Restoration, preservation and conservation of iron and steel structures: Adaptations relating to strength, stiffness and stability

G.G. Nieuwmeijer
Faculty of Architecture, Delft University of Technology, P.O. Box 5043, NL 2600 GA Delft, The Netherlands
Email: s.lispet@bk.tudelft.nl

Abstract

In the 19th century construction methods differed from those used today. Calculations were simple or sometimes not even made at all. Regulations were few or nonexistent and engineers often worked from their own experience and insight.

Old structures do not usually satisfy current regulations and insight with regard to strength, stiffness and stability. Indeed, we must ask ourselves whether it is necessary that they should do so. Modifications may be necessary in relation to strength and stiffness when the original structure fails to meet modern requirements or because it has been weakened by corrosion. Adaptations can be made by strengthening existing elements, changing joints and the addition or replacement of structural elements.

Ideas about stability were also different in the 19th century. Supplementary measures to historic structures include the addition of stability diagonals or the use of roof or facade elements such as diaphragms.

Many old buildings are important for historical or cultural reasons. When restoring such buildings it is necessary to consider what they will look like later. It is necessary to consider whether it is obvious that restoration has taken place or whether the original appearance should be retained to show how buildings were previously constructed. Often restoration is carried out pragmatically and the restoration methods used depend on the restoration philosophy and the means available. The objective should be to execute the adaptations in an honest way so that no falsification of history occurs.
Introduction

Structures must conform to regulations relating to strength, stiffness and stability. When a structure is being designed, the appropriate sizes for the elements can be determined by calculation. Usually the regulations provide sufficient guidance in relation loads, material properties and the required safety margins for the calculations to be made. In the past things were different. When older structures are recalculated, they do not usually satisfy all the requirements relating to strength and stiffness. Moreover, the structures may have been weakened by corrosion.

In addition to strength and stiffness, a structure must also be stable. That means that it may not collapse. The stability in the horizontal sense must be guaranteed. In the 19th century, ideas were different from current ideas, especially those relating to stability.

Strength

The first methods for calculating trusses were introduced by J.W. Schwedler and C. Culmann in 1851. These were analytical methods. However, the graphical methods of Culmann (1864) and Cremona (1872) were much more suitable for trusses.

In the Netherlands, the calculation of roof trusses started only in the third quarter of the 19th century, although calculation for bridges had begun a little earlier. Before that, dimensions were determined from experience. When calculation began the estimation of the loads was left to the engineer himself. One of the earliest calculations in the Netherlands was that made for the platform roof spans of the Delftse Poort II Station in Rotterdam (1877). Although the estimates fell short, the complicated calculation was carried out correctly. The bridge over the Lek at Kuilenburg (1868), now Culemborg, with a main span of 154 m, was at that time the biggest bridge in the world. It was constructed as a triple truss, the calculation of which was not understood at that time.

Figure 1: Railway bridge, Kuilenburg, 1868. The bridge is constructed as a triple truss, which could not be calculated at that time. It was assumed that each of the trusses I-III took one third of the loads.
Moreover, there was little insight into metal fatigue under dynamic loading. Whether building on the basis of experience or of early methods of calculation, engineers took some precautions. The test loading of roof trusses and bridges was general usage.

When testing trusses, only vertical downward loads, whether evenly or unevenly distributed, were considered. Little or no account was taken of wind loads, which may also be directed upwards. From the design of the platform roof span of the Gare Montparnasse, Paris (1840) it can be seen that it was not designed for horizontal wind loading.

For buildings with a complex shape, or those on which the immediate environs exert great influence, the regulations for wind loading provide little guidance. Only by investigating on site or by using models in wind tunnels can the actual loading be approximated. When investigating on site one can consider placing strain gauges or deformation gauges at critical points. After sufficient information has been acquired for various wind speeds and directions, the data can be processed statistically. The anticipated wind loading can then be predicted. By using wind tunnel experiments, it is possible to determine coefficients of wind loading by subjecting the model to various wind speeds. In long structures, considerable temperature stresses may occur if no provision is made to accommodate them. These may give rise to damage, especially at the ends of the structure.

