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Sustainable steel buildings through Natural Fire Safety Concept

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Biography

Jean-Claude (JC) Gerardy is a structural engineer from the University of Liege in Belgium. He started his career in Arcelor research department from 1990 (formerly ARBED research). During that time, he was involved in the Eurocodes on steel and composite structures. From 1993 to 1997, he moved to New York as resident engineer for promoting steel in high-rise buildings, trusses and bridges in North America. He was representing Arcelor within ASTM, AWS (American Welding Society), AISC (American Institute of Steel Construction) and the SSPC (Steel Shapes Producer Council). From 1997 to 2000, he came back to Europe as sales manager of long products in the Eastern Countries, Middle East, Africa and India. After being general manager of the e-business platform for the distribution network of Arcelor, he joined Arcelor International Singapore in 2003 as Mill Sales Director for the Far East. In 2005, he moved to Istanbul as Managing Director in charge of the sales of Arcelor in the Near East. Since 2007, he is technical advisory for all Eastern European countries.

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Abstract

Sustainable construction means optimized utilization of raw materials and energy during their entire life cycle and reducing to a minimum any adverse effects on the environment. This paper describes the Global Natural Fire Safety Concept (NFSC) and highlights its importance for sustainable construction. In contrary to conventional methods of guaranteeing structural fire protection for steel structures with board claddings or reactive (intumescent) fire protection systems, active fire fighting measures as well as probabilistic aspects on the fire occurrence are respected. Hence by optimizing the material use, the costs for fire protection can strongly be reduced. The application of the NFSC is described on the basis of realized buildings. The NFSC produces real safety for people and at the same time guarantees the needed fire resistance for the structure in real life. It was established in the scope of European Research sponsored by the ECSC and is now fully considered in the European Standards.

Keywords: natural, fire, steel, sustainability

Introduction

The use of steel as construction material for buildings is a first step towards ecological, sustainable building. The entirety of the production of steel beams and columns are made from indefinitely recyclable ferrous scrap. Steel is a sustainable, flexible material by fulfilling all esthetic expectations [1]. But at elevated temperatures the mechanical properties of steel (and concrete) are decreasing.

The traditional way of "fire design" is the cladding of columns and beams with fireproof materials (spray, board or paint). Because of the cladding the temperature increase in the construction is reduced and the member resist to the fire for a longer time. No information about the real behavior of the structure and the safety is given by this method. In the last decades a new approach of fire design was developed. By taking the active fire fighting measures (e.g. sprinkler) and the real fire evolution into account, the Natural Fire Safety Concept (NFSC) is a more realistic approach for the structural safety in case of fire. The material use is optimized; the costs needed for fire protection are strongly reduced and, in some cases, omitted [2]. Compared to modern Fire Safety Concepts, the traditional method is a waste of material, resources and energy.

Evolution of real fires

A real fire can be distinguished in three different phases (Figure 1): First, the pre-flashover or growth phase (A), the fire load begins to burn; temperature within the compartment varies from one point to another, with important gradients and there is a gradual propagation of the fire. The average temperature in the compartment grows; if it reaches about 300°C to 500°C, the upper layers are subjected to a sudden ignition called flashover and the fire develops fully.

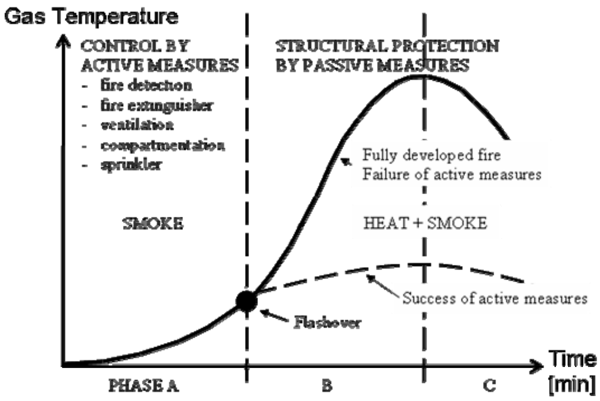

Figure 1 : Realistic Fire Evolution

In the second phase (B), after flashover, the gas temperature increases very rapidly from about 500°C to a peak value, often in excess of 1000°C, and becomes practically uniform throughout the compartment. After this phase, the available fire load begins to decrease and the gas temperature necessarily falls (C, cooling phase). The fire severity and duration of these phases depend on many parameters: The amount and distribution of combustible materials (fire load); the burning rate of these materials; the ventilation conditions (openings); the compartment geometry and the thermal properties of surrounding walls.

