Transactions on the Built Environment vol 55, © 2001 WIT Press, www.witpress.com, ISSN 1743-3509

Assessing 19th century 'fireproof' buildings

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Abstract

Construction details of 19th century fireproof buildings are discussed. The paper deals more specifically with Brussels industrial iron framed buildings. The innovations and developments of construction techniques are illustrated by going deeper into three representative Brussels case-studies. The changes in construction techniques and the applications of new materials are explained by the evolving insight in 'fire safety'.
Some attention will be paid to international developments, more specifically the introduction of the Eurocodes. Directions are given on how to apply this knowledge when dealing with 19th century 'fireproof' buildings.

1 Building fireproof

In the beginning of the nineteenth century, a building was considered fireproof when all the combustible materials were replaced by incombustible ones. As a consequence an alternative had to be found for the wooden framed buildings. The typical fireproof construction was iron-framed with brick vaulted floors. Covering wood - instead of replacing it - to increase the fire safety was accepted but such a construction was only called 'semi-fireproof' or 'slow burning'.
English designers first introduced the iron and brick fireproof system in textile mills and warehouses in the 1790s. In Brussels, the dock warehouse was the first building where the fireproof system had been applied on a large scale.

1.1 Brussels dock warehouse 1844-1847

After a competition, organised by the Brussels community in 1842, the first stone of the dock warehouse was laid by king Leopold 1st in 1844. The building was inaugurated in 1847.

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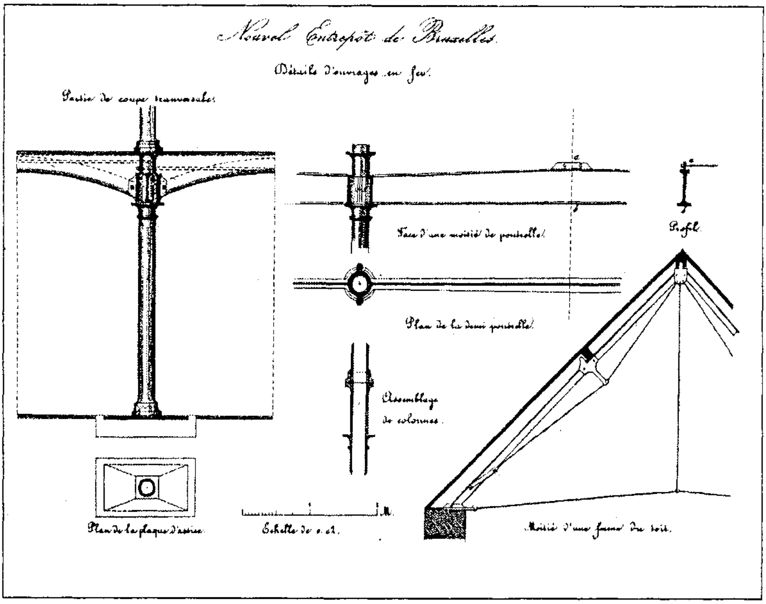

Figure 1: Construction details of the Brussels dock warehouse 1844-1847 [1]

