ABSTRACT: The Winter Garden, the largest of the Royal Glasshouses, is situated at the Royal Domain in Laeken in the northeast of Brussels, Belgium. This glasshouse was built between 1874 and 1876 in order of king Leopold II, according to the design of architect Alphonse Balat. A two-dimensional analysis demonstrated the basis structural behaviour under a series of symmetrical load combinations: the structure works as a cupola with a tension and a pressure ring. The stress levels and deflections in the structure have to be evaluated in a three-dimensional model which is still in progress. For the time, it seems that the norm values are not exceeded. The major threat for the metal structure is corrosion. Previous interventions and a very aggressive tropical indoor climate inflicted heavy corrosion damage. Nowadays, this elaborate plain tour de force must undergo a major restoration.

1 BUILDING THE WINTER GARDEN

The typology of glasshouse buildings originates from the desire for a peaceful and green neighbourhood in the overpopulated cities during the Industrial Revolution. The first iron glasshouse is the iron hot-house in Hohenheim near Stuttgart (Germany) dating back to 1789 (Kohlmaier & Von Sartory 1991). The evolution of glass and iron production techniques in the nineteenth century was essential for the development and spread of the glasshouses.

The Winter Garden of Laeken is part of a major complex of glasshouses in the Royal Domain in the northeast of Brussels, Belgium (Figure 1). The complete set of glasshouses takes up an area of 1.5 ha, covered with 2.5 ha of glass (Goedleven 1988). All entities are built between 1817 and 1905 in order of king Leopold II, who reigned the country from 1865 until his death in 1909. He is known as the king who fundamentally changed Belgium and Brussels in an architectural as well as in an urban development manner. Despite the fact that Belgium is a small country, he wanted it to radiate grand charisma. He used his personal influence, private funds and the profits from the Congo colony to realize many of his ideas.

Alphonse Balat (1818–1895) was the royal architect from Leopold's accession until his death. He was one of the architects who lead in the Belgian Art Nouveau movement. Besides the well-known Museum for Old Arts in Brussels and the Royal Palace in Laeken, he also designed most of the glasshouses of the Royal Domain, including the Winter Garden (Figure 1, no. 3). The Winter Garden (1874–1876) is a significant cultural legacy and an important artefact of the evolution of structural steelwork and Art Nouveau in Belgium. It is the first glasshouse on the Royal Domain with a complete iron and glass covering. The Winter Garden was meant to be a glasshouse for social events and to this very day, it still performs that task.

For the design of the Winter Garden, Alphonse Balat referred to the Palm House (Kew Gardens, London, 1844–1848) designed by Decimus Burton and Richard Turner. Balat used the structural concept of the Palm House for his Winter Garden and applied this to a circular ground plan. The design of the Palm House in its turn was inspired by the Great Conservatory (1836–1840) of Joseph Paxton which was unfortunately demolished in 1920. This influence is clearly shown in Figure 2.

The structure of the Winter Garden consists of 36 arch trusses which are rotated around a central point and form one large dome (Figure 3). The Winter Garden can be divided into two main parts (Figure 4). The first part consists of the dome in the middle of the glasshouse, which is topped off with a small cupola and a royal crown. The second part consists of a side aisle around the middle dome. These two parts are separated by a circular architrave on sandstone columns.
As people would intuitively feel that a cupola geometry (part one as described in the previous paragraph) produces lateral thrusts, Alphonse Balat added an outer arch (part two) to each truss of the cupola. By doing so, he suggests the structure being composed by arches – structures that can withstand thrusts – rather then a cupola. The structural surplus value of the outer arches is still being investigated. However, it is generally felt that this (visual) addition results in a harmonious and aesthetically more beautiful construction.

Figure 1. Map of the Royal Glasshouses of Laeken, Brussels (Koppelkamm 1988; translated by the author).

Figure 2. Historical influences in the design of the Winter Garden (Kohlmaier & Von Sartory 1991).

Figure 3. Building the Winter Garden, December 30th 1875 (Prentenkabinet of the Royal Library, s III 100752).

a) The Great Conservatory in Chatsworth (1836-1940) by Joseph Paxton

b) The Palm House in Kew (1844-1848) by Decimus Burton and Richard Turner

c) The Winter Garden in Laeken (1874-1876) by Alphonse Balat
2 THE WINTER GARDEN TODAY

2.1 Maintenance of the structure

When king Leopold II passed away in 1909, the ownership of the Royal Glasshouses passed on to various institutions. The land, purchased by Leopold II, and the glasshouses constructed on that land, became property of the *Royal Donation*, a semi-private institute. The other glasshouses, situated on the piece of land that he received to fulfil his duties as a king, are owned by the *Regie der Gebouwen*, a governmental institution. The borderline between these two adjacent properties can be diagonally traced through the Congo House (Figure 1, no. 4). The shared ownership of the glasshouses does not facilitate restoration procedures.