There are two types of fire, controlled respectively by ventilation and by fuel (fire load) characteristics (Figure 2). Ventilation controlled fires take place when openings of the compartment are relatively small compared to its overall dimensions. An increase of the opening areas results in higher peak temperatures and a faster decay phase. If the air supply is sufficient, so that the fire is fuel controlled, the amount of fire load and its arrangement have a decisive influence on fire severity.

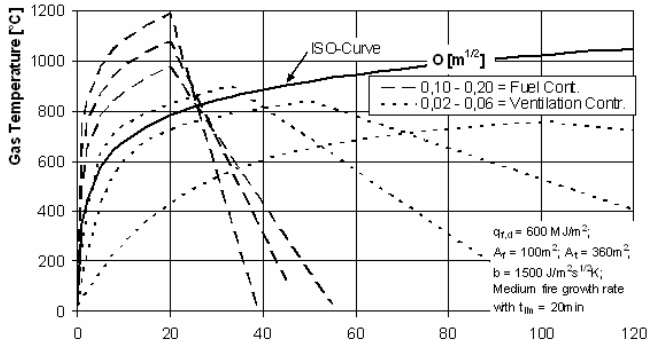

Figure 2: Temperature Time Curves (EN 1991-1-2: 2002, Annex A + ISO)

To summarize, short and relatively benign fires can be expected when the air flow rate into a compartment is rather high and the fire load density rather small. On the other hand, higher temperatures and longer durations take place with higher fire load densities and little heat dissipation through openings and walls. The design fire exposure, together with structural data for the proposed structure, thermal properties of the structural materials and coefficients of heat transfer for various surfaces of the structure, give the necessary information to determine the temperature development in the fire exposed structure. Together with the mechanical properties of structural materials, the load characteristics, and the variation of resistant forces and moments, it is possible to determine thermal stresses and load bearing capacity in fire conditions [3].

The Natural Fire Safety Concept (NFSC)

The NFSC or Global Fire Safety Concept, is a more realistic and credible approach for the analysis of structural safety in case of fire. It takes account of active fire fighting measures and real fire characteristics. In June 1994 the European Research "Natural Fire Safety Concept" started. It has been undertaken by 11 European partners and was coordinated by PROFILARBED-Research, Luxembourg. The research project ended in June 1998 [2].

