The development of structures and its details is determined by both structural requirements and the main stream of contemporary architectural art.

An interesting detail of such a development is the change of the constructional type of riveted connections of truss girder bridges in cities.

Within some decades, the form and the dimensions of the connections using so called gusset plates have changed considerably. That can be recognised by some bridges in Berlin starting from a simple form, after that changing to a more ambitious type caused by discussions about architectural aspects of subway viaducts in Berlin during erection of the first subway line and at the end coming to a simple technical type which is not satisfactory in terms of architectural quality, however, following the new ideas of Bauhaus and Functionalism and aspects of structural safety.

The development is presented by giving some examples and mentioning the discussion at that time.

An engineering aspect is introduced by looking at the structural behaviour under severe loading and explaining «weak» structural details which had to be changed for the design of future bridges.

Some research work performed recently at BAM, Berlin, opens the opportunity of rational investigations and rating of those bridges for extending their service life considerably, sometimes with some strengthening and additional inspection procedures.
INTRODUCTION

An important and interesting part of architecture is «Engineering Architecture» which not necessarily is the outcome of architectural design, rather then of engineering thinking and insight. Nevertheless, this manner of engineering design is influenced by the stream of contemporary arts. Examples for Engineering Architecture are numerous, e. g. the Eiffel Tower, Paris and the CN Tower, Toronto, and bridges like the Golden Gate Bridge, San Francisco, and the Tower Bridge, London.

A less ambitious structure is the steel viaduct of the subway system in Berlin which had been completed in 1902—exactly hundred years ago. Studying the viaduct, the combination of optimal design in terms of economy and safety and in terms of esthetics becomes obvious (Landsberg 1904), figure 1.

The forms of Art Nouveau (called Jugendstil in Germany) have influenced the design with the pleasant shape of structural elements and details. However, the very filigran truss girder system—giving a feeling of lightness—conflicts to some extend with the requirement of structural safety. The contrast to later on built bridges is obvious when looking at figure 2.

While most buildings will be designed only following architect’s ideas about forms which do not concern questions of statics—e. g. the Buildings by Gaudi in Barcelona—bridges have to be safe in its first priority. And this requirement causes conflicts in many cases.

There are several examples of structures which outline the paths of forces like the Eiffel Tower or the Olympic Roof at Munich. Their form is satisfying also in terms of esthetics, however, sometimes it is only interesting from an engineer’s point of view like the new railway bridge in Berlin-Spandau, figure 3.

Truss girders were an outcome of looking for stable bridge structures which minimise the weight. Their overall design as well as their structural details are subject of looking for adequate appearance.

STEEL VIADUCT OF THE SUBWAY BERLIN

The «Hoch- und Untergrundbahn» (subway) Berlin opened its service in 1902. The system has been
extended during the following years. Some of the original parts have survived war time and demolition mania later on. Now they are protected by law as monuments of Engineering Art (Jäger und Wachter 1999).

The figures 4 and 5 give some impression about the development of the systems and the details.

Considering the viaduct at Berlin-Kreuzberg, the optimisation of the gusset plates can be studied. Even now, we are able to analyse the stressing of different structural elements, also — to some extend — the stresses in the gusset plates and their response to fatigue loading — the ever and ever repeated loading by traffic which — at the end — causes fatigue cracks and failure (Brandes 2000).

As far as we could find out by modern engineering approaches and by many fatigue testing on complete original bridges (Helmerich und Brandes 2002), the engineers who designed the viaducts have succeeded in constructing very small gusset plates, however reaching a stress level at the most stressed regions that caused doubts about the resistance to fatigue loading for 100 years or even more.

After extensive investigations, we found, that the real stress level permits a life time for more than hundred years, may be two hundred years. Nevertheless, in some other cases, bridges of a similar type had to be replaced after only some years because of cracks in the gusset plates.

**THE MECHANICAL EVALUATION**

The investigation, evaluation and rating of existing bridges is more and more common, mainly stimulated by the lack of financial means of the owners of bridges. In most of the cases, hidden reserves of load carrying capacity can be discovered. That means that the bridge can be used for some more years or decades, sometimes with some minor repair or strengthening.

For engineers, the investigation of an existing bridge is quite different to the straight forward procedure of designing a new bridge according to today standards. After many decades of service, bridge elements may have suffered from loading or the attacks from the environment. That has to be included in a safety assessment, however, no approved procedure is available how to do this in a satisfactory manner.

