transmission to the professional fire brigade of the town of Luxembourg.

▪▪▪▪ **manual fire suppression** is favored through the short time of maximum 20 minutes needed by the fire brigade to reach the CCI building, through the existing and excellent safe access routes as well as staircases put under overpressure in case of fire alarm, through the numerous fire fighting devices existing all over the building, and through the smoke exhaust in staircases.

▪▪▪▪▪ furthermore **life safety** is ensured by the numerously existing and extremely redundant safe escape ways (figure 6).

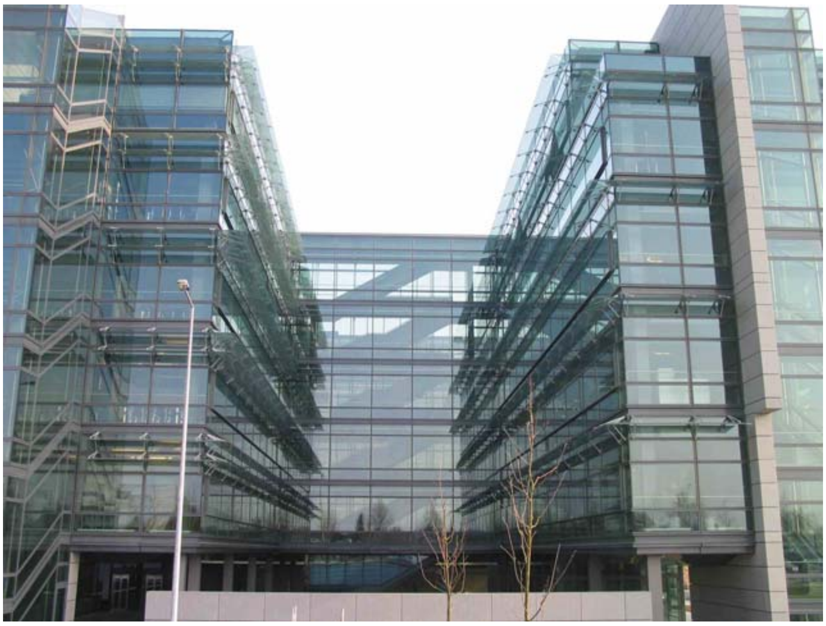


Figure 6. Chambre de Commerce with façade view and escape staircases in January 2004

Steel columns have been fabricated and erected as continuous components, consisting of rolled sections varying from HE260M at column bottom to HE260A at column top, and reinforced by lateral steel plates so to form a box section. Furthermore longitudinal stiffening steel ribs have been welded to that cross section, so to confer to those fully visible and unprotected columns an appealingly structured outside aspect (figures 7, 8 and 9).

Figures 7 and 8. Sculptured steel columns, a modern way of carved Doric stone columns, created by the late Claude Vasconi, 1940-2009

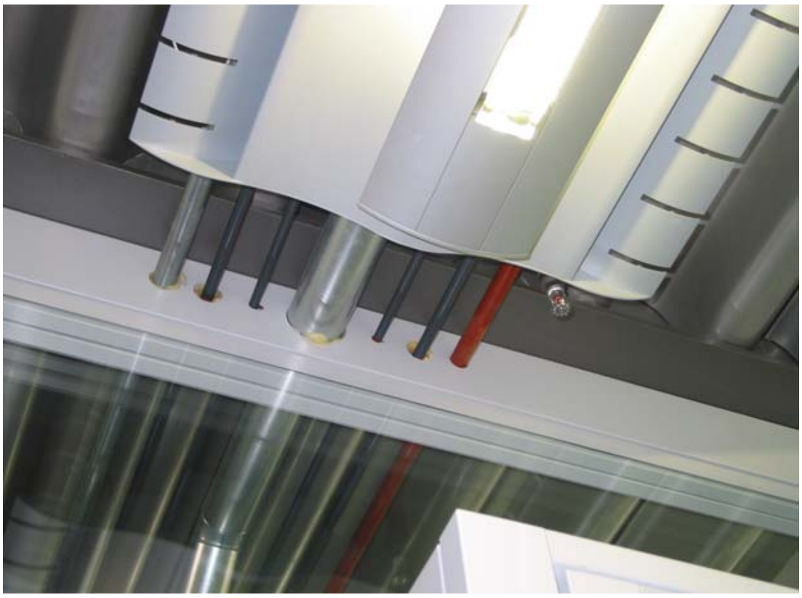
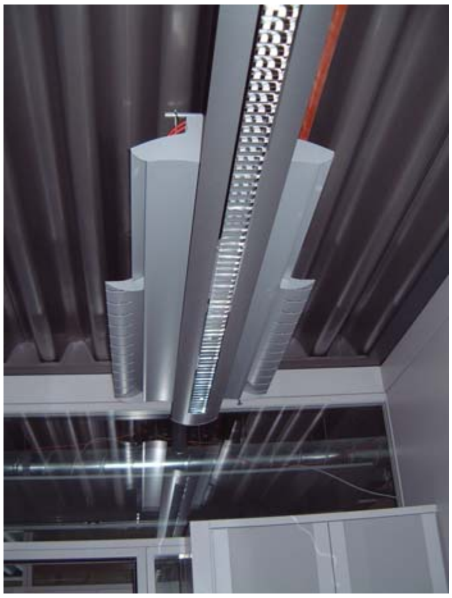
Figure 9. Chambre de Commerce with visible, unprotected steel columns supporting the composite beams

Composite beams are normally composed of the rolled section HE280B reinforced by a steel bottom plate. They are encased in the concrete of the slabs, except for the lower flange which remains visible; for spans longer or equal to 10m these beams are sustained by a pair of massive tension rods with a diameter of 50 mm. These beams, remaining visible in the offices, could be used by the occupants as gymnastic bars as far as they do not contain the separation walls of adjacent offices (figures 10 and 11).

Figures 10 and 11. Tension rods sustaining the composite beams

The natural design fire curve has been calculated using the software OZONE. The most critical fire scenario leads to air temperatures of approximately 500°C, which in turn provoke maximum steel temperatures of 350°C. The influence of these temperatures has been checked through the thermo-mechanical computer code CEFICOSS (Schleich et al. 1990), which clearly indicates that, under such a natural heating, no failure, nor any critical deformation will occur.

Figures 10 and 11 also show the 180mm deep stainless steel sinusoidal profile decking, which served as support for the reinforced in-situ concrete, and which constitutes the definitive ceiling surface. This facilitates heat exchange between the water cooled respectively heated slab and the office volume in summer and winter time. In summer time cooling is assisted by air distribution units, suspended from the profiled decking and letting drop cold mixed air (figures 12 and 13).

Figures 12 and 13. Lighting and air distribution units suspended from the profiled decking, also created by the late Claude Vasconi, 1940-2009

It may be noted that this building got the European Award for Steel Structures in 2003.

DEXIA-BIL Main Office Building, Esch-sur-Alzette (2003-2006) / Arch. Claude Vasconi & Jean Petit / Engineer Bollinger+Grohmann and Simon & Christiansen

The new DEXIA-BIL main office building with 1200 employees has become operational end 2006. This modern building of 67000 m^2, comprises three office blocks A, B and C connected through the atrium covered by a steel-glass roof spanning 33 m. The whole complex includes four underground levels with 1400 parking places.

Building A is a 19 level tower office building with a height of 75 m and buildings B and C have a height of 39 m. All of them are supported by composite frames. The corresponding columns and beams are kept visible and present unprotected steel surfaces, which permits to fully exhibit the filigrane nature of steel. Of course again the full set of active fire safety measures as presented in EN1991-1-2 was implemented.

Figures 14 and 15. Conceptual views in 2002 by the late Claude Vasconi, before construction

All columns include a central steel profile HEA, B or M with an outer circular steel tube. All around that central steel profile a spiral wire of 10 mm diameter and a step of 100 mm has been placed. In order to guarantee composite action, shear connectors were welded to the web of the steel profile. The inside of the steel tube has been filled up with the C50/60 concrete grade. Figure 16 gives a view on a part of the nine columns situated behind the façade of building A, curved with a radius of 48,75 m.

These columns support the loads transmitted from the various floors through composite beams of very special feature, which are all perpendicular to the curved façade and are situated on a spoke belonging to a slice of 52 degrees forming the circular arch for the curved façade, a basic architectural aspect. Figures 17 to19 show that these beams offer the following particular aspects:

▪ beams are composite and continuous over two spans of a maximum of 15,4 m and 6 m.

▪▪ these beams are composed of welded sections with varying heights.

▪▪▪ the lower flange of the beams is a full circular section of 60 mm diameter no more existing at the intermediate support, where a conventional flange of 300mm·15mm is supporting the compression forces.

- the beams are folded inside the main span, according to their longitudinal axis at 2,7 m distance from the intermediate support, with an angle varying up to 35 degrees.
- the web of the beams contains numerous openings of various dimensions.
- the intermediate support may be represented by a steel beam, so that this support is in fact given by a spring of a certain elasticity.