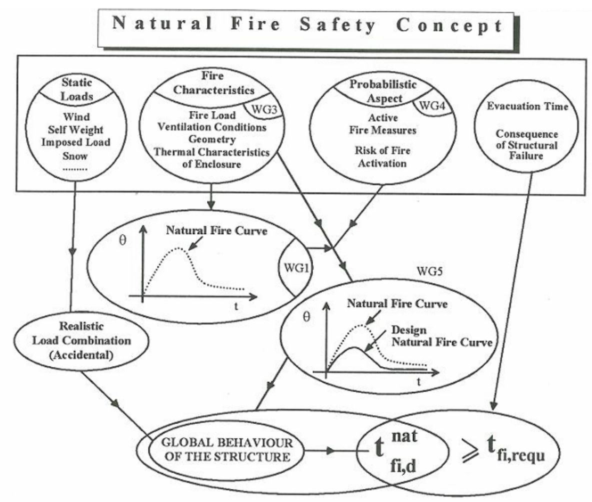

Figure 3 : Natural Fire Safety Concept

The NFSC takes into account: a) the building characteristics relevant to fire growth: fire scenario, fire load, pyrolysis rate, compartment type and ventilation conditions; b) quantifies the risk of fire start and considers the influence of active fire fighting measures and occupation time; this risk analysis is based on probabilities deduced from European databases of real fires; c) deduces from the previous step, design values for the main parameters such as the fire load; d) determines the design heating curve as a function of the design fire load that takes into account the fire risk and therefore the fire fighting measures; e) simulates the global behavior of the structure submitted to the design heating curve and the static load in case of fire; f) deduces the fire resistance time nat $t_{fi,d}$; this may often be infinite such that the structure is able to support the loads from the beginning to the end of the fire; g) verifies the safety of the structure by comparing the fire resistance time nat $t_{fi,d}$ with the required time depending of the evacuation time and the consequences of the failure.

The European Research on the NFSC [2] allowed to analyze natural fire models based on more than 100 new natural fire tests; consequently permitting to consider natural fire models in the European Standard. Furthermore these natural fire models allow, through design fire load, to consider the beneficial effect of the active fire safety measures i.e. by safe escape ways, proper smoke venting or by conveniently designed and maintained sprinkler systems. Also the danger of fire activation is taken into account. Thus the so-called Global Fire Safety Concept produces real safety for people and at the same time permits to guarantee the required structural fire resistance in real live. A prescription of the verification of steel structures in case of fire according to the European Standards is given in the following chapter.

The NFSC and the European Standards

According to the EN [6, 7, 8] the design of structural members in fire situations has to be carried out at the ultimate limit state. It should be verified that, during the relevant duration of fire exposure t:

$$E_{fi,d,t} \leq R_{fi,d,t} \quad (1)$$

where $E_{fi,d,t}$ is the design effect of the actions in the fire situation determined from the accidental combination rule, including effects of thermal expansions and deformations and $R_{fi,d,t}$ is the design value of the corresponding resistance in the fire situation. As an alternative to (1) the verification may be carried out in the time or the temperature domain [7].

Mechanical Actions

The probability of the combined occurrence of a fire in a building and an extremely high level of mechanical loads is very small. Therefore actions on structures from fire exposure are classified as accidental actions and shall be combined by using the following accidental combination:

$$E_{fi,d,t} = \sum G_{k,j} + (\psi_{1,1} \text{ or } \psi_{2,1}) * Q_{k,1} + \sum \psi_{2,i} * Q_{k,i} + \sum A_{d,t} \quad (2)$$

where $G_{k,j}$ is the characteristic value of a permanent action j; $Q_{k,1}$ is the characteristic value of the leading variable action 1; $Q_{k,i}$ is the characteristic value of the accompanying variable action i; $\psi_{1,1}$, $\psi_{2,1}$, $\psi_{2,i}$ are combination factors for buildings according to Table A1.1 of [6] and A_d is the design value of an accidental action resulting from the fire exposure. The accidental action is represented by the temperature effect on the material properties and the indirect thermal actions created either by deformations and expansions caused by the temperature increase in the structural elements, where as a consequence internal forces and moments may be initiated, P-δ effect included either by thermal gradients in cross-sections leading to internal stresses. Generally this leads in the accidental fire situation to a loading which corresponds from 50% to 70% of the ultimate design value of actions at room temperature.

Design resistance of structural steel in fire

At elevated temperatures the mechanical properties of steel are decreasing [8]. In comparison to room temperature (20°C), the modulus of elasticity decreases at 100°C and the yield strength at 400°C (Figure 4).

