Appraiser of Historic Industrial Buildings Designed 1880-1940

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ABSTRACT: Historic steel constructions are an important part of the industrial building stock. For appropriate maintenance and restoration of such historic buildings and evaluation of load-carrying capacity specific knowledge of historic constructions is required. This article presents the results of a research project dealing with historic steel structures, funded by the German Research Foundation (DFG). The research work was carried out by the Institute of Steel Construction, TU Dortmund, in cooperation with the Institute of Historic Building Research and Conservation, ETH Zürich. In the completed research project the important facts, like mechanical properties of historic steel, particular design methods and construction characteristics, were examined and merged for industrial buildings built between 1880 and 1940. An integral investigation of all aspects was made by analysing the load-carrying capacity of a couple of exemplary historic roof structures according to current regulations. These investigations led to the result, that sufficient resistance of most links of lattice trusses could be proved also taking account of the requirements of modern standards. Also, the analysis of still existing industrial halls showed that structures were in good condition. The result of the integral investigation was that maintenance and restoration of most historic steel structures could be promising due to good load bearing capacity.

INTRODUCTION

Since the beginning of industrialization in the second half of the 19th Century many industrial buildings were erected of steel. These historic buildings still form an important part of the industrial building stock. For sustainability and economic reasons, engineers, architects and owners have to answer questions of maintenance and restoration and the evaluation of load carrying capacity. Compared to modern steel construction, different material properties, design methods and constructional techniques have to be taken into account. The evaluation of the load carrying capacity of historic buildings requires an integral investigation of all these aspects.

During a meanwhile completed research project these significant facets were regarded, confined to single storey industrial buildings built between 1880 and 1940. In addition to historic and contemporary literature an extensive source of construction documents of the company Gutehoffnungshütte (GHH) was available. GHH was one of the important German companies in steel constructions in the first half of the 20th Century which engineered numerous steel buildings. On the basis of construction documents of meaningful steel constructions, historic static calculations and construction methods could be analyzed in detail and compared to former expertise, historic building regulations, material characteristics and contemporary research status.

INITIAL SITUATION AND OBJECTIVES

The condition of historic steel constructions can only be appraised adequately taking into account various interacting aspects. The diversity of material properties, static calculation methods and construction techniques was separately analysed, but was not interrelated, compared or evaluated yet. There are extensive works on historic steels, which provide a good indication of the material properties (Käpplein et al. 2001; Mang et al. 1998; Mang 1979; Mang et al. 1996; Reiche 2000). Bargmann compiled building regulations from 1870 to 1960 but did not evaluate these regulations regarding to engineering issues (Bargmann 2001). For construction of steel buildings, a broad variety of historic literature is available (inter alia Foerster 1903; König 1902; Bleich 1932; Bleich 1933), but so far there is no compilation or evaluation of typical industrial halls of the considered period.
An entire presentation of historic steel buildings was made by Frank Werner and Joachim Seidel in "Der Eisenbau" (Werner et al. 1992), determining the beginning of steel structures in the 18th Century until the mid-20th Century. So far, a compilation specified on industrial halls was not provided. The aim of the conducted research was to improve the applicable, integral knowledge about historic steel construction. By analysing historic literature and historic documents of the GHH and by performing object studies individual information was merged. Therefore the research results could help architects and engineers which are involved in historic steel constructions
- to gain knowledge about the essential data at the beginning of a project
- to allow a quick appraisal of the construction
- and to get knowledge about restoration and reconstruction of buildings.

ANALYSED ASPECTS

Material
The knowledge of the material used in historic steel structures, its properties and composition is essential for appraising the load-carrying capacity, robustness, continued use and restoration of historical steel buildings. The production processes of iron and steel influence material properties.
In building structures between 1880 and 1940 cast iron, wrought iron and mild steel was used. The brittle material cast iron - the first iron material used for load carrying structures - was used very rarely in the relevant period. Wrought iron was intricately manually produced in the puddling process, which is described in (Paulinyi 1987). This process resulted in high slag inclusions, which were distributed lamellarily and lead to an anisotropic material behaviour. Wrought iron had a low ductility due to high phosphorus and sulphur concentrations (Reiche 2000 p. 4-2). From 1890 wrought iron was replaced by mild steel, which offered higher quality due to the industrial production process. These were the converter processes (acid and basic Bessemer processes), the Siemens–Martin open-hearth procedure and the electric steel procedure. These processes are described in (Verein Deutscher Eisenhüttenleute 1953 pp. 90 et sq.). During the converter procedures air was blown through the converter charged with molten iron. This procedure led to increased nitrogen concentrations in the material resulting in ageing and embrittlement of the material. Using the basic Bessemer process phosphoric pig iron could be converted, but increased phosphorus concentrations remained in the steel and led to restricted cold formability. High-quality steel was produced in the open-hearth process. By the use of a basic lined open hearth furnace, steel with less phosphoric concentrations than basic Bessemer steel was obtained. In addition steel with less nitrogen could be produced so that steel with less sensitivity to ageing was generated. However, the sulphur combustion gases of the open-hearth procedure caused slight sulphur impurities (Reiche 2000 p. 3-4). Historic mild steel provided similar strength like current steel S 235, but was significant inhomogeneous and had restricted ductility and weldability.