Because of this obvious complexity it was decided to test, at scale 1/1, one continuous composite beam with spans of 14,48 m and 6 m at the Laboratory Magnel in Belgium on 15 and 16.12.2004. This test demonstrated that the beam's behavior was fully in line with the design calculations as well regarding deformations in service, as for resistance at the ultimate limit state in normal conditions of use according Schleich et al. (2006b).


Figures 16 and 17. DEXIA-BIL building A; intermediate floor level with the visible, unprotected nine composite circular columns supporting the composite beams on the left, and with visible, unprotected composite beams on the right

Figure 18. DEXIA-BIL building A; specially shaped composite floor beam at fabrication shop of Victor Buyck, Eeklo (B), in November 2004

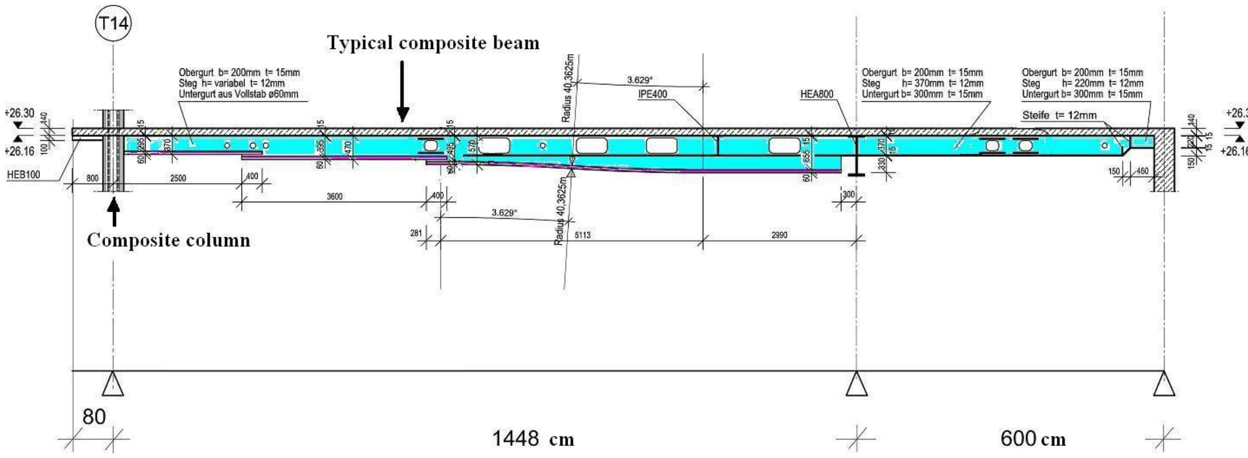


Figure 19. DEXIA-BIL building A; lateral view on specially shaped composite floor beam with a total length of 20,5 m

Regarding the design in the fire situation, the natural fire safety approach was chosen following Schleich (2005). As a consequence the different factors related to a natural fire scenario have to be chosen according to EN 1991-1-2 (2002), i.e:

▪ the partial safety factors δ_{qi} are given by:

Size of compartment 675 m^2	→ δ_{q1} = 1,67
Occupancy offices	→ δ_{q2} = 1,0

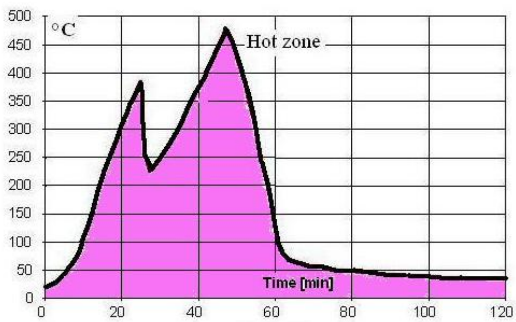
▪▪ the differentiation factors δ_{ni} are given by:

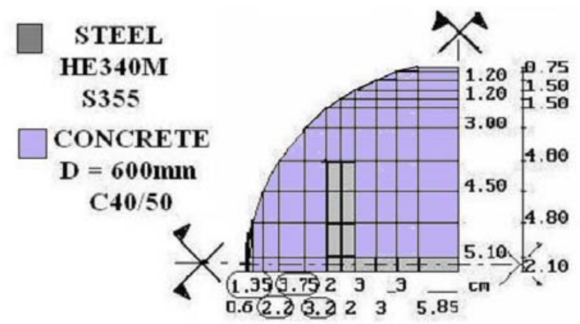
Sprinklers	→ δ_{n1}= 0,61
Independent water supply	→ δ_{n2} = 0,87
Automatic smoke detection and alarm	→ δ_{n4} = 0,73
Automatic alarm transmission to fire brigade	→ δ_{n5} = 0,87
Off site fire brigade available	→ δ_{n7} = 0,78
Safe access routes	→ δ_{n8} = 1,0
Fire fighting devices existing	→ δ_{n9} = 1,0
Smoke evacuation in staircases	→ δ_{n10} =1,0

▪▪▪ Hence the design fire load is obtained from

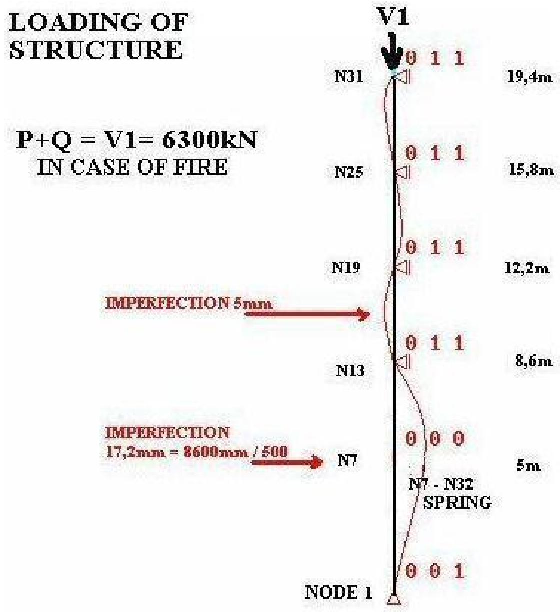
$$\boldsymbol{q_{f,d}} = q_{f,k} \cdot m \cdot \delta_{q1} \cdot \delta_{q2} \cdot \prod \delta_{n_i} = 511 \cdot 0{,}8 \cdot 1{,}67 \cdot 1{,}0 \cdot 0{,}263 = \mathbf{180\ MJ/m^2} \qquad (11b)$$

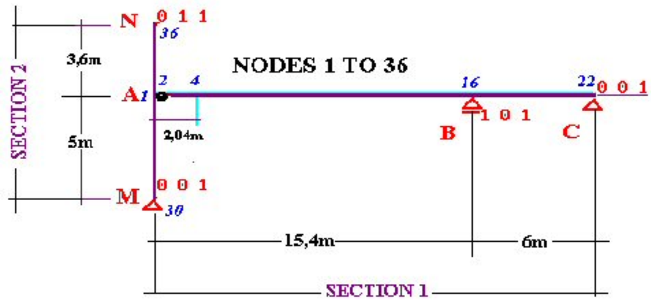
Together with the assumptions of a medium fire growth rate t_α = 300s and a maximum rate of heat release RHR_f = 250 kW/m^2, the software OZONE (Cadorin, 2003) gives the natural fire curve as shown in figure 20. This fire curve was applied to the continuous composite column detailed in figures 21 and 22 and leading to maximum concrete temperatures of 255°C, respectively to a maximum horizontal deformation of ~ 5mm.





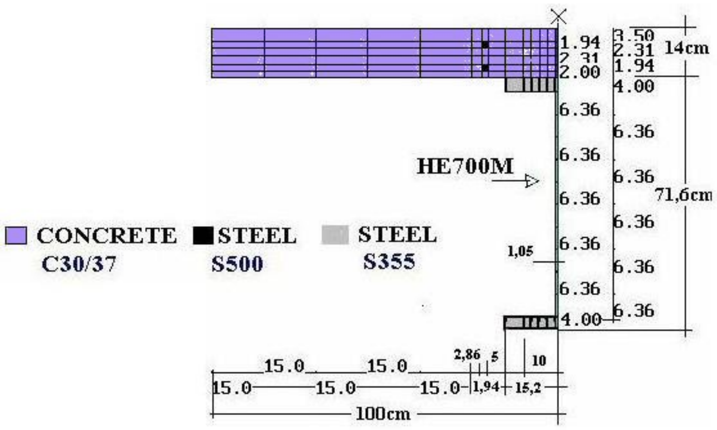
Figures 20 and 21. Intermediate floor level with natural heating on the left, and cross-section mesh of column on the right

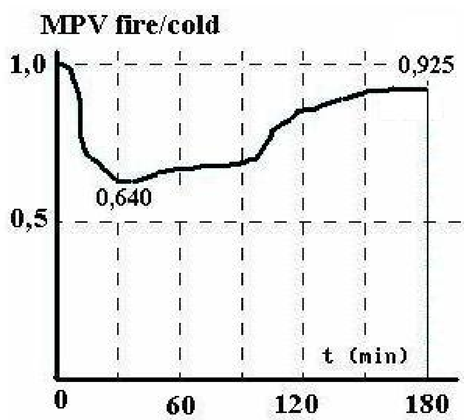




Figures 22 and 23. Loading conditions of continuous column on the left, and continuous column connected to continuous beam with 36 nodes & 34 finite beam elements on the right

Furthermore, in order to discover internal load redistributions during heating, the entity composed of a continuous beam connected to the corresponding continuous column was analysed on behalf of the software CEFICOSS (Schleich et al. 1990), as shown in figure 23. The corresponding composite beam cross-section is illustrated in figure 24. This leads to a maximum deflection of 4 cm in the composite beam at 30minutes of natural heating, but also to a horizontal displacement of ~ 4 cm at the level of connection beam to column.