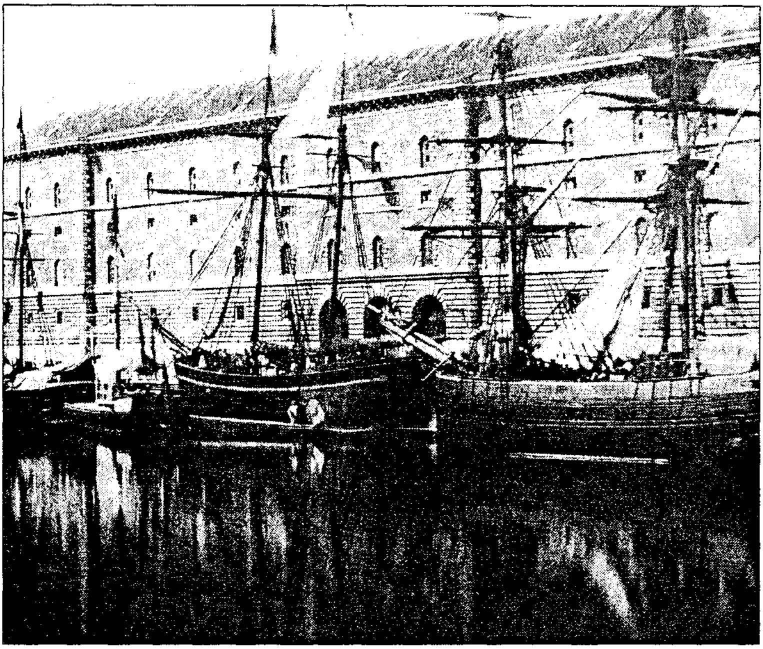

Figure 2: Brussels dock warehouse around 1860 [2]

The 4 storey dock warehouse is built up around three inner courts. The inner space of the building is divided into smaller rooms by load bearing walls. In the cellar wine was stored, the upper floors were reserved for grain and other merchandise.

As can be seen in figure 1 the construction details were clearly based on the English fireproof mills; no combustible materials were used. The floor consisted of a brick barrel vault - spanning 3m75 - carried by a cast iron beam. Iron tie-rods, connecting the middle of adjacent beams, were imbedded in the brick vault to protect them from fire. (Unfortunately, by doing so they became structurally less efficient). The design of the cast iron beam - spanning 6m10 - was based on Hodgkinson's recommendations: a hump-backed beam with an asymmetrical cross-section. The beam ends are wrapped around the hollow circular column and connected by using a shrink ring. The columns are assembled by simply sliding the upper over the lower column. The roof trusses are wrought iron.

Constructing the floors in the shape of a vault involved two major drawbacks. Since the upper surface had to be levelled, additional material was needed, making the floor heavy: the self-weight of the floor came to 75 kN/m^2 (10 times more than a timber floor). Secondly, the construction height of the floor increased equal to the span of the arch. The enlarging of free space had to be weighed against the height (and the weight) of the floor.

1.2 Pawnshop 1859-1862

These drawbacks were solved when applying light-weight floors. In these light-weight floors a secondary system of beams was introduced. The primary beam carried now a series of small vaults (figure 3 and 4). By applying this kind of floor in the pawnshop building, the floor height could be reduced to only 25 cm. And the self-weight decreased to 45 kN/m^2.

In the pawnshop, the girders are made of wrought iron, being better in tension than cast iron. The shape of the cast iron beam reminds of two I-profiles placed one on top of the other (figure 4). In another building, a paper factory dating from 1863, the primary beam has the same shape, but in this case the beam is really built up of two wrought iron I-profiles connected to each other. Apparently the pawnshop seems to be the last building one comes across cast iron beams.

In the pawnshop all the exposed iron is protected. The girders are placed between the beams to imbed them in the vault. The exposed under flange of the beam and the girders are protected with plaster. The cast iron columns are covered with white stone. This covering of the iron elements must be seen in an overall atmosphere of mistrust towards the behaviour of iron in case of fire, as explained in the next section.

1.2.1 Piano factory 1890s

The construction of the piano factory illustrates the further developments. First wrought iron, later mild steel profiles were riveted together to form the