Construcational elements
Industrial halls were built from iron and steel in form of semi-finished products. Already in the year 1880 common and static optimized section forms were standardised in the German standard section regulations (Heinzerling et al. 1880), of which seven editions were published until 1908 (inter alia Heinzerling et al. 1881; Kommission zur Aufstellung von Normalprofilen 1908). There were different section series (Figure 1), whose dimensions were exactly prescribed. With the general standardization efforts in Germany usual steel sections were also integrated in the German industrial standards. In addition, wide flange beams were incorporated into the section series. Sections, regulated in the German standards, are described in (Deutscher Normenausschuss 1927). Examining the development of the section forms between 1880 and 1940 it is noted that the profile heights were adjusted to the improved rolling technology. Dimensions of I-sections developed the most while other sections basically remained. First only standard I-beams with narrow flanges and an inner flange slope were regularised. Since 1902 wide flange I-beams with inner flange slope (named Grey or Differdinger beam) were rolled in Germany. With rolling technology improving, parallel wide flange beams (named Peinerträger) could be produced. The wide-flange beams (Figure 2) offered the advantage of a lower profile height and higher carrying capacity under pressure compared to similar standard I-sections (N.u. 1930). The Peinerträger were the predecessors of today's wide flange beams (HEB). Present common profile forms have been obtained, normally even with same dimensions.

Figure 1: Historic profile types (German standard sections as from 1880)

Figure 2: Historic wide-flange beams: Differdinger beam (since 1904), Peinerträger (since 1914)
Connection devices

A change in connection methods had great influence on the design forms. Different connection devices (rivets, bolts and welding joints) cause different shapes, sizes, appearances, structural systems and carrying capacities of the connections and components. Riveting was the most common connection in the period between 1880 and 1940. Riveting required suitable connection details using plates and angles resulting in high labour costs and great construction weight. However, the riveted connection had the advantage that no special requirements to the basic material were demanded (Käpplein et al. 2001 p. 57). The screwed connection had less significance than the riveted connection (Königer 1902 p. 40). Beginning in the thirties of the 20th Century welding was used to connect structural elements of steel buildings. The advantage of welding in contrast to riveting was a significant material saving, because no connection plates and angles were needed and there were no reductions of the sectional area by the rivet holes. Furthermore, the literature mentions the uniform, monolithic appearance of welded structures; it seemed to be “all of a piece” (Sahling et al. 1952 p. 1). In the thirties engineers assumed that the steel used in buildings was basically suitable for welding. After analysis of material damages caused by welding weldable steel was developed (Sahling et al. 1952 p. 6; Werner et al. 1992 p. 122). The welding technology enhanced as well. Until advantages of welded constructions - material savings through direct force transmission - had been utilized, engineers had to gain experience and to develop connection designs specified for welding. Initial welded connections used configurations, which were adopted from riveted connections. Therefore initial welded connections did not use fully the advantages of welding. One example is the girder splice in historic structures made with welded plates, instead of today’s design with butt weld. Connection designs specified for welding enhanced over the years so that welding finally led to a fundamental change in the steel construction design (Sahling et al. 19522 pp. 82 et sqq.). Welding offered some advantages to the riveted connection, but in period between 1880 and 1940 welding did not replace riveting completely.

Design methods

The knowledge about the determination of internal forces and design-methods also influenced the type of construction. In the 19th Century iron modular constructions using trusses, girders and arched girders paved the way for the development of structural analysis, because these structures were favourable for structural modelling. By the end of the 19th Century, the calculation methods were limited to certain structural systems, such as lattice trusses, simple and continuous beams (Ramm 2000). For determination of internal forces mostly graphical methods were applied. The graphical methods were the equilibrium polygon with the polygon of forces for beams and the Cremona diagram for lattice structures. The conventional historic methods for the determination of internal forces of statically determinate systems are described in (Müller-Breslau 1912). The basis for the calculating of statically indeterminate lattices was already provided in the 19th Century by Maxwell and Mohr (Kurrer 2002, pp. 240 et sqq.). Out of it Heinrich Müller-Breslau elaborated a calculation method for statically indeterminate frameworks, described in (Müller-Breslau 1913). However, this method (today’s force method) often required solving large systems of equations and therefore required considerable calculation effort. Engineers tried to avoid or to simplify these extensive calculations. (Ramm 2000) describes that this was possible by
- a strong simplification of the static model, reduced to the minimum
- application of tabular values (e.g. Kleinlogel 1914; Stahlwerks-Verband 1924 pp. 500 et sqq.).

Table 1: Historic design rules for steel construction.

<table>
<thead>
<tr>
<th>Field of application</th>
<th>Essential content</th>
<th>reference</th>
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<tbody>
<tr>
<td>Prussian design regulations 1890</td>
<td>General building construction</td>
<td>Design loading</td>
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<tr>
<td>Prussian design regulations 1910</td>
<td>General building construction</td>
<td>Design loading</td>
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<td>Prussian design regulations 1919</td>
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The period between 1880 and 1940 was marked by a significant development of engineering knowledge and thus of design rules. First broad regulations for building construction were issued in 1890 in Prussia. Until 1925 several revised versions were issued (Table 1). Since the thirties the Prussian regulations were ultimately replaced by German industrial standards, which standardised the different regional rules within Germany (cp. Mertens 1919).