Figures 24 and 25. Cross-section mesh of composite beam on the left, and minimum proper value MPV evolution in function of natural heating on the right

The minimum proper value MPV of the entity beam - column is shown in figure 25, which clearly indicates that failure was never to be envisaged and that the structure even recovers practically its full strength after that natural fire.

The main lessons the author wants to tell young engineers, after having had the chance but also duty to proceed to this fire resistance design, are as follows:

- implementing the full set of active fire safety measures, as foreseen in EN1991-1-2 (2002), permits to keep structural steel unprotected

▪▪ attention has to be paid to constructive detailing and to a correct design for normal conditions of use

▪▪▪ in case of high rise structures, like this one, vital structural elements shall be considered as key-elements and shall be designed according to EN1991-1-7 (2006).

Figures 26 and 27. DEXIA-BIL tower building as finished end 2006 with enameled steel façade and in the foreground concrete columns of the former blast furnace charging device on the left, and on the right with the atrium based on a 3-D space steel truss spanning between the various buildings

Under these conditions the following amazing result could be obtained, which consists in finally having conceived and realized a tower building, 75m high according to figures 26 and 27, with steel columns and steel beams kept visible and unprotected. It is for the first time that such an innovative step has been undertaken, not forgetting that the active fire safety implemented brings even people's safety to the highest possible level.

Nevertheless apart from the fortunate situation that the Architect and the Official Authorities have accepted the application of the global fire safety concept, **we have to address special thanks to Claude Vasconi,** who captured every possibility now offered to get visible steel. That explains that the **lower flange of the beams**, shown in figures 17 to 19 and **consisting of a full circular section of 60 mm diameter,** is progressively going downwards, remaining however always visible as the false ceiling follows that movement (figures 28 and 29).

Furthermore the **nine composite columns**, supporting all the loads on the curved façade of building A, exhibit **a remarkable slenderness, following the view offered in the atrium over a height of 20 m** according to figure 30.

Further the **steel-glass roof** spanning the atrium over 33 m has to be mentioned, as the 3-D steel truss **resembles lace-work**. Figure 31 shows how this brings light into the atrium, and so facilitates communication between the different buildings.

Figures 28 and 29. Lower visible and circular steel flange of all the spoke-like composite beams supporting the floors 6 to 16. In a total 99 similar beams were implemented

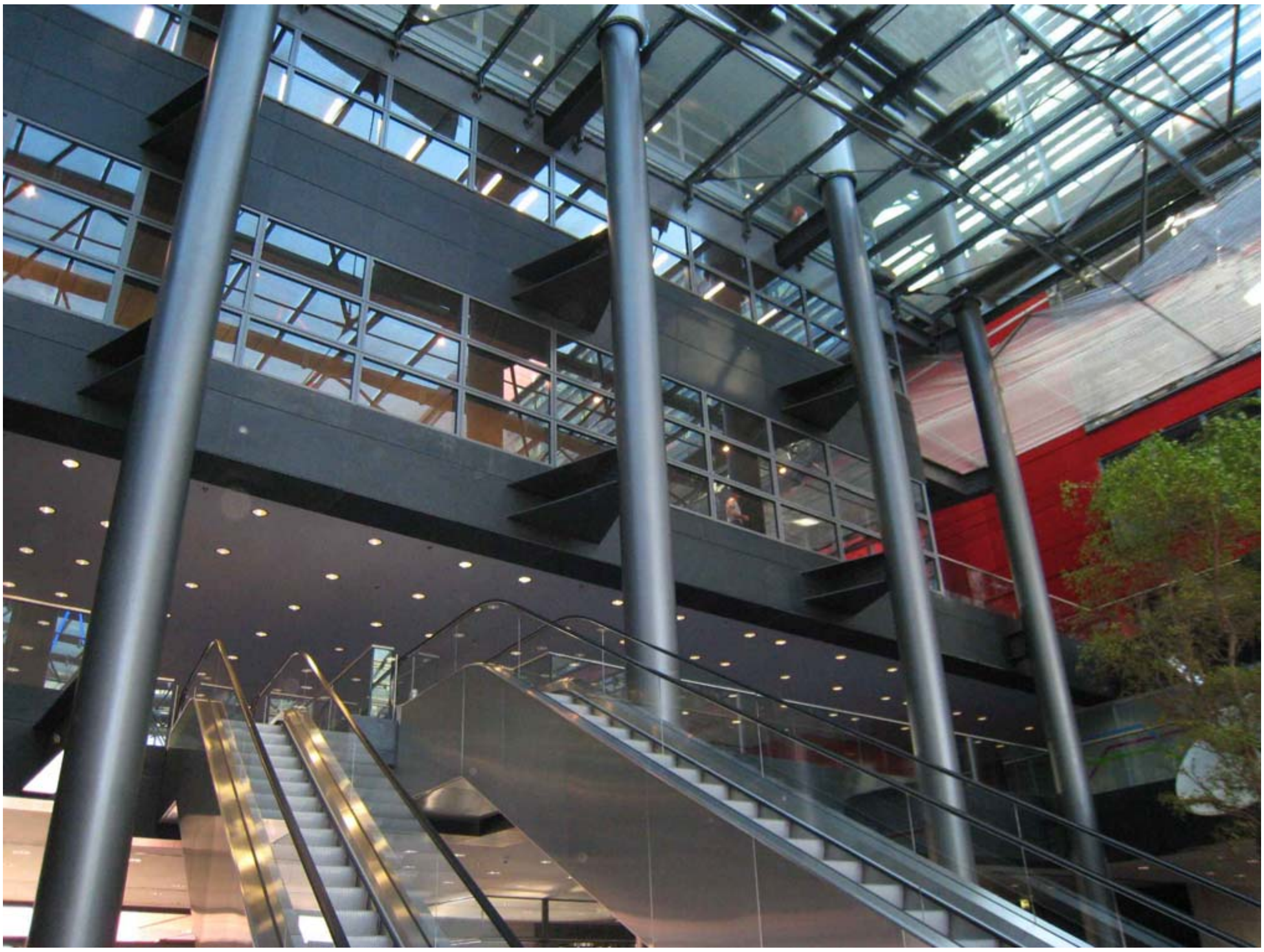


Figure 30. Slender composite columns climbing in the atrium over a height of 20 m, composed of steel tube, internal H-section, spiral wire and concrete; no reinforcing bars were used. The columns are completely visible and are not covered by any fire protection material