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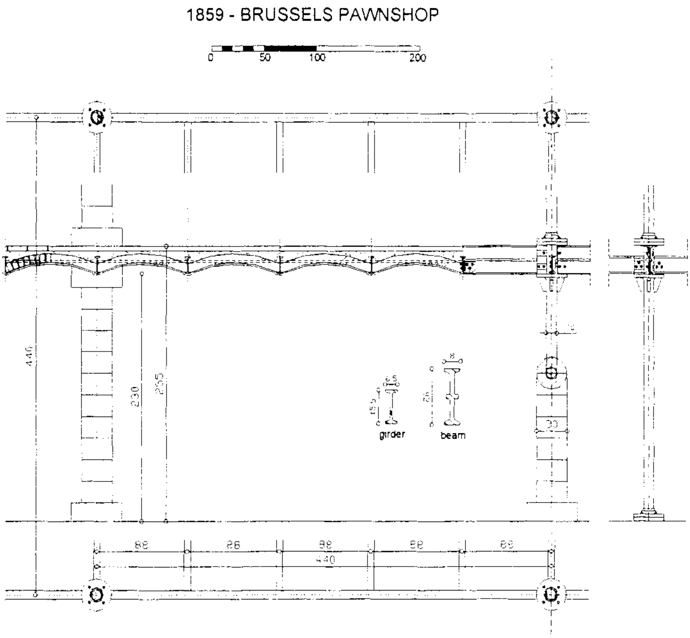

Figure 3: Construction details of the Brussels pawnshop (1859)

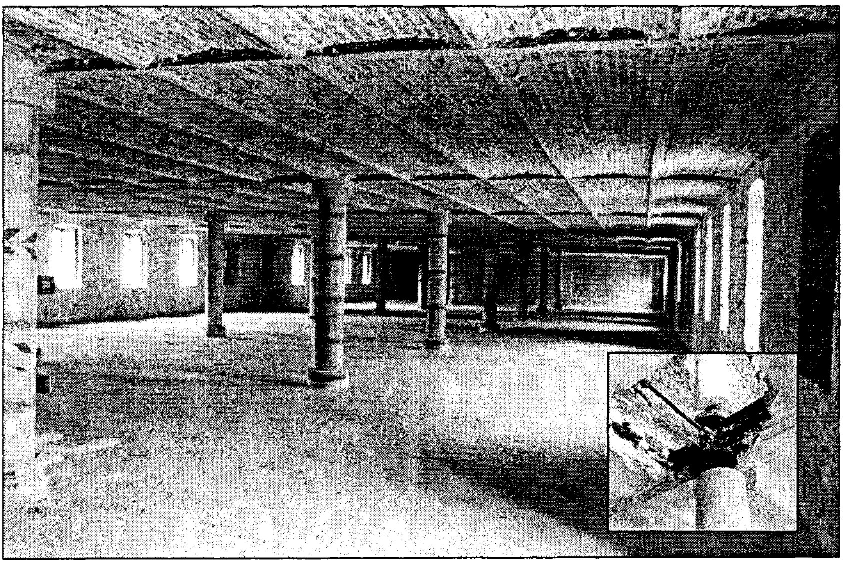

Figure 4: Interior view of the pawnshop during renovation. Detail (right): the encasement of the cast iron column and the structure of the light-weight floor

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primary beams. The brick arches are replaced by concrete vaults. The columns are cast iron. In this building the three materials (concrete-steel-cast iron) are confronted. Later on, cast iron columns disappear and structures are conceived as a full iron or full concrete frame. The third Brussels maritime warehouse 'Thurn and Tassis', built in 1899, illustrates both construction techniques.

2 Fireproof concept

Since cast iron had been applied as a structural element in fireproof buildings contradictory information about its behaviour in fire has been spread. This can be ascribed to several facts.

In the early times, one had implicit faith in cast iron frames as a fireproof construction system. Information about the actual behaviour of cast iron elements in fire was mainly derived from reality, since structural elements were not fire tested. In 1844, 1847 and 1861 British fireproof buildings collapsed while burning, causing cast iron to be labelled unreliable in fire. As a consequence one recommended to encase it when structurally used. Despite such admonishments British mill designers continued to use the iron and brick fireproof system. Also in Brussels trust as well as mistrust was known among architects because the encasing of the iron structure in the pawnshop was exceptional.

S. Wermiel [3] explains how American fire experts responded to the great fires of Chicago and Boston in 1871 and 1872. The experts noticed that on the one hand the fireproof buildings acted as a barrier, preventing the fire from passing from one building to another. On the other hand, when examining the inner structure, the exposed iron turned out to be deformed. It was stated that, to survive a fire, building materials had not only to be incombustible, but they had to be able to resist the effects of heat as well.