It has been a very interesting challenge to find out the real behaviour of the viaducts by measurement of the forces within the structural elements under traffic loading (Herter, Fischer und Brandes 2002) and by testing some dismantled bridges of the same kind which had been replaced before, in the big testing hall of BAM (Helmerich und Brandes 2002), figure 6.

During the tests in the testing hall, we took the opportunity to search for hidden cracks in the gusset plates by radiographic inspection, figure 7. This task is very complicated because the cracks always start from rivet holes and are covered by some steel layers.

Figure 5
Development of gusset plates' form: Full line: real system; small dotted line: unfavourable in terms of appearance; dotted line: stressing of the gusset plate becomes to large

Figure 6
Fatigue test on an original truss girder of the subway Berlin in the testing hall of BAM
and the heads of the respective rivet. The result of the tests was very encouraging. We found that cracks can be detected when they reach about 4 mm length. Then, the future propagation of cracks can be assessed. In most cases, many years are needed to come to a crack length which may cause danger for the bridge, figure 8, figure 9.

While we performed the tests on a load level more then double of the real load, in reality, the crack propagation —if any crack will be initiated— will be very slow.

The overall result of the investigations is that the engineers who designed the viaduct had found the optimum of dimensioning the gusset plates. They are the weakest elements of the viaducts as the investigation showed, however, they are strong enough to resist the loading for a long period of time.

It should be mentioned, that some years after the construction of the viaducts in question, gusset plates have been dimensioned much thicker and larger. The
reason for this change was that gusset plates shall not be the weakest structural elements because the inspection of gusset plates is nearly impossible. However, if other structural members are weaker, they exhibit first cracks which can be detected easily by routine inspection, and this is crucial for structural safety.

**How to protect old steel bridges from being replaced?**

The recently developed methods of investigating steel bridges which are about 100 years old, offer a rational tool to assess the safety of the bridge sufficiently.

During the last decades, many old steel bridges have been replaced by new bridges because the knowledge about the condition of the bridges had not been satisfactory. Only improvement of the methods available for the evaluation of old structures has lead to a better situation. Just now, it should be impossible to demolish an old structure without applying all the new tools of *minimal invasive methods* for a sound rating.

Minimal invasive methods comprise all the methods which give a better understanding of the behaviour and the state of condition of a structure: Exact visual inspection, measurement of geometric conditions and strains and deformation under loading, non-destructive testing like ultrasound and radiographic inspection, dynamic identification of the structure etc.

The idea of minimal invasive techniques originates from the medical sciences where exactly the same methods are used to obtain a comprehensive view of the conditions of a patient.

There is much more to develop to avoid that monuments will be demolished only because of lack of knowledge about their structural safety. However, a first important step has been done.

**Another Example**

A very important bridge in terms of history of engineering is the Stubenrauch-brücke in Berlin which was built in 1908, designed by the famous engineer Karl Bernhard (Bernhard 1908), figure 10. About 15 years later on, the bridge has been strengthened and at a second time in the 1930ths. The second strengthening concerned the gusset plates which had to be enlarged when following the new ideas of engineers from that time. Also the bars between the two arches were strengthened by adding broad steel plates which changed the appearance to the worse. In figure 11, the type of strengthening is clearly visible. The gusset plates had been enlarged by additional steel sheets which were welded to the existing plates. At that time, welding of the old material was not favourable, as we know now. However, when investigating the bridge in 1996, we could not find cracks near the weld seams.

With our newly developed tools, presumably, an investigation as that in the 30th had had resulted in not doing any strengthening.
SUMMARY

The design of engineering structures like bridges referred in its forms to those of contemporary art. In performing an actual design, the requirements of structural safety sometimes conflicted — and conflict today — with ideas about forms adequate to the mainstream of architecture of the time in question. It is of interest for understanding of the engineering art to study the development of structural systems and detailing regarding mechanical structural analysis on the one hand and favoured architectural forms on the other hand.

The shape of gusset plates is a very special case in that field of construction history.

Remark: It should be mentioned that for the preservation of monuments like bridges which underlie safety requirements as long as they are in use, methods of investigation as we have developed are indispensable.

REFERENCE LIST