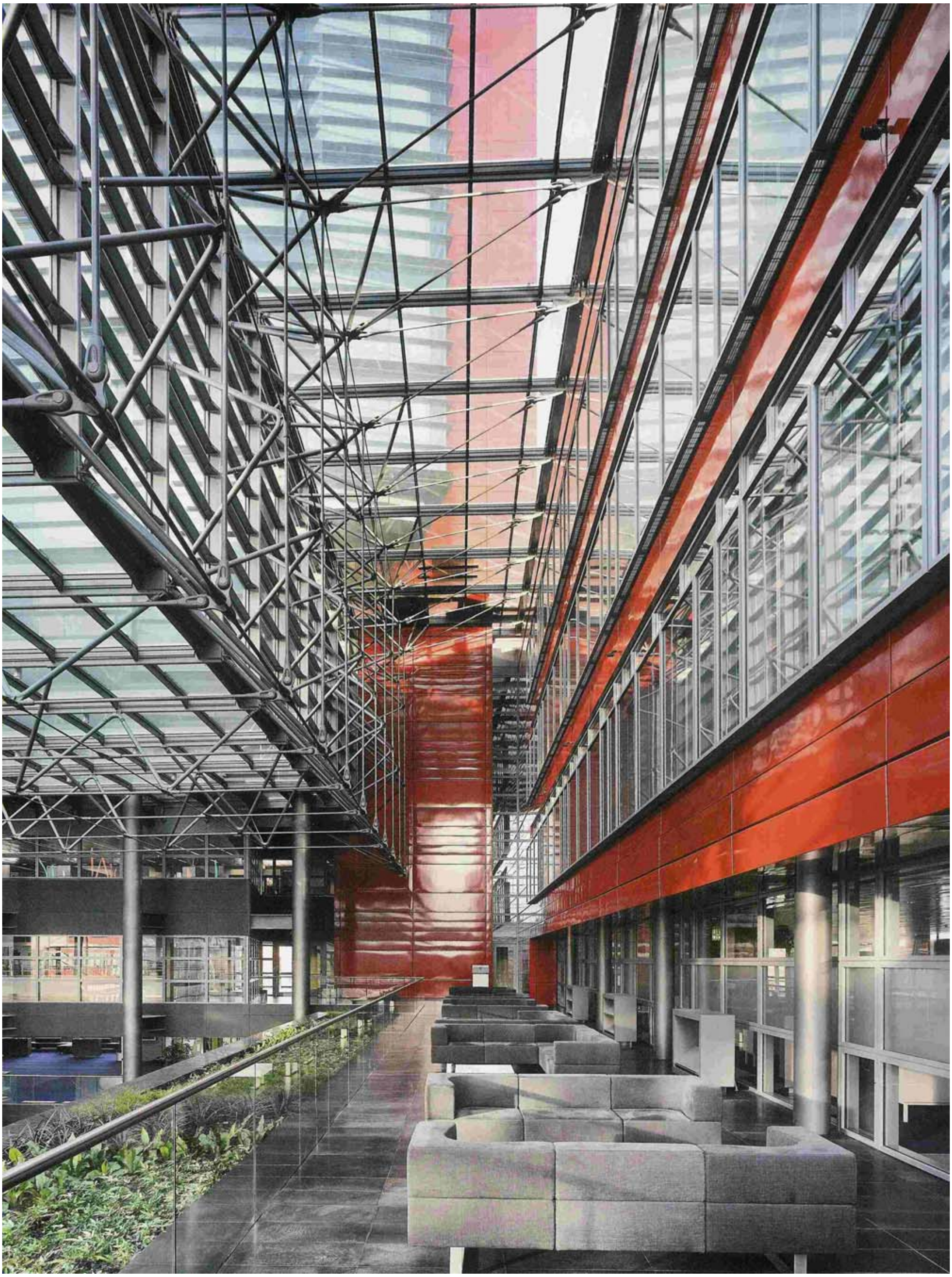


Figure 31. Lace-like 3-D steel truss spanning atrium over 33 m, with view on tower building

EUROPEAN COURT of JUSTICE, Luxembourg (2002-2008) / Arch. Dominique Perrault, Paczowski & Fritsch, M3 Architects / Engineer Schroeder & Associés and InCA

Last but not least the building of the European Court of Justice in Luxembourg, dated from 1972 as shown on figure 32, was refurbished and enlarged from 2002 to 2008 allowing re-use the existing steel structure for the Core Building (see figures 33 and 34). However whereas in the previous construction inside steel columns and beams had been protected in 1972 by insulation material, in the present new building **steel columns and beams are kept visible and hence are in general no more protected by insulation. This illustrates the important progress achieved nowadays through correctly managed fire engineering.**

Figure 32. European Court of Justice in Luxembourg, erected in 1972, a creation of the Architects Jean-Paul Conzemius, Francis Jamagne and Michel van der Elst

This is indeed possible as active fire safety measures were implemented i.e. use of materials with no toxic gas emission in case of fire, well defined compartments, overall smoke detection, automatic alarm transmission to the public fire brigade, safe escape and access ways, existing fire fighting devices, and finally a quite effective and **mechanical smoke extraction in the fire situation**.

However **no sprinklers** were installed. Hence in general, when the impact of the fire load was low, the maximum gas temperature obtained and the resulting temperatures in columns and beams permitted to keep steel elements unprotected. This happened f.i. in the Large Audience Hall represented in figure 35 and situated on level 2, whose height is 17 m and built volume represents 9800 m^3, and where the maximum temperature in the 1,5 m high beams should be only 160°C as shown in figure 36.

A similar and even less fire endangered area is the great entrance hall on level 3, called "Salle des Pas Perdus", with a length of 60 m and a built volume of 23000 m^3 represented on figure 37.

A quite different situation arises in those areas where the fire load becomes important, among others due to timber claddings foreseen by the architect in order to embellish the corresponding compartments. This happened in the Medium Audience Halls on level 6, where the maximum air temperatures attain 830°C at 170 minutes. In this case an acceptable maximum steel temperature of 470°C, inside the 1 m beams crossing these halls, could only be guaranteed by protecting these beams on behalf of a convenient thermal insulation. Figure 38 shows the evolution of these temperatures and illustrates the importance of fire fighting initiated by the fire brigade as soon as possible.

Figures 33 and 34. European Court of Justice in Luxembourg, December 2008, with outside (on the left) and inside (on the right) structural steel based on a large extent on steel columns and beams taken from the structural steel of the initial Court of Justice erected in 1972

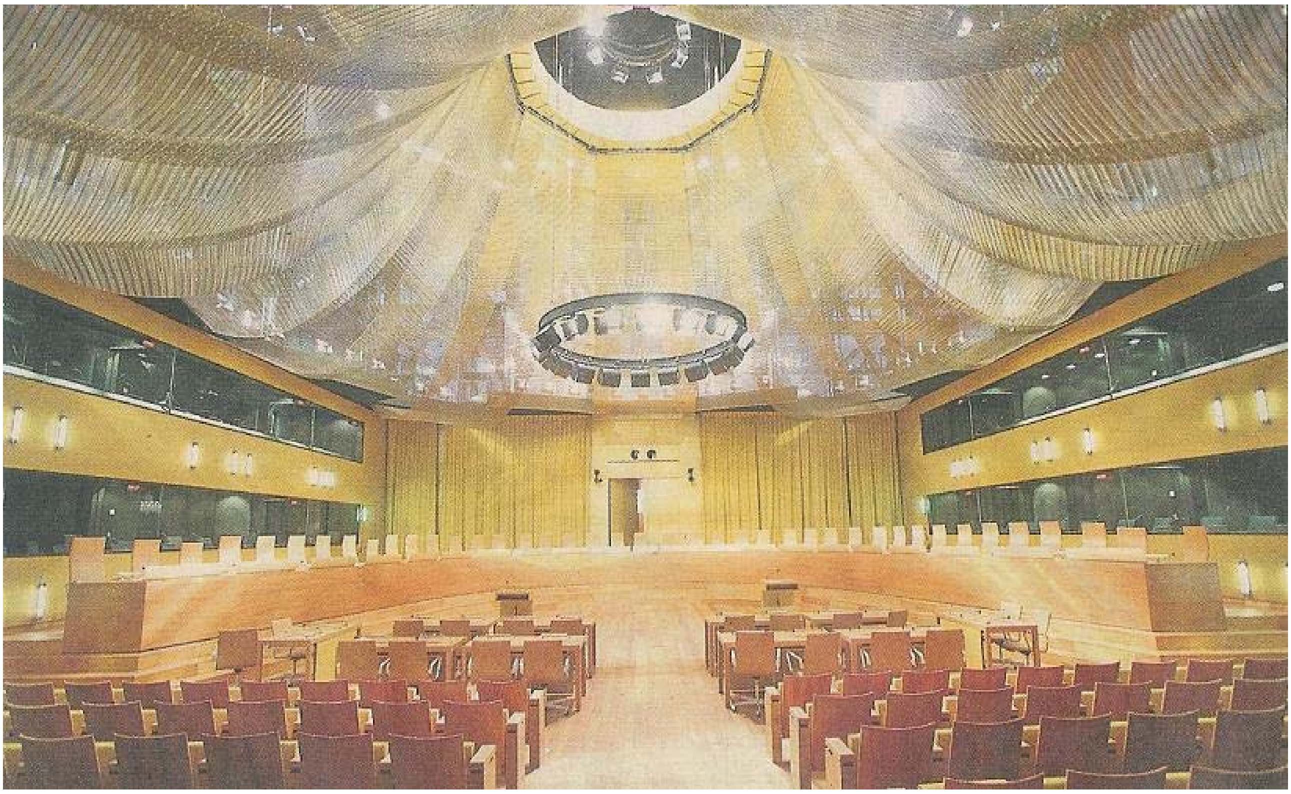


Figure 35. Large Audience Hall containing 57 seats for magistrates and assistants, 275 seats for the public and 24 cabins for translation, is covered by a suspended golden colored steel lace-work