So the discussion whether a construction was fireproof or not, resulted not only from the insight in the fire behaviour of structural elements, but rather in the meaning of the word 'fireproof'.

Nowadays the term fireproof is no longer used; we distinguish the 'reaction by fire' and the 'resistance to fire'. The reaction by fire is related to the behaviour of the material within a fire (combustibility, ignition, flame spread, toxicity of the gas, ea.), while the resistance to fire is related to the behaviour of structural elements (the load bearing-, the insulation- and the integrity criterion). Taking these terms in account, one can say that cast iron has a good reaction by fire in contrary to its resistance to fire.

3 Resistance to fire of cast iron columns

To examine how cast iron columns reacted to the effect of heat, a series of fire tests were carried out in Germany and America in the 1880s and 1920s. Unprotected as well as protected columns were tested. But shortly after, cast iron fell into disuse and the investigation of its fire behaviour was stopped.

In the 1980s questions about the fire safety of cast iron structures rose again since buildings had to be brought up to the latest construction standards while renovating them. By that time standard fire tests were set up to determine the fire resistance of structural elements exposing them to the ISO standard fire curve. And the fire resistance of the structural elements was determined by the period of time during which the element could fulfil its load bearing function under these ISO standard fire conditions. The fire resistance of a structural element was expressed in minutes.

Since the early tests on cast iron columns were carried out under different conditions, it was difficult to interpret the results. Moreover, as the number of tests was small, additional information was needed. Therefor a second series of tests was carried out in England and Germany in the 1980s.

In the 1990s König [4] investigated the material characteristics of heated historical grey cast iron. The examination pointed out that, when heating cast iron, the mechanical properties were not affected until reaching a temperature of 400°C. Between 400°C and 600°C cast iron loses 70% of its strength. At 800°C only 5% of its original strength is left. So when testing a cast iron column under ISO standard fire conditions, the degree of loading as well the geometry of the profile are important. Generally speaking, the fire tests [5] pointed out that the fire resistance of an unprotected hollow cast iron column is about R30. Lowering the load level and adapting the massivity, will increase the fire resistance but R60 can barely be reached. When filling the inner core with concrete the fire resistance increases with 15 minutes, mainly due to the increased heat capacity of the column. When applying an intumescent coating to the outer surface of the column, a fire resistance of R90 can be reached with a relatively thin film. For periods of fire resistance of more than 90 minutes, intumescent coatings can still be used but the required thickness will harm the overall character of the cast iron element.

Although several fire tests have been carried out up till now, assessing the fire safety of an existing cast iron column stays difficult. And since historic cast iron columns can only become more rare, it is very important to use all possible information and knowledge available to assess the structures. In this respect the research on steel constructions has to be exploited, since the behaviour of steel in fire shows great similarities.

4 Using fire engineering science

By the recent introduction of the Eurocodes in the European countries the door is opened to a full fire engineering approach. The Eurocodes provide clear formulas to calculate the temperature in a compartment and in the structural elements. In EC1 the basis of design and actions on structures is explained. EC2 to EC6 deal with a construction material. Part 2 of each of these codes concerns the structural fire design.

An important improvement is the introduction of the 'natural fire concept' to calculate the temperature in a compartment [6]. Contrary to the ISO standard fire, the natural fire takes in account the actual fire load in the building, the

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geometry of the building as well as the window openings (ventilation factor) and the thermal inertia of the compartment boundaries.

The influence of the different parameters is illustrated by calculating the natural fire for compartments based on the 19th century fireproof buildings. When using the natural fire temperature-time curve, as stated in EC1, the size of the compartments is limited to 100 m^2. This restriction results from the one-zone model which assumes that the gas temperature within the compartment is uniform. In the following calculations and graphs 'theoretical' compartments are used, based on the geometry of the fireproof buildings.