Since the death of Leopold II, few of the Royal Glasshouses were restored. The Winter Garden merely received some refurbishments in the 1980’s, funded by the *Regie der Gebouwen*. Some cross-sections were reinforced by welding new parts on to the old ones. However, the weldability of the initial material was never investigated and therefore the durable efficacy of this intervention remains questionable. Heavily corroded profiles were replaced, yet without recording these changes in an appropriate report. The whole structure was sand-blasted and repainted. The glass covering exists of many small flat rectangular single glass panels. To reduce the heating costs, all these panels were replaced by coated glass jointed with mastic to improve the insulation qualities.

For the sake of the well-being of the perennial plants and trees and for the visitors’ safety, restoration works could not be scheduled during winter nor during the two weeks of public opening in spring. Therefore, all work was carried out in different stages, which considerably complicated the work, follow up and coordination.

2.2 Pathology of the metal structure

The metal structure of the Winter Garden is mostly unchanged, compared to the original construction dating back to 1876. Therefore, great historical value is attached to this building and any future restorations have to be done with the greatest respect to the original structure.

The major threat for the metal structure is corrosion. By filling the joints between the glass plates with mastic, the ventilation of the inside air has been dramatically reduced. This well intended intervention resulted in more condensation on both the glass and the metal structure. Together with the very aggressive tropical indoor climate, this has lead to increased profile corrosion on some vulnerable spots (Figure 5-a).

During previous interventions, a series of profile cross-sections were reinforced by welding new parts on to the old ones, e.g. on the iron column between the side aisle and the middle dome (Figure 5-b). The tension ring at the bottom of this column was cut off from the column, steel plates were welded on the column profiles and the tension ring was welded on the added plates. The tension capacity of these welds is unknown, as the weldability of the original iron was never determined.

Some profile connections show missing rivets (Figure 5-c). These connections have to be repaired, so loads can be transferred properly.

During previous restoration works, the whole structure was sand-blasted and repainted. Nowadays, the...
Regie der Gebouwen did again some tests with special techniques to remove the paint and corrosion (Figure 5-d). The techniques were evaluated on the time it took to rub a specific profile, the grade of efficiency of the rubbing technique and the nuisance for the tropical plants inside the glasshouse. The most efficient technique appeared to be a hammering technique where needles remove paint and corrosion from the iron. After cleaning the profiles, they need to be repainted as soon as possible to avoid new corrosion.

3 STRUCTURAL ANALYSIS OF THE WINTER GARDEN

The three-dimensional structure of the Winter Garden is quite refined. Every single member of the metal load-bearing structure consists of richly ornamented compound profiles (Figures 6 & 7).

In order to understand the basic structural behaviour of the Winter Garden under symmetric load combinations, a two-dimensional model was investigated. The historical reference to the Palm House in Kew and the Great Conservatory in Chatsworth implies that the structure works as a dome with a pressure ring at the top and a tension ring at the bottom of the cupola.

If this is the case, the outer arch of the aisle part will merely carry minor loads and fulfils purely an aesthetic function. This hypothesis will be verified in the two-dimensional structural model.

This two-dimensional model has its limits. In reality, every load on one of the 36 arches is distributed to the other arches via horizontal concentric rings as well. As a consequence, all the arches work together to bear the loads, especially asymmetric loads. In the two-dimensional model, this effect is neglected for the greater part. However, given the specific construction and functioning of the metal structure of the Winter Garden, it is indispensable to determine the stresses and deflections in a three-dimensional finite elements model.

The two-dimensional calculations were performed on two models: one of the inner arch of the side aisle and one of the arch of the middle dome together with the outer arch of the side aisle and the column between these two. In the model, the support conditions of the structure are modelled as follows:

- the support at the bottom of the side aisle is fixed (Figure 8-v);
- the support at the sandstone columns is fixed (Figure 8-w);
- the connection of the outer arch of the side aisle and the arch of the middle dome is fixed (Figure 8-y1);
- the connection of the column and the arch of the middle dome is hinged (Figure 8-y1);
- the connection of the inner arch of the side aisle and the column is hinged (Figure 8-x).