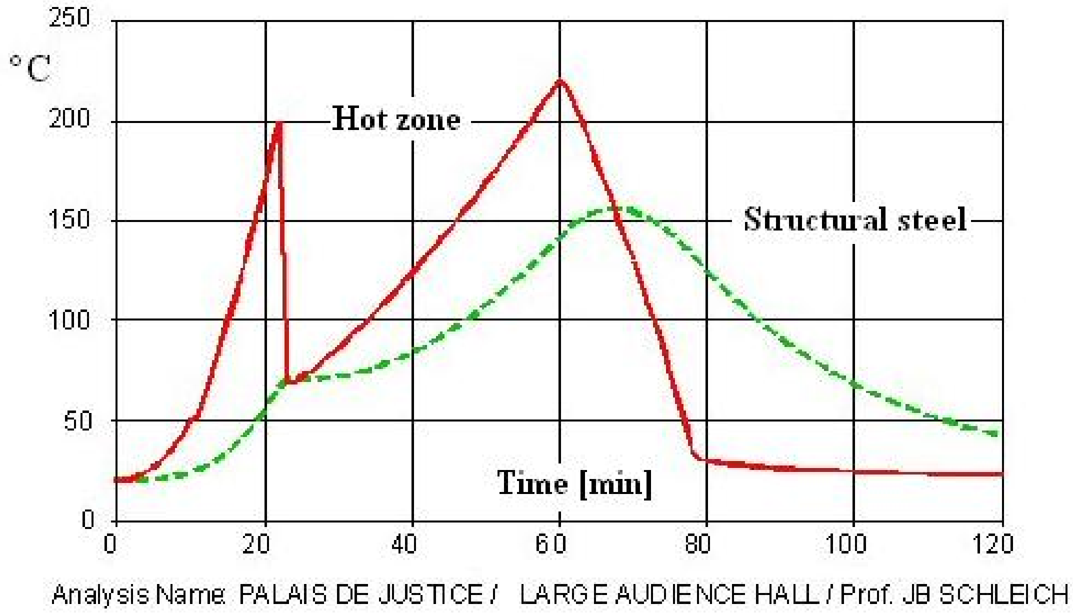


Figure 36. On top of the large audience hall unprotected steel beams, with a height of 1,5m and a peak steel temperature of 160°C at 67'

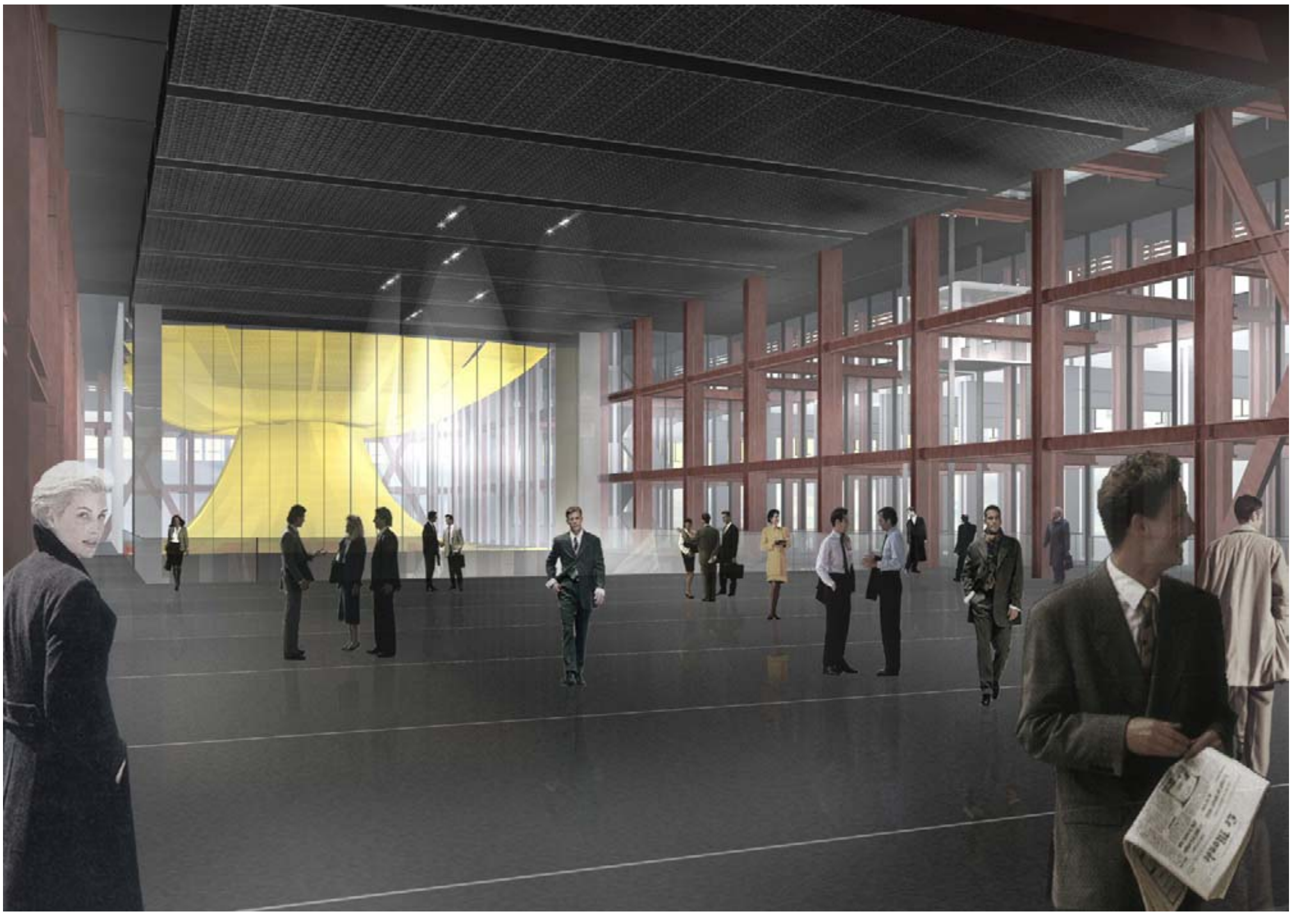


Figure 37. Conceptual view in 2002 by Dominique Perrault of the European Court of Justice in Luxembourg with inside structural steel, visible and not protected; this view looks inside the great entrance hall on level 3, called "Salle des Pas Perdus", towards the large audience hall

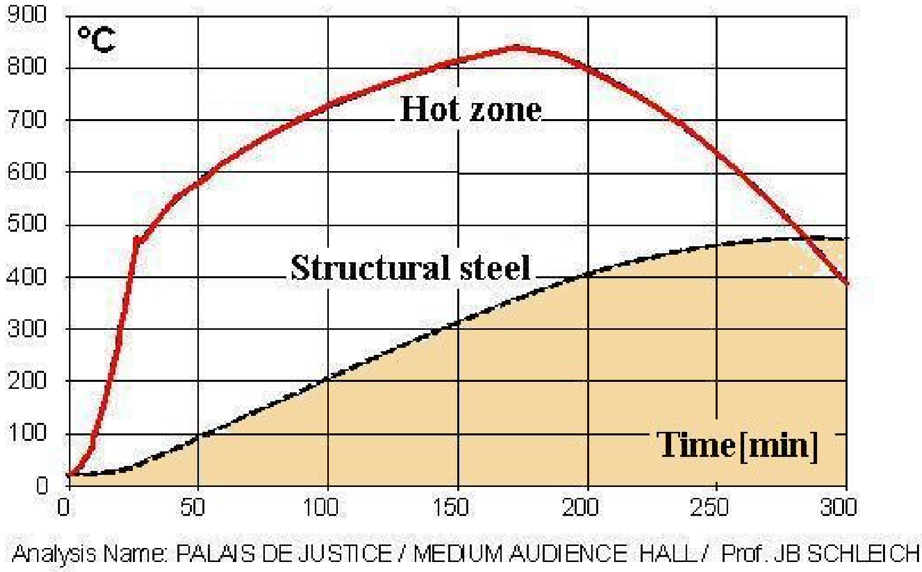


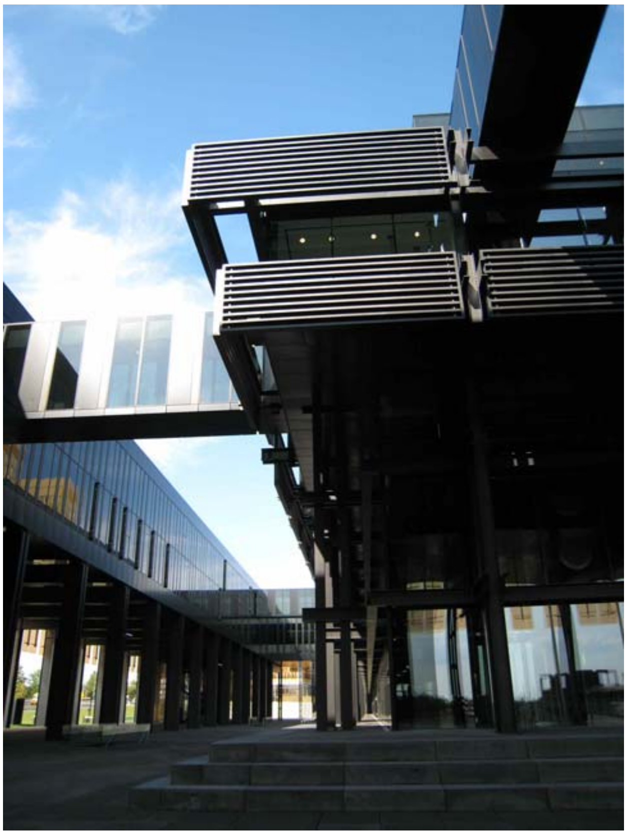
Figure 38. Peak air temperature 830°C at 170 min in the medium audience hall situated on level 6, and peak steel temperature 470°C at 280 min inside the 1m insulated steel beams of this hall

Finally some practical fire safety decisions were implemented such as

- design of composite beams with full shear connection.
- vertical wind bracings needed for the lateral stability of the steel structure were designed with a clear redundancy i.e. as well in the longitudinal as in the transversal direction these heavy bracings were doubled. As a consequence in case of failure of one bracing due to temperature effects, lateral stability may always be guaranteed by the second still valid bracing.