4.1 Ventilation factor

The typical 19th century fireproof buildings are constructed on a regular grid: rectangular layers are piled up and covered with a saddle roof. In figure 5 these layers are ranged according to their geometry: window openings are situated in the small or in the large façade. The position as well as the number of windows will influence the ventilation factor and as a consequence the growth of the fire.

To illustrate the effect of the ventilation parameter the temperature time-curve is given for two compartments based on the extremes of the case-studies. Figure 6 illustrates that when the ventilation is high, the fire is intense, but short; after 30 min the fire dies out. The column, situated in this compartment, reaches a maximum temperature of 600°C after 20 minutes. When the ventilation is low, the fire grows slowly. After 30 minutes the temperature in the column is about 450°C but rises finally to 700°C, after 70 minutes. Both scenarios ask for different treatment.

4.2 Fire load

The fire load density represents the total amount of combustion energy per unit floor area. The load densities are tabled for different uses. Most of the nineteenth century fireproof buildings are used as office, dwelling, shop or storage. So the fire load density can vary from 250 to 2000 MJ/m^2.[6]

Active fire protection measures are taken into account by multiplying the fire load density by a differentiating factor. For approved fire extinguishing systems the fire load can be reduced to about 60% [6] . Tabled values are not provided in the EC, but they can be derived from other publications, stating updated information.

Figure 7 illustrates how the temperature raises in a compartment with a fire load density of 450 MJ/m^2 (ex. an office) and 2000 MJ/m^2 (ex. storage). If the office-compartment would be equipped with an active fire extinguishing system, a reduced fire load is taken into account (0,6 x 450MJ/m^2). By doing so the maximum temperature in the column decreases from 600°C to 420°C. In the latter the column will stand the fire, even when 100% loaded.

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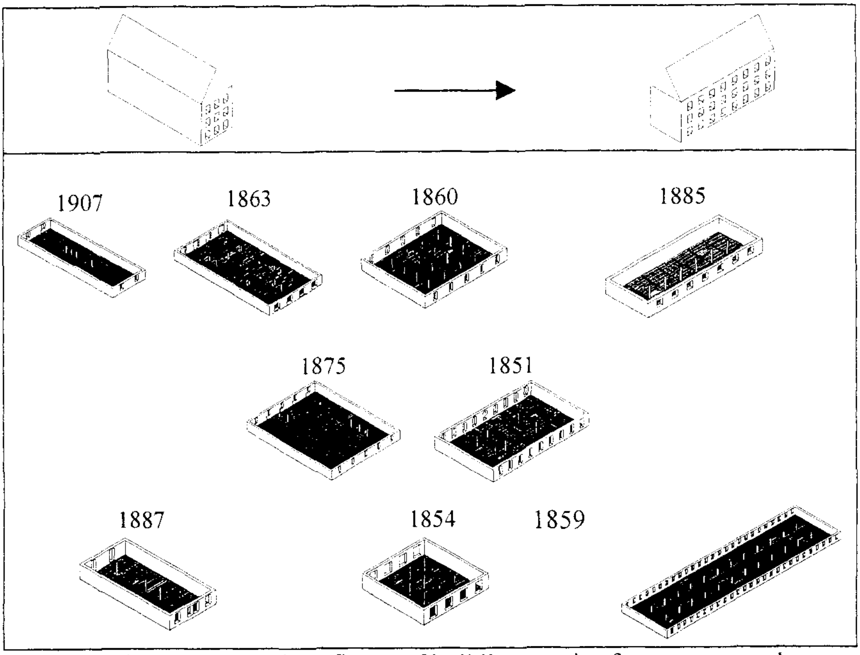

Figure 5: The geometry of the fireproof buildings varies from square - elongated. Window openings are positioned on the small or on the long side.

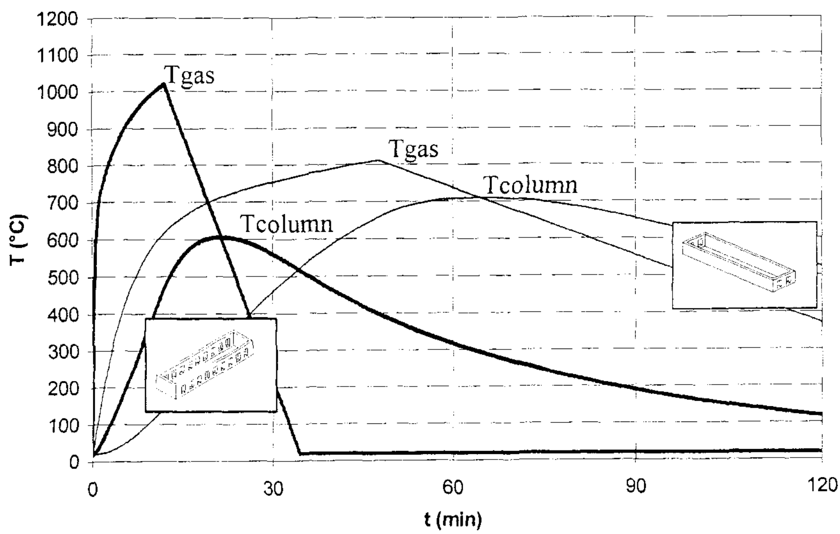

Figure 6: Temperature-time curve of the natural fire in a compartment with high or low ventilation. Temperature in an unprotected column within those compartments. (fire load 600 MJ/m², U/F 40 m^{-1}, b 1057, O_{low} 0.028, O_{high} 0.112)

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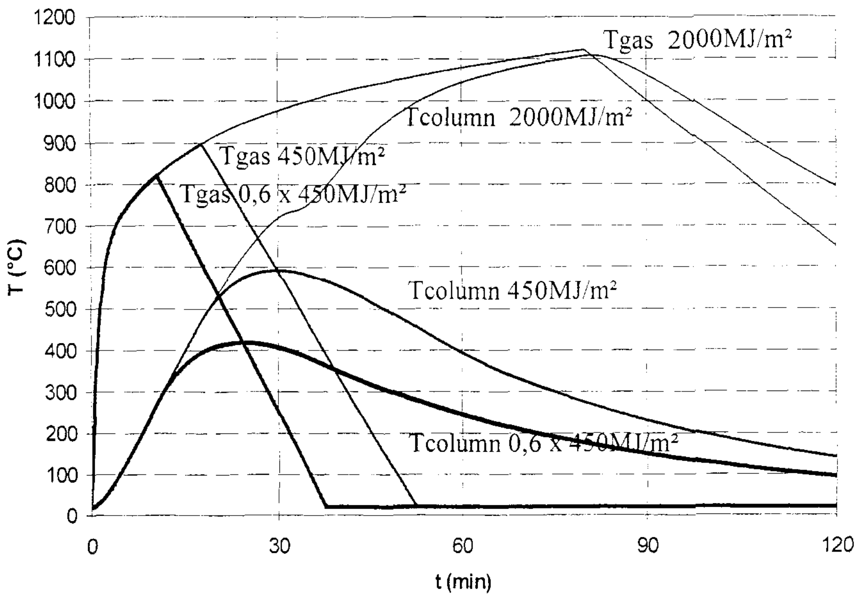

Figure 7: Temperature-time curve for the natural fire in a compartment with a fire load density of 450 and 2000 MJ/m². Temperatures of a column within those compartments (U/F 40 m˙1, O 0.062, b 1057)

4.3 Temperature in the profile

In the above examples the temperature in the cast iron columns is calculated by using the geometry of the column as input in a computer program developed for steel structures. Since the properties of steel and cast iron are similar, but not equal, this is just an approximation. More accurate calculations can be undertaken starting from the gas temperature and taking the real properties of cast iron into account, provided in Königs report [4].

5 Conclusion

Since the 18th century efforts have been undertaken to build structures to stand a fire. New insights led to improved construction techniques and building materials.
The recent developments in fire engineering can be applied to protect and safeguard the fireproof buildings. Computer simulations of natural fires are helpful to choose the right means to meet the set requirements.

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