The following paragraph describes how the three-dimensional behaviour was simulated in the two-dimensional model. The support of the two-dimensional arch by the horizontal concentric rings was first modelled by sliding supports. This way, the concentric rings act as elements without vertical stiffness and an infinitely large horizontal stiffness.
The analysis of the model with these support reactions showed that the above assumption was too much of a simplification. To model the three-dimensional behaviour in a more accurate way, the stiffness of the concentric rings was determined and introduced into the two-dimensional model by springs (Figure 8).

The two-dimensional model was then analysed under symmetrical loading combinations made up of self-weight and symmetrical snow load. The snow load only applies to the structure that carries the glass covering, namely the arch of the middle dome and the inner arch of the side aisle (Figure 9). The asymmetric snow load, the wind load, the maintenance load and temperature effects will be evaluated through three-dimensional calculations.

The aim of the two-dimensional analysis consists of assessing whether the pressure ring at the top (Figure 8-z) and the tension ring at the bottom of the cupola (Figure 8-x) can carry all the lateral thrusts. These findings would give an indication of how the structure works. If these rings cannot withstand the lateral thrust, the outer arch of the side aisle is needed for the structure’s stability and therefore does not only have an aesthetic function as assumed before. The pressure ring is located at the boundary of the small cupola and the middle dome. The tension ring is situated at the bottom of the column. The other concentric rings connecting to the arch of the middle dome (Figure 8-y) will all help carrying the lateral thrusts. The stress levels in the structure without the outer arch of the side aisle are investigated as well as the stresses in the outer arch itself when the complete model of the metal structure is considered.

These stresses need to be compared with the material properties of the used iron, which are currently unknown. These properties will be determined through tensile tests and a metal analysis in the course of the next year. The current interpretation of the results of the two-dimensional calculations is therefore based on the standard material properties:

- yield limit = 235 MPa from Eurocode 3;
- design value of the tensile strength = 100 MPa as the common historical value (de Bouw unpublished);
- Young modulus = 210 kN/mm$^2$ from Eurocode 3.

The two-dimensional calculations according to the Eurocodes reveal that the stress levels, the instabilities and the deflections of the structure do not exceed the norm values. The maximum stress level appears at the bottom of the inner arch of the side aisle and runs up to 53 N/mm$^2$ (which is 23% of 235 N/mm$^2$ and 53% of 100 N/mm$^2$). The maximal buckling risk is 90% of the buckling capacity of a profile under compression and bending and occurs near the bottom of the arch of the middle dome. The horizontal and vertical deflections are less than 10% of the laid out deflection limits. Consequently, the buckling of the arches is the most critical check of the metal structure. However, the global supporting effect against buckling of the concentric rings can only be taken into account in a three-dimensional model. At present this three-dimensional model is still under development and no final conclusions can be made about the maximum occurring stresses and deflections.

4 CONCLUSIONS

The Winter Garden of the Royal Glasshouses of Laeken is part of the important Art Nouveau movement in Belgium. The current metal structure of the Winter Garden is only minimally modified, compared to when it was built from 1874 to 1876. Currently, this masterpiece must undergo a far-reaching restoration. The principal threat for the metal structure is the corrosion of the compound profiles.

In the first two-dimensional simplified model, the structure without the outer arch of the side aisle can withstand all the applied symmetrical loading combinations (in terms of stress levels and horizontal and vertical deflections). The second model, where the outer arch was added to the structure, shows that only a minimum of stresses occur in the additional arch.

The following conclusions regarding the structural behaviour of the Winter Garden can be drawn from the simplified two-dimensional analysis.

First, the outer arch acts as a backup structure for the arch of the middle dome and for the inner arch of the side aisle. This conclusion reinforces the impression that architect Alphonse Balat added the outer arch solely to ease the viewer’s mind. The viewer was not yet visually acquainted with the very thin innovative metal constructions emerging at that time.

Secondly the stress levels and the horizontal and vertical deflections do not exceed the limiting values as prescribed in the Eurocodes. This conclusion
is however only valid for the applied symmetrical load combinations.

Further work implies a three-dimensional finite elements analysis under asymmetric load combinations to confirm the structural suitability of the Winter Garden with the Eurocodes as well as material testing to obtain the material properties of the used iron.

REFERENCES

de Bouw, M. Assessment of the metallic roof trusses in Belgian school buildings between 1860 and 1914. Unpublished PhD theses.