Usually, government regulations stipulate that structures must meet the current regulations relating to strength. When people may be on or underneath the structure, this seems to be self-evident. However, we must ask ourselves whether it is indeed necessary to satisfy all these regulations. With regard to fireproofing regulations in The Netherlands, a distinction is made between existing and new buildings. In the Netherlands too, the safety requirements for classic automobiles relate to the year in which they were built, while aeroplanes are built with a considerably lower safety coefficient than that required for bearing structures in buildings.

Figure 2: Platform roof, Gare Montparnasse, Paris 1840. In the calculation wind loading was not taken into account

Figure 3: a-e diagram for cast iron, wrought iron and steel.
When considering safety, one can look at the failure mechanism. A beam that is overloaded will show this by greater bending. An overloaded column may suddenly buckle and thus fall without warning. Lateral instability may also occur unexpectedly. A lower coefficient of safety can be used for bending than for lateral instability.

The importance of a specific structural element may also play a role. Failure of a secondary beam is of less consequence than the collapse of a column. An important consideration is whether the loss of an element leads to progressive collapse or to the redistribution of forces.

The type of material may also be important. Steel has a clear area in which plastic deformation takes place, after which strain hardening occurs. The large plastic deformation may indicate overloading. Wrought iron has a less clear flow area and its failing strain is lower than that of steel. Cast iron fractures suddenly at tension with a very small strain.

The state of an object may also exert an influence. If it is subject to a preservation order, great value is attached to the original construction and the original material. Its failure to comply with the regulations will be given more consideration than is usual for other structures.

Further considerations relate to restrictions on loading and, for bridges, speed limits. Maximum loading and speed must therefore be clearly indicated. In areas with high snow loading it may be possible to introduce heating so that the snow does not lie. In extreme conditions, a building must be closed to the public.

When a structure fails to meet the safety requirements the following measures may be taken:

- strengthening of the existing structural elements
- changing the joints
- the addition of structural elements
- replacement of structural elements

The Palm House in Kew Gardens (1848) consists of a central section with two wings. The arched wrought iron beams are I-shaped in cross section. They are curved deck beams with bulb shaped lower flanges. Research in preparation for the restoration, which was completed in 1989, revealed that they did not satisfy current requirements. They were strengthened by welding strips onto the upper and lower sides of the bulb profiles and by changing the joints with the foundation. The strips on the upper sides of the profiles are obscured by other structures while those on the underside remain visible.

Figure 4: Palm House, Kew, 1848.
Figure 5: Palm House, Kew, 1848. The I-bulb profile is strengthened by welding steel strips onto the top and bottom. Originally the I-bulb profile stood in a cast iron base plate and the space between the main beam and the base plate was filled with lead. Strengthening has been achieved by embedding the lower end of the beam in concrete, producing a rigid joint with the foundation.

The beams of the wings originally stood in cast iron base plates. The space between the main beam and the base plate was filled with lead so that the end bearing behaved as a hinge. By embedding the lower ends of the beams in concrete, a rigid joint with the foundation was created, with a more favourable distribution of forces in the beams. After completion, this change was invisible. Corroded parts of the lower flange were removed and new ones were welded into position. In places where the body of the beam or the junction between body and flange were in a poor state, strengthening plates were welded on. After painting, these changes in the structure were inconspicuous, but they do consciously show the restoration in an honest way.

In the restoration of the platform roof spans at ‘s-Hertogenbosch (Den Bosch) Railway Station, strengthening and changing of the joints has taken place.

These will be considered in the paper by L.I. Vakar entitled: ‘The historical railway stations roofs of ‘s Hertogenbosch’. For bridges, adaptation must be found by reducing the span. At the land ends of the tubes of the Conway Tubular Railway Bridge (1848), new piers were built. These piers are in historic style and the way that they lead the forces into the body of the tube gives the impression that they are part of the original structure.
The piers introduced into the centre of the span of the Albert Bridge in London (1873), which was originally an cable stay bridge, are worse. In 1884, the bridge was strengthened by suspension chains, making it into a combination of a cable stay bridge and a suspension bridge. In 1973, the extra supports, constructed in historic style, were placed in the centre. Both piers are highly detrimental to the bearing system, but at least they permit continued use by modern traffic.