Figure 39. Two transversal wind bracings situated between levels 3 and 6, similar wind bracings have been foreseen between levels 6 and 9; as a total four transversal and four longitudinal wind bracings were erected for the central core building which covers a surface of 4070 m^2

- foresee a redundant connection on levels 6 and 7 through eight pedestrian bridges between the central core building, containing the different audience halls, and the new two-storey ring-like building, containing 10500 m^2 offices for magistrates, and supported by heavy unprotected steel frames spanning 16,8 m with a height of 9,3 m. This ring-like building is downward connected to the free space of the esplanade through eight open air corkscrew stairs, so allowing numerous redundant safe escape ways.

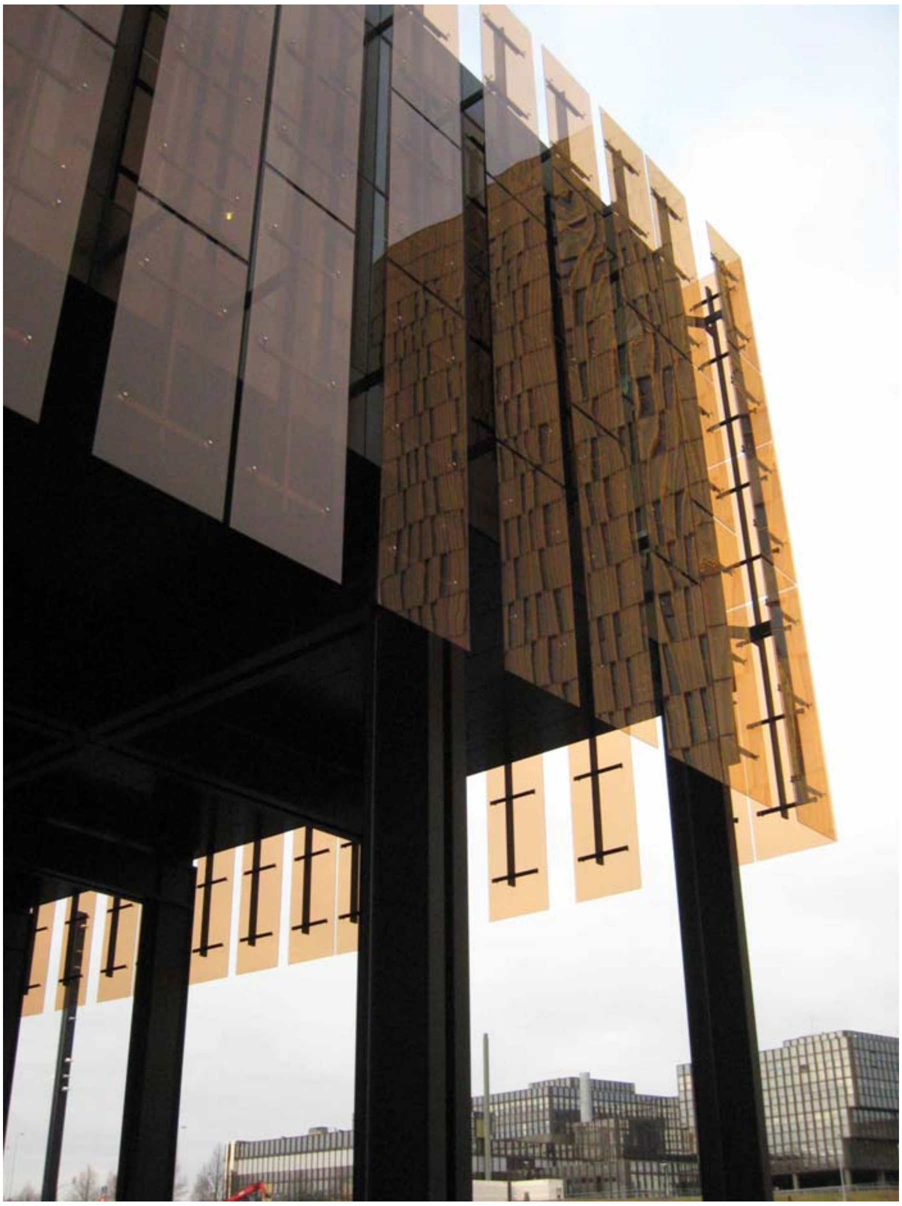



Figures 40 and 41. View on pedestrian bridges between the central core building and the new two-storey ring-like building (on the left) and view on open air corkscrew stairs (on the right)

As a conclusion let's focus on the perfect recycling of 80% of the structural steel from the building dated 1972, which was demounted, transported to the fabricators workshop, cleaned by sand-blasting, adapted to the new project geometry, painted and erected to get the central core building. It is of course admirable that the vast majority of the steel beams could remain unprotected, as explained before, so permitting the architect Dominique Perrault to present steel simultaneously as bearing and aesthetical building components.

As however black seems to be the favorite color of this Architect, all steel was painted in black, conferring to this monumental entity an air of sobriety and coldness. Fortunately the outside cladding of the new two-storey ring-like building, consisting of vertical irregular and golden glittering glass panels, see figures 42 and 43, brings some life and warmth to the new European Court of Justice.

It may be noted that this building got the European Award for Steel Structures in 2009.



Figures 42 and 43. Glittering glass panels hiding the new European Court of Justice

Les Rives de Clausen, Luxembourg (2006-2010) / Association of architects ASSAR - Marc Ewen / Engineer Schroeder & Associés

This ambitious project began in 2004 on the former site of the Mousel and Clausen breweries and took its final shape during the years 2006 to 2010. In fact M Immobilier is the company responsible for the concept and development of the Rives de Clausen project, which comprises gastronomy, culture, business with offices and retail, as well as residential units. Whereas gastronomy and culture has been located in the historically old brewery buildings which were quite beautifully restored, offices, retail and residences have been foreseen in new buildings (see figure 44). The construction of an underground car park became an absolute necessity and comprises 400 parking places on two levels, but this also required the building of a new bridge over the river Alzette.

Figure 44. Aerial view on the Rives de Clausen project on "the rive gauche" of the river Alzette, with in the background the stone railway viaduct dated 1861

For offices and retail located inside the buildings C1 to C6, with a total of 6000 m^2, a steel structure has been adopted comprising steel columns as well as slim floor beams spanning 7,5 m from column to column. All of the area in between columns was covered by prestressed hollow core slabs, strengthened first through an 8 cm thick **concrete topping reinforced** by a steel mesh 6mm·150mm. But for fire resistance reasons these slabs needed also to be strengthened by **shear bars crossing the slim floor beams** every 60 cm and **anchored into the opened cells of hollow core slabs** (see figures 45 and 46).

Both reinforcements shall be foreseen for the fire situation as follows from EN 1168 (2010) and Van Acker (2003), otherwise fire resistance of hollow core slabs is not guaranteed.

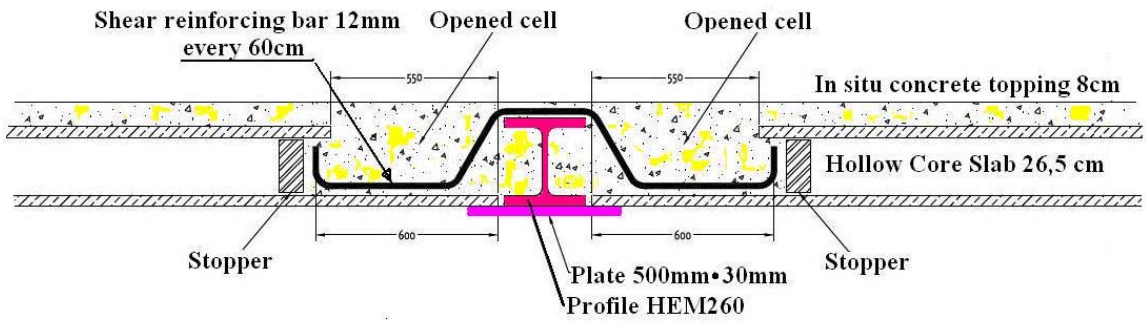


Figure 45. How to connect hollow core slabs to slim floor beams; the necessity of opening cells according to figure 46

Figure 46. The correct way of preparing hollow core slabs before erection

The different buildings, with a maximum of three to four levels, could be designed according to natural fire models following the new European Standard EN1991-1-2 (2002). That standard, dealing with actions on structures exposed to fire, contains in Annex E all numerical values allowing estimation of the design fire load, and gives in Annex D the rules required to be fulfilled by any software program in order to calculate the real heating evolution.

In the specific situation for offices and retail, safety aspects were addressed in the following way:

▪ the **danger of fire activation** has been limited on one side by the limitation of the size of compartments to a maximum of 700 m^2 and exceptionally to 1000 m^2, and on the other side by the choice of a clear occupancy of offices respectively of retail areas.

▪▪ **automatic fire suppression** is given through an automatic water extinguishing system of sprinkler heads installed all over the buildings, underground levels included. Sprinkler heads were installed with a density of one head per 12 m^2, so delivering in case of release 5mm of water per minute; only in some critical areas sprinkler density was doubled to one head per 6 m^2. Sprinkler redundancy is guaranteed among others by independent water supply consisting in a water tank of 80 m^3

▪▪▪ **automatic fire detection** is obtained by installation of smoke detectors all over the building, and by automatic alarm transmission to the professional fire brigade of the town of Luxembourg.

▪▪▪▪ **manual fire suppression** is favored through the existing and excellent safe access routes as well through the smoke evacuation in staircases in case of fire alarm and through the numerous fire fighting devices existing all over the building.

▪▪▪▪▪ furthermore **life safety** is ensured by the numerous safe escape ways.

As a result the most critical fire scenarios lead to air temperatures of approximately 600°C, which in turn provoke maximum steel temperatures of 170°C in the **lower steel flanges of the slim floor beams** encased in the concrete slabs. Hence these flanges **could be kept unprotected** (see figure 45). Columns composed of the steel profiles **HEB240 to HEB300** are heated up to 450°C, quite below their critical temperature of 600°C, which in turn allows having these **columns visible and also unprotected.** It follows from this that steel columns are visible all over this building complex and so confer an exceptionally light and elegant inside view of the area dedicated to offices (see figures 47 and 48).

Compared to the previously given examples of structures, all designed also according to natural fire conditions, this one called "Les rives de Clausen", is of course the smallest but a quite interesting one, as it has rather modest dimensions and as it was initiated by a private promoter. Furthermore the complex had to be introduced into a historically difficult environment due to the old brewery buildings from 1825, to the fortification of the so-called "Bock" initiated by Count Sigefroy in 863, and to the stone railway viaduct dated 1861.

But as says the proverb "small is beautiful", this set of buildings presents a real appealing outside look as it is shown on figures 49 to 51.

Figures 47 and 48. On the left slim floor beam bolted to continuous steel column in August 2007; on the right visible and unprotected steel columns inside the office areas in June 2010

Figure 49.

Figure 50.

Figure 51. Conceptual view in 2007 by M Immobilier of the buildings C1 to C6 with inside structural steel, visible and not protected, and with in the background the stone railway viaduct dated 1861

SUSTAINABILITY

As so much is said about sustainability by anybody, at any occasion, it is useful to go back to the initial meaning coming from forest management. Accordingly "the use of a forest follows sustainability, if as many trees in m^3 are cut in a year as new trees in m^3 are growing in that same period". This concept was first created in 1713 by Hans Carl von Carlowitz (1645-1714), and has been transmitted to economy and social domain end of the XXth century. Today thoughts and acts are considered as sustainable, if life standards of the present generation are improved without damaging the conditions of life of the future generations.

The question is how to apply this last definition to architecture? On the basis of the UN-Conference 1992 in Rio de Janeiro, a building or a dwelling may be called sustainable if, apart from its traditional required properties concerning architecture, occupancy and technical performances, it also has an everlasting minimized impact on the environment.

Further to that requirement I believe however that some more aspects shall be considered i.e.

▪ At first structural steel components can all be made from indefinitely recyclable ferrous scrap and may even be recovered or re-used without extensive transformation. As in the future the percentage of insulated structural steel by cladding or by reactive paints will vanish, recycling facilities of any type will be improved.

▪▪ Future transformation needs due to a building enlargement or to a change in occupancy are of course facilitated, first by the steel structure which in itself easily allows horizontal and vertical extension, then by the absence of any insulation which always would disturb the works.

▪▪▪ Active fire safety measures may be easily adapted to a future new occupancy, so by modifying the size of compartments, changing the escape ways, adapting smoke detection or adding if necessary sprinklers.

▪▪▪▪ Thanks to fire engineering, fire is considered as an exceptional loading, which will contribute to the enhancement of the robustness of the building and consequently to its durability.

▪▪▪▪▪ Regarding the live cycle assessment, the global cost covering the life time of the building shall be minimized.

This last requirement however may be in contradiction with the wish to minimize the impact of a construction on the environment, which in itself represents an unsolved problem. So it must be admitted, that we are still not in the position to build in a perfectly sustainable way. It would be wise to push research and technical development in order to get new effective technologies, instead of paying for climate remissions, by the way a fully crazy proceeding.

Figure 52. The "flying carpet" roof of the Art Institute of Chicago, by Renzo Piano

Now certain aspects can not be put into a rigid corsage, but shall be viewed individually like

▪ The modern wing of the Art Institute of Chicago conceived by Renzo Piano (born 1937) and which opened to the public in May 2009. This building resembles a temple of light, including the so-called "Flying Carpet" roof made of aluminium blades, that shields the galleries from harsh direct sunlight (see figure 52). These blades are calibrated for Chicago's latitude, so to let light only from the north come through. Indeed in order not to damage paintings, only indirect light from the north is admitted. Futhermore in order not to compromise the color of the paintings, all walls in the new wing are white. But Renzo Piano guards his spaces against sterility by adding the muted warmth of white oak flooring throughout.

▪▪ It should be made clear that building sky-scrapers is not necessarily a sustainable building procedure, regarding at least energy consumption during construction as well as in service. Furthermore loading conditions become excessive when considering wind effects, earthquake shocks, tsunami waves, climate variations and also fires. In fact such high rise as the 828m high "Burj Khalifa" in Dubai is clear megalomania, favoring greediness and insolvency, but is for sure not a construction likely to live in nor with perfect safety as demonstrates the recent malfunction of elevators on February 10th. That has sparked the sudden closure of the 124th floor observation deck just a month after the building opened.

▪▪▪ **Hence as a conclusion let's be smart enough not to get excited about building the tallest, but instead we shall build the best for the sake of people.** Therefore we shall really favor the development f.i. of steel houses permitting to build save against hurricanes, earthquakes, even floods and fire. As shown on figures 53 and 54 this is perfectly feasible and would help quite a lot of people to get their own home.

Figures 53 and 54. Prefabricated steel houses, easy to erect and with high safety level

This combined with proper walling and high insulation standards would help to save energy. Of course heating facilities have also to be improved as f.i. the heat pump procedure based on the extraction of heat from the underground, once operational, may be the sustainable solution. Another research field with a high potential regarding energy savings would consist in developing a type of glass with the ability of insulating against heating up in summer, whereas in winter the same glass, collecting light from the sun, would rather contribute to the heating up of rooms.

It is clear that many examples of successful steel houses exist all over the world, as shown hereafter in figures 55 to 58. However those are unique specimen, probably rather expensive, but may contribute in one way or the other to find means of improved sustainability. It is of course not sufficient to develop steel houses designed by well-known architects, but it is crucial to inform in a credible way the bulk of architects of among others the efficiently manufactured light steel components. And above all, and I hope that this will be well understood and action be taken by the steel community, **we have to present to the architects convenient detailing solutions, concerning the integration of structural steel into the other building components, respectively its interaction with all existing fluids or power supplies**.

Figures 55 and 56. Steel house in Church Point / Sidney, from UTZ SANBY Architects

Figures 57 and 58. Steel house in Tasmania / Australia, from ROOM 11 Architects

CONCLUSION

Concerning fire safety and fire blaze it should be underlined that loss of lives exclusively results from human error either because of a Building Code which is not applied, either because of panic during evacuation. Safe and passable access routes are needed, so that the fire brigade may reach the fire and put it down with the required speed. But compartments inside buildings as well as space between two houses or two blocks shall be able to fulfill their crucial role of limiting fire spread (The Daily Star 2010). It is the responsibility of the architect to make sure that, further to his natural inclination to beauty and aesthetics, life safety prescriptions are correctly implemented. Finally sustainability is not just about environmental issues, but also includes social and economic priorities, which makes it so difficult in finding the adequate proceeding.

REFERENCES

Baus, R., Schleich, J.B. (1986), Résistance au feu des constructions mixtes acier-béton, détermination d'un niveau précis de sécurité, *MEMOIRE C.E.R.E.S., Université de Liège,* n° 59, 51 pages.

Cadorin, J.F. (2003), Compartment fire models for structural engineering, *Thèse de doctorat,* 17.6.2003, Université de Liège.

DIN EN 1991-1-2/NA (2009), Nationaler Anhang, National festgelegte Parameter, Eurocode 1 - Einwirkungen auf Tragwerke - Teil 1-2/NA: Allgemeine Einwirkungen - Brandeinwirkungen auf Tragwerke, *DIN*, Berlin.

Dotreppe, J.C. (1980), Méthodes numériques pour la simulation du comportement au feu des structures en acier et en béton armé, *Thèse d'Agrégation de l'Enseign. Supérieur,* Université de Liège.

EN 1168 (2010), Hollow core slabs, *CEN*, Brussels.

EN 1990 (2002), Eurocode - Basis of structural design, *CEN*, Brussels.

EN 1991-1-2 (2002), Eurocode 1 - Actions on structures, Part 1.2 - Actions on structures exposed to fire, *CEN*, Brussels.

EN 1991-1-7 (2006), Eurocode 1 - Actions on structures, Part 1.7 - General actions, accidental actions, *CEN*, Brussels.

Fontana, M. et al. (1999), A survey of 40,000 building fires in Switzerland, *Fire Safety Journal 32, 1999, Elsevier Science Ltd,* 137-158.

Franssen, J.M. (1987), Etude du comportement au feu des structures mixtes acier-béton, *Thèse de Doctorat,* 12.2.1987, Université de Liège, ISSN 0075-9333.

Holický, M., Schleich, J.B. (2001), Probabilistic risk analysis of a structure in normal and fire situation including life safety, *Proc. of the International Conference ICOSSAR 2001, Newport Beach,* California, USA.

Klaus, J. (1995), Rechnerisch/experimentelle Untersuchungen zur Erfassung des Einflusses von Massnahmen, zur Verhinderung der Brandausbreitung und zur Brandbekämpfung, auf die Brandraumtemperaturentwicklung bei Naturbränden, *Studiengesellschaft Stahlanwendung e.V., Projekt 224,* Düsseldorf.

Kordina, K. *et al*. (1985a), Untersuchungsbericht N°85636, *Amtliche Materialprüfanstalt für das Bauwesen,* TU Braunschweig.

Kordina, K. *et al*. (1985b), Untersuchungsbericht N°85833, *Amtliche Materialprüfanstalt für das Bauwesen,* TU Braunschweig.

Martin, D.M. *et al*. (1999), The behaviour of a multistorey steel framed building subject to natural fires, *ECSC Pilot Project 7215-CA/806 etc.*, F-NL-UK, 1994-97.

Minne, R. et *al*. (1985), Fire test reports N° 5091 to 5099, *Laboratorium voor Aanwending der Brandstoffen en Warmte-overdracht*, Gent University.

Schleich, J.B. (1987a), REFAO-CAFIR, Computer assisted analysis of the fire resistance of steel and composite concrete-steel structures, *C.E.C. Research 7210-SA/502 1982/85, Final Report EUR10828 EN,* Luxembourg.

Schleich, J.B. (1987b), Numerische Simulation, zukunftsorientierte Vorgehensweise zur Feuersicherheitsbeurteilung von Stahlbauten, *Allianz Versicherungs-AG, Der Maschinenschaden 60, Heft 4,* S. 169 bis 176.

Schleich, J.B. (1988a), The effect of local fires on overall structural behaviour, *AISC 1988 National Steel Construction Conference*, Miami, June 8-11, Proceedings AISC, 42-1 to 42-13.

Schleich, J.B. (1988b), Numerische Simulation, Zukunftsorientierte Vorgehensweise zur Feuersicherheitsbeurteilung von Stahlbauten, *Bauingenieur Bd 63,* 17-26.

Schleich, J.B. *et al*. (1989), Numerical simulation of test frames A2-I and A2-II tested at the "Amtliche Materialprüfanstalt für das Bauwesen, T.U. Braunschweig" in April 1989, *C.E.C. Research 7210-SA/112*, *Activity A2/B1*.

Schleich, J.B. *et al*. (1990), Computer Model CEFICOSS for the fire resistance of composite structures, *IABSE Symposium Brussels, Mixed Structures including New Materials, Report IABSE,* Volume 60, ISBN 3-85748-061-0, 395-400.

Schleich, J.B. *et al*. (1991), REFAO-II Practical design tools for composite steel-concrete construction elements, submitted to ISO-fire, considering the interaction between axial load

N and bending moment M, *C.E.C. Research 7210-SA/504 1985/88, Final Report EUR 13309 EN*, Luxembourg.

Schleich, J.B. *et al*. (1993), REFAO-III, Practical design tools for unprotected steel columns submitted to ISO-fire, *C.E.C. Research 7210-SA/505 1986/88, Final Report EUR 14348 EN,* Luxembourg.

Schleich, J.B., Cajot, L.G. *et al*. (1997a), Development of design rules for steel structures subjected to natural fires in large compartments, *C.E.C. Research 7210-SA/517 etc B-E-F-L-NL, 1993-1996, Final Report EUR 18868 EN*, Luxembourg.

Schleich, J.B., Cajot L.G. *et al*. (1997b), Development of design rules for steel structures subjected to natural fires in closed car parks, *C.E.C. Research 7210-SA/518 etc B-E-F-L-NL, 1993-1996, Final Report EUR 18867 EN,* Luxembourg.

Schleich, J.B. (1998), Influence of active fire protection on the safety level & its consequence on the design of structural members, *« Abschlussarbeit Nachdiplomkurs Risiko & Sicherheit », 1.09.1998, ETHZ*, Zuerich.

Schleich, J.B., Cajot, L.G. *et al*. (2002), Competitive steel buildings through natural fire safety concept, *C.E.C. Research 7210-SA/522 etc. A-B-CH-D-E-F-FI-I-L-NL-UK, 1994-1998, Final Report EUR 20360 EN*, Luxembourg.

Schleich, J.B., Cajot, L.G. *et al*. (2003), Natural fire safety concept, full scale tests, inplementation in the Eurocodes and development of a userfriendly design tool, *C.E.C Research 7210-PR-060 etc. D-F-FI-L-NL-UK, 1997-2000, Final Report EUR 20580 EN*, Luxembourg.

Schleich, J.B. (2005), Handbook 5, Design of buildings for the fire situation. *Leonardo da Vinci Pilot Project CZ/02/B/F/PP-134007, Development of skills facilitating implementation of Eurocodes*, Czech Technical University, Prague, 250 pages.

Schleich, J.B. (2006a), Modern buildings with integrated fire resistance, *ICMS 2006, Steel a new and traditional material for building*, *Poiana Brasov*, Roumania, September 20-22, ISBN 10:0-415-40817-2, 553-560.

Schleich, J.B. *et al*. (2006b), Analyse du rapport d'essai sur une poutre mixte acier-béton, *Essais des 15 et 16.12.2004 au Laboratoire Magnel de Gant / Nouveau complexe DEXIA-BIL à Belval Ouest*, Simon & Christiansen, Luxembourg.

Schleich, J.B. (2007), Zielorientierter Brandschutz gemäss den heissen Eurocodes, *Brandschutz-fachtagung, Schloss Schallaburg - Melk,* Österreich, 12 - 13 February.

Schleich, J.B. (2008), Performance based design for the fire situation, leading to economic and safe fire resistance, *17th Congress of IABSE, Creating and Renewing Urban Structures*, *Proc. intern. symp.* Chicago, September 17-19*,* ISBN 978-385748-118-5.

Schleich, J.B. (2009), Performance based design for the fire situation, theory and practice, *Nordic Steel Construction Conference*, Malmö, September 2-4*,* Publication SBI 181, ISBN 91-7127-0582, 146-155.

Schleich, J.B. (2010), Performance based design for the fire situation, from theory to codes & from codes to practice, *Joint IABSE - fib Conference, Codes in Structural Engineering, Dubrovnik,* Croatia, May 3-5*,* Publication SECON-CSSE, ISBN 978-953-7621-05-6, 395-402.

The Daily Star (2010), The devastating blaze, *Editorial*, Dhaka, Bangladesh, June 5.

Van Acker, A. (2003), Shear resistance of prestressed hollow core floors exposed to fire, *Structural Concrete, Journal of the fib*, Vol. 4, No. 2, June, ISSN 1464-4177, 65-74.

Wesche, J. *et al*. (1989), Untersuchungsbericht N°8559/2108, Durchführung von zwei Naturbrand-simulationen an einhüftigen Rahmen aus Verbundbauteilen, *Amtliche Materialprüfanstalt für das Bauwesen,* TU Braunschweig.