Snow and wind loads have particular importance for the loaded assumptions for industrial halls. The snow load evolved from a fixed value of 0.75 kN/m² into a differentiated value depending on the roof pitch. However, there was no dependence on the height or geographical location of the building. Figure 3 presents the snow load of historic regulations compared with today's loads, regulated in (DIN 1055-5: 2005). Current loading approaches depend on the location of the building: the snow load of zone 1 is far below historical, loading zone 2 did not exceed the historical loading in most cases. Current values of zone 3 significantly exceed historic loadings for common roof pitches.

Regarding to wind loads, there were significant developments in the historic regulations. In the 19th century wind loads were applied generally and undifferentiated. Over the years also the pitch of the component and the height and form of the building were taken into account. The separated consideration of wind pressure and suction – as it is done today (cp. DIN 1055-4: 2005) - was uncommon until 1938. Because of many different influences and the missing separation into areas with pressure and suction it is difficult to compare historical wind loads with the current. Calculations on the wind load of an exemplary roof structure with a standard roof pitch up to 30° indicated that historical regulations rules wind pressure, although according to today's standards wind suction has to be applied.
The dimensioning of historic steel structures was executed with allowable stresses concerning historic regulations. The allowable stresses increased progressively over the years due to the improvement of design procedures and materials. Figure 4 presents the development of allowable stresses of mild steel, later called St 37. The historic standards regulated basic allowable stresses, which could be heightened in certain cases, e.g., for exact calculations or certain structural members. The comparison of current stress analysis according to (DIN 18800-1: 1990) to historic allowable stresses reveals that the safety factor at the beginning of that period was 1.5 to 2 times higher than it is today. Later the safety corresponded to today's safety. The safety factors in the considered historical period were defined from experience and considerations on the preciseness of methods of proof. Thus different of historic and current safety levels result.

The proofs for compression members developed significantly in the regulations for steel construction. The first rules of the year 1890 did not contain stability proofs. From 1910 the Prussian regulations demanded a proof based on the Euler-hyperbola with a safety factor of either 4 or 5. The Prussian regulations of the Year 1925 established the $\omega$-method, which was later adopted into the German standards. The slightly modified $\omega$-method was used as the basic method for buckling analysis through decades. Figure 5 compares the historic buckling checks with today's buckling checks according to (DIN 18800-2: 1990) with the European buckling curves. The checks performed with the $\omega$-method were safe compared to European buckling curves (see Figure 5, right). The checks before the year 1925, which are performed using the Euler-hyperbola, are safe for compression members with high slenderness, but unsafe for compact members in certain cases (see Figure 5, left).

INTEGRAL INVESTIGATIONS

Analysis of historic drawings and static calculations

The investigations are based on current and historic literature and especially on historic drawings (for example Figure 6) and static calculations. Documents of about 60 industrial single story halls were chosen, which contained detailed engineering drawings and in many cases static calculations. A chronological schema gives a fast overview of all analysed buildings.
The consideration of the span of the roof trusses revealed, that is that mainly smaller halls from 10 to 15 m span were built in the 19th Century. With the beginning of the 20th Century spans increased, and sometimes exceeded 30 metres. The material enhancement and increase of the allowable stresses caused the enlargement of spans, but did not effect a development towards new load bearing systems. The influence of the development of steel sections on the construction system was simply seen by the increasing use of the wide flange beams in the twenties and the thirties of the 20th Century. From this period wide flange beams were increasingly used for lowly loaded columns, which were primarily composed uniformly of small steel sections with lacings and battenings by riveting. Also girders were designed as wide flange beams.

Structural systems of industrial halls were strongly influenced by the development of connection devices. The production of rigid riveted connections was labour-intensive, so that riveted connections were usually hinged. Welding offered an easy construction method for rigid frames. In the analysed projects constructions with riveted rigid connections (e.g. Figure 7) could be found rarely. Before welding was applied in steel constructions, variously shaped lattice trusses were predominantly used for roofs. With the use of welding technology in the thirties of the 20th Century more frames were used, because they could be constructed easily. There were no welded lattices in the analysed projects. Thereby it became evident that riveting was an established connection method for lattice structures and was not replaced by welding within the period between 1880 and 1940.

The historic static calculations from the documents of the GHH were analysed during the project implementation. Considering assumed loads historic regulations were mainly observed. The dead load, which is often applied approximately, was not safe in all cases.

The internal forces of statically determinate systems were usually determined calculationally or graphically using simple balance considerations. Statically indeterminate systems were often simplified as far that they have been statically determinate, for example by inserting hinges. In the cases of extremely simplified structural systems engineers have to be especially aware of the fact that internal forces do not correspond to real internal forces, so proofs are not safe. The force method was used rarely. For special structural systems (frames, arches) tabular values were