The platform roof spans of the Hollands Spoor Station, s' Gravenhage (1893) consisted of two bays. The arched beams are trusses with a v-shaped strut pattern. Although the trusses meet the current stringent regulations a number were so severely affected by corrosion that replacement was necessary. The objective was to retain their appearance, even though modern materials and techniques were being used. During the restoration a quarter of the roof was destroyed by fire, so the deformed trusses were replaced in the same way. Because the greater part of the replaced structure is high above the traveller’s level, these changes are scarcely noticeable. It is an honest reconstruction and only those with a special interest will recognise that restoration took place in around 1990. Fortunately, it was decided not to weld on rivet heads or, worse still to glue on plastic imitation rivet heads, which might have made the structure appear more original.
Figure 8 Suspension bridge over the Menai Strait, NW Wales, 1826. The bridge before and after 1940, when the suspension chains were radically changed.

The deck of the Menai Strait Bridge in NW Wales (1826) was originally suspended from four chain cables, each of which consisted of four chains. In view of the increase in the traffic load and the danger of collisions with the changers between the traffic lanes, in 1940 all sixteen chains were replaced by two cable chains. These are on the outer sides of the bridge and each is made up of two chains. At the same time, the deck was also changed. The new chains are made of high quality steel and although the shape of the links remains about the same, they are bigger. From a distance the bridge looks the same as it did before, but seen from close to its image has been considerably changed.

Stiffness

In addition to requirements relating to strength, there are also requirements relating to stiffness. These may be a visual and psychological in nature. With inadequate stiffness, the finishing of a building may cause problems or the drainage of the precipitation may be impeded. In bridges, fatigue may play a role.

When the sagging of a roof is clearly visible under loading this will appear unpleasant and may create an impression of insecurity, even though its strength is not in question. The finishing construction must be able to withstand the deformation caused by the sagging of roofs and floors. Large-scale sagging may cause cracking in partition walls, while doors and windows may stick and panes
of glass may crack. Precipitation remains standing on sagging roofs, which increases the chance of leakage, while the extra weight causes even further sagging. The possible accumulation of water is a determinant for the required strength. In the horizontal sense too, demands are made on the stiffness of a building. With inadequate stiffness, movements resulting from wind loading will be appreciable. Such horizontal movements may be unpleasant and induce a feeling that they are unsafe. Here too, the finishing construction may cause difficulties.

The psychological aspect also plays a role in bridge design. The railings are usually much stronger than they need to be from the point of view of strength. Strong vibration and big oscillations must be avoided, both from the psychological point of view and in view of the danger of fatigue. Stiffness is particularly important for suspension bridges.

The maximum permitted deformation for a structure must be determined. For buildings, regulations in which the maximum bending of beams and the maximum horizontal deformation of buildings are defined provide guidance. In addition, it is wise to investigate what the finishing construction can bear and whether precipitation drainage is safeguarded. This includes determining how much movement can be accommodated in joints between panels of partition walls and how much deformation door and window frames can bear before they stick.

This is usually more difficult for bridges. The dynamic behaviour of large bridges and of their parts should be investigated. In the past bridges in particular often had a structure that was too weak. Although a lesson could have been learnt from the past, fatigue caused the collapse of the Tacoma Narrows Bridge. Even while it was under construction in 1940, movements that were not taken seriously occurred. During a storm shortly after its completion, torsion oscillations developed which cause the failure of beams in the deck and the suspension cable. This led to the collapse of the bridge deck. Stiffening measures are often the same as those used to strengthen structures that have been mentioned previously. Two examples of this are given below.

A block of flats in Delft, built in 1968 was too weak in the longitudinal direction. The building was later stiffened by the addition of extra struts near the end facade.

The Menai Straits suspension bridge in NW Wales (1826), with its span of 579 ft (almost 180 m) has been stiffened several times. The light wooden deck had already been replaced by a stiffer wooden deck in 1839. In 1940, this deck, together with the suspension chains, was again replaced by a stiffer one. This indicates that there has been a continuing struggle with the stiffness of the bridge. The designer Thomas Telford though that it was impossible to build suspension bridges with spans exceeding 600 ft.

**Stability**

When structures are being designed, stability is an important consideration. The stability must be guaranteed or in other words, the structure may not collapse. In modern steel structures, stability is usually ensured by the use of stability
diagonals. In large halls, these usually consist of crossed diagonals, the size of which is related exclusively to tension. In multi-storey buildings and bridges, K-struts are also used. Sometimes stability is obtained by using portal frames with rigid corners. So far, we have been concerned only with external stability but structural elements can also be internally unstable. This happens when they buckle or when lateral instability or folding occurs. To prevent the buckling of flanges of beams they must be supported at regular intervals. Connections known as stability diagonals are used for both beams and the upper edges of bridges.