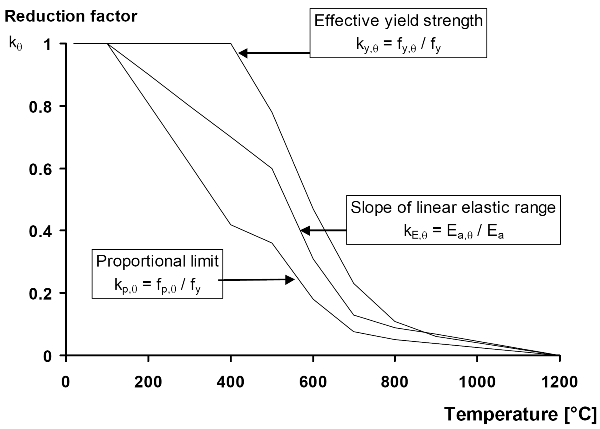

Figure 4: Reduction factors of carbon steel at elevated temperatures

Thus the design resistance of steel in fire situation depends on the thermal actions and the material properties at elevated temperatures. To determine the gas temperatures in the compartment the appropriate temperature-time curve has to be defined first. Then the increase of the temperature in the structural member can be calculated by using simple calculation methods or advanced calculation methods. The design resistance is determined with the temperature and the mechanical properties at elevated temperatures.

Thermal Actions

The thermal actions are given by the net heat flux h_{net} [W/m2] to the surface of the member. On fire exposed surfaces the net heat flux should be determined by considering heat transfer by convection and radiation [7].

$$\dot{h}_{net} = \dot{h}_{net,c} + \dot{h}_{net,r} \quad \text{[W/m2]} \quad (3)$$

The net convective heat flux component should be determined by:

$$\dot{h}_{net,c} = \alpha_c * (\theta_g - \theta_m) \quad \text{[W/m2]} \quad (4)$$

with αc is the coefficient of heat transfer by convection [W/m2K]; θ_g is the gas temperature in the vicinity of the fire exposed member [°C] and θ_m is the surface temperature of the member [°C]. To define the gas temperatures θ_g, [7] gives the opportunity to use Nominal temperature-time curves (= ISO fire curve) and Natural fire models with parametric temperature-time curves.

a. Nominal temperature-time curves

In EN 1991-1-2: 2002 [7] three nominal temperature-time curves are given. The standard temperature-time curve (or ISO fire curve) is given by:

$$\Theta_g = 20 + 345 * \log_{10} * (8 * t + 1) \quad \text{[°C]} \quad (5)$$

Where t is the time [min] and the coefficient of heat transfer by convection α_c = 25 W/m2K. This fire curve does not represent realistic fire conditions in a compartment. The temperature is always increasing; the cooling phase and the real fire load of the compartment are not considered. This curve has no probabilistic background. The real fire evolution is not considered and it is not possible to calculate realistic temperatures with this curve. But this curve is simple to handle (only one parameter, the time t).

b. Natural fire models – parametric temperature-time curves

In the last decade modern design models to describe the real fire behaviour are developed. These natural fire models take into account the main parameters which influence the growth and development of fires. Natural fires depend substantially on fire loads, openings and thermal properties of surrounding structure. The gas temperature in the compartment can be determined with parametric temperature-time curves. These curves are considering the ventilation by an opening factor and the design value of the fire load density [7, Annex A].

Also advanced fire models taking into account the gas properties, the mass and the energy exchange are given in [7, Annex D]. A distinction is made between one-zone models, assuming a uniform, time dependent temperature distribution in the compartment and two-zone models assuming an upper layer with time dependent thickness and with time dependent uniform temperature, as well as lower layer with a time dependent uniform and lower temperature.

An essential parameter in advanced fire models is the rate of heat release Q in [W]. It is the source of the gas temperature rise, and the driving force behind the spreading of gas and smoke.

The following temperature-time curve is valid for fire compartments up to 500m^2 of floor area. It is assumed that the fire load of the compartment is completely burnt out [7, Annex A]:

$$\Theta_g = 20 + 1325 * \left(1 - 0.324 * e^{-0.2t^*} - 0.204 * e^{-1.7t^*} - 0.472 * e^{-19t^*}\right) \quad [°C] \qquad (6)$$

where t* = t * Γ and Γ = (O/b)^2/(0.4/1160)^2; O is the opening factor [m$^{1/2}$]; b = (ρ*c*λ)$^{1/2}$ in [J/m^{2}s$^{1/2}$K]. The maximum temperature θ_{max} in the heating phase happens for t* = t^*_{max} with

$$t^*_{\max} = \max\left[\left(0.2 * 10^{-3} * q_{t,d} / O\right); t_{\lim}\right] \quad [h] \qquad (7)$$

where $q_{t,d}$ is the design value of the fire load density related to the total surface area At of the enclosure.

b.1. Fire load densities

The design value of the fire load density $q_{f,d}$ is defined as [7]:

$$q_{f,d} = q_{f,k} * m * \delta_{q1} * \delta_{q2} * \delta_n \qquad [MJ/m^2] \quad (8)$$

where $q_{f,k}$ is the characteristic fire load density per unit floor area [MJ/m^2]; m is the combustion factor; δ_{q1} is taking into account the fire activation risk due to the size of the compartment and δ_{q2} the fire activation risk due to the type of occupancy; δn = $\Sigma\delta_{ni}$ is taking into account the different active fire fighting measures i from Tables E.1 and E.2 [7]. These active measures are generally imposed for life safety reason. EN considers that all active systems such as sprinklers will be well maintained and fully operational during the whole life of the structure.

Table E.1 — Factors δ_{q1}, δ_{q2}

Compartment floor area A_f [m²]	Danger of Fire Activation δ_{q1}	Danger of Fire Activation δ_{q2}	Examples of Occupancies
25	1,10	0,78	artgallery, museum, swimming pool
250	1,50	1,00	offices,residence, hotel, paper industry
2 500	1,90	1,22	manufactory for machinery & engines
5 000	2,00	1,44	chemical laboratory, painting workshop
10 000	2,13	1,66	manufactory of fireworks or paints

Table E.2 — Factors δ_{ni}

δ_{ni} Function of Active Fire Fighting Measures									
Automatic Fire Suppression		Automatic Fire Detection			Manual Fire Suppression				
Automatic Water Extinguishing System	Independent Water Supplies 0 | 1 | 2	Automatic fire Detection & Alarm by Heat	Automatic fire Detection & Alarm by Smoke	Automatic Alarm Transmission to Fire Brigade	Work Fire Brigade	Off Site Fire Brigade	Safe Access Routes	Fire Fighting Devices	Smoke Exhaust System
δ_{n1}	δ_{n2}	δ_{n3}	δ_{n4}	δ_{n5}	δ_{n6}	δ_{n7}	δ_{n8}	δ_{n9}	δ_{n10}
0,61	1,0 | 0,87 | 0,7	0,87 or 0,73		0,87	0,61 or 0,78		0,9 or 1 or 1,5	1,0 or 1,5	1,0 or 1,5

c. Steel temperature development

The calculation of the development of temperature fields in the cross section of a structural member exposed to fire involves solving Fourier's differential equation:

$$\frac{\partial}{\partial x}\left(\lambda_\Theta \frac{\partial \Theta}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_\Theta \frac{\partial \Theta}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_\Theta \frac{\partial \Theta}{\partial z}\right) + Q = \rho c_\Theta \frac{\partial \Theta}{\partial t} \qquad (7)$$

Q is the internal heat source and is equal to 0 in case of non-combustible walls. The boundary condition is expressed from the net heat flux $h_{net,d}$. Simple models for the steel temperature development calculation are based on the resolution of the equation (3) in the hypothesis of uniform temperature distribution in the cross section of the structural member. According to [3] the increase of temperature $\Delta\Theta_{a,t}$ in an unprotected steel member during a time interval Δt [s] should be determined from:

$$\Delta\Theta_{a,t} = k_{sh} * \frac{A_m / V}{c_a * \rho_a} \dot{h}_{net} * \Delta t \qquad [°C] \qquad (8)$$

where k_{sh} is the correction factor for the shadow effect; A_m/V is the section factor for unprotected steel members [1/m]; ca is the specific heat of steel [J/kgK] and ρ_a is the unit mass of steel [kg/m^3].

Examples

In this chapter the advantages of the application of the NFSC is shown on three examples: an open parking structure, realized 2004 in France and two multi-story buildings erected 2003 and 2007 in Luxembourg. According to the building use, fire scenarios were determined, a realistic natural fire curve was calculated and the structure was verified for the elevated temperatures. Cost estimated for passive fire protection was generally based on [10]. The real savings may vary depending on the used fire protection products and the manufacturer.

a. Parking "CARREFOUR", Aix en Provence, France

Till 2004 it was impossible to built open car parks with unprotected steel members in France as no difference between open and closed car parks was made in the regulation from 1975. Due to the research and fire tests done by CTICM, PAB and Arcelor a design model based on real fire scenarios and realistic fire loads was developed [9].

The parking "Carrefour" is the first open car park realized with unprotected steel beams; it was the starting point for a new generation of parking structures in France and launched a large interest in this construction type.

Architect: Yves Melia – Sud Architectes
Erection: Baudin-Châteauneuf
600 Places, 12400 m2,
Grid 15 x 10m / Span composite slab a = 3,33m (Cofraplus 60)
Primary steel beams: HE 500A/550B S355,
Total length +/- 500m; +/- 93t
Secondary steel beams: IPE 450/500 S355,
Total length +/- 4400m; +/- 370t
Circular composite Columns

The structure is designed to resist a real fire without any failure [9]. The aesthetic and light structure with unprotected secondary and primary beams fulfills all architectural expectations.

Figure 6 : « Carrefour » - Composite Floor

Estimated saving for the secondary beams compared to spray-protected beams: approx. 30.000 €.
But a sprayed structure would never fulfill the architectural expectations!
Compared to fireproofing painted beams, the savings are approx. 160.000 € and 12.000 kg of paint.

Figure 7 : Banque Populaire (Luxembourg)

With the realized solution no energy must be spend on the maintenance of passive fire protection. The steel structure is easy to demount and is almost 100% recyclable.

b. Banque Populaire, Plateau de Kirchberg, Luxembourg

Architect: Tatjana Fabeck,
Thomas Krähenbühl
Design: Schroeder & Associés
Contractor: Hochtief Luxembourg

4 + 6 Storey office building 6400m2,
(+3 underground parking floors)
Hybrid Composite Cellular Beams HE 400B/M, S460, Span 16,8m
Composite Slab of 16cm (C30/37), Span 4,2m
Columns HD 400, S 355
Fire Safety Concept:
- Active fire fighting measures: Sprinklers with water reservoir 20m^3; Automatic alarm detection; Automatic alarm transmission to the fire brigade

Figure 8 : Banque Populaire – Cellular Beams

Connection with an extended end plate (Figure 9)

Fig. 9 : Connection

The natural fire curve of the most critical fire scenario is shown in Fig. 10. The maximum gas temperature is 490°C; the maximum steel temperature is less than 330°C. No significant reduction of the steel yield strength has to be done. With the application of the Natural Fire Safety Concept it was possible to use unprotected columns and unprotected beams. This amazing result is due to the implementation of the full set of active fire fighting measures. Compared to spray protected steel beams, the estimated savings are about 30.000€ and compared to fireproof painted beams about 66.000€ and 4.000 kg of paint. A protection of the columns with fireproof board would cost additional about 70.000€ and 15.000kg of board. The total estimated savings due to the application of the NFSC are approx. from 100.000€ to 136.000€.

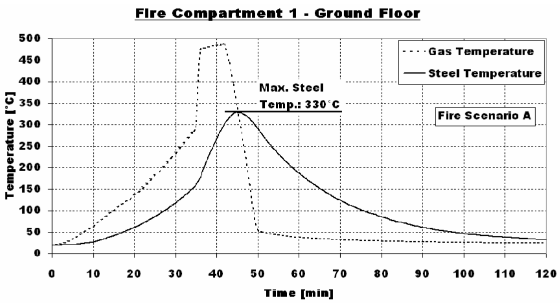

Fig. 10 : Banque Populaire - Natural Fire Curve


Fig. 12 : Centre Médical – Slim Floor System

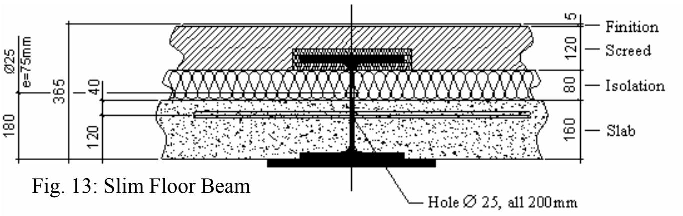

Fig. 13: Slim Floor Beam

c. Centre Médical de la Clinique d'Eich, Luxembourg

This building is an extension of the "Clinique d'Eich", Luxembourg. To respect the floor levels of the existing building and to guarantee a clear height of 2865mm the total slab thickness was restricted to 365mm.

Therefore the Slim Floor system with composite beams was chosen. Due to the application of the NFSC it was possible to use unprotected columns and unprotected beams.


Fig. 11 : Centre Médical

Architect: G + P MULLER Luxembourg
Design: Schroeder & Associés S.A.
Slim Floor Beams, Span 6,5m;
Fire Safety Concept with active fire fighting measures: Sprinklers, Automatic smoke ventilation, Automatic alarm detection, Automatic alarm transmission to the fire brigade

In the fire design situation, the load bearing capacity of the Slim Floor Beam (Fig. 13) is calculated by taking the composite action into account. The collaboration of the concrete slab and the SFB is achieved by additional transversal reinforcement (∅ 20, all 200mm). Compared to a conventional fire design procedure, protecting the columns and the lower flange of the SFB with fireproof board the estimated savings are about from 90.000€ to 100.000€ and about 20.000kg.

Conclusion

The EN procedure for providing structural safety in case of fire is quite realistic as it takes account of real fire characteristics and of existing active fire fighting measures. It consists in estimating the real behavior of a structure subjected to the natural fire which may arise under those real fire conditions. The consideration of real actions leads to real safety and also to optimized economy. Applying active fire fighting measures such as fire detection, alarm, automatic alarm transmission to the fire-fighters, smoke exhaust systems and sprinklers, provides protection to people that safety of people is ensured in an optimal way. The passive protection by insulation, needed in former times to guarantee the stability of the structure in case of fire, is strongly diminished and the budget dedicated to the fire safety will be used in a perfectly efficient way. Instead of paying for protection materials in order to fulfill ISO fire requirements of 90 minutes and more, this money can be more efficiently used for active fire safety measures and get more sustainable buildings easily recyclable. Besides, active fire safety produces real safety for the people, not only the buildings.

Steel sections are today almost exclusively produced with scrap, infinitively recyclable. In addition to these effective production processes, steel constructions offer the advantage of prefabrication and short erection time.

References

ARBED S.A. ***Constructing in steel: the ecological choice***, Luxembourg 2002

ECSC, ARBED S.A. ***Natural Fire Safety Concept***, Luxembourg 2001

International Iron and Steel Institute; ***Fire Engineering Design for Steel Structures***, Brussels 1993

SCHLEICH J.-B. ***Einwirkungen auf Tragwerke im Brandfall*** – EC 1, ISFSSS Cologne 2003

SCHLEICH J.-B. ***Globales Brandsicherheitskonzept***, Stahlbau 67 (1998),

CEN; EN 1990. ***Basis of structural design***, CEN Central Secretariat, Brussels, 2002

CEN; EN 1991-1-2. ***Actions on Structures***, Part 1-2–Actions on structures exposed to fire, CEN Central Secretariat, Brussels, 2002

CEN; EN 1993. ***Design of steel structures-Part 1-2: General rules-Structural fire design***, CEN Central Secretariat, Brussels, 2005

Fraud, Zhao, Joyeux, Kruppa . ***Guide pour la vérification du comportement au feu de Parcs de stationnement largement ventiles en superstructure métallique***, CTICM, 2003

UNTEC, Groupe Métal, Arcelor. ***Economie et solutions acier***, Carnets De L'Acier, 2006