In the 19th century, there were different ideas about stability. Less attention was paid to it and stability diagonals were frequently omitted because they were thought to be ugly. Both analyses of buildings and desk studies reveal that there was often something wrong with the stability of structures.

Diagonals were sometimes present but not well executed. In the platform roof of Haarlem Railway Station, the diagonals are fastened to a ring that is not stiff in its own plane. If there are no diagonals in the roof of a hall, this function may be taken on by the roof plates. This is often the case with tongued and grooved wooden covering and is certainly so when the covering is laid diagonally. The corrugated sheets that were frequently used in the past, and even glass, may have some function in providing stability. This may cause problems, especially when glass is used. Glass is a strong material but it has a brittle failure character and high notch sensitivity. It is thanks to the glass that the greenhouse at Bicton Gardens in Devon remains standing without any problem. In the exhibition halls in the Pleasure Gardens (Parc du Cinquanenaire) (1888), Brussels, there are no stability diagonals where there are glass plates. During heavy storms the windows sometime crack. Owing to its high strength, under some conditions glass is suitable for use as a stabilising diaphragm. This is the case in the pavilion designed by Benthem and Crouwel for Sonsbeek 86, that now stands on the premises of the Autotron in Rosmalen. In addition to its use as a stabilising element, glass is also used as a bearing element in the columns.

Figure 9: Modern hall with stability struts. These struts in the planes of the facade and roof ensure that the hall is stable in both longitudinal and transverse directions and cannot collapse.

Figure 10: Platform roof Haarlem Railway Station 1908. The stability struts are fastened to a flexible ring and therefore function poorly.
Figure 11: Pavilion Baltard, Nogent-sur-Marne. During the reconstruction stability-struts were added.

Figure 12: Paddington Railway Station, London, 1854. The steel roof plates provide the stability.

Figure 13: Hoge Brug, Zwolle, 1883. The connection between the upper edges is extended by a trave on each end.

Further research in this field is now underway at Delft University of Technology. In particular laminated glass, which is mounted in silicon adhesive, seems to have a good potential. If the stability of an existing structure is not up to standard, stability diagonals can be added or the stability can be provided by stiff planes.
In 1975 the demolition of the Central Market Hall (1866) of Paris was started. One of the pavilions was dismantled and reconstructed in Nogent-sur-Marne, near Paris. During this reconstruction, measures were taken to ensure stability. On the facades heavy struts were mounted in the corners on both the ground floor and in the roof structure. Diagonals have also been added under the roof panes, which are made of profiled steel sheets. The struts in the corners are pronouncedly visible.

If supplementary measures in the ostensibly stiff facade surfaces had really been necessary, they could have been taken in a more elegant manner. The profiled steel plates in the roof could also have worked as diaphragms, so the diagonals there would also have been unnecessary.

There were no stability diagonals in the platform roof of Paddington Station, London (1854). The roof plates were replaced several times, the last renovation being in 1990. On this occasion, coated corrugated iron with the same profile as the original galvanised corrugated iron sheets of 1854 were used. The plates are fixed with self-tapping stainless steel screws and work as diaphragms.

To prevent horizontal instability the stability diagonals are fitted between the upper edges of the Hoge Brug, Zwolle (1883). For reasons of safety, during the restoration in 1993, these were extended by the addition of a trave on each end. This was permitted by the profile of the free space and the upper edge is now laterally supported at more points than was previously the case.

Conclusion

When restoring old structures it is often necessary to made modifications with regard to strength, stiffness and stability. Because many such structures are important for historic and cultural reasons, these modifications must be carried out with care. It is important to decide how much of the restoration work may be seen, considering whether the original appearance should be retained, to show how buildings were previously constructed or whether the changes should be visible. The choice will depend on the historical value, the state of the structure and the available financial means. The modifications should be made in an honest way so that no falsification of history occurs. When minor changes have to be made to valuable structures, these changes must be executed in such a way that they are only visible to the experienced eye. If many elements must be replaced this can be done in such a way that an interesting combination between old and new is created.

References

Material from the archives of the History of Structural Design Group, Faculty of Architecture, Delft University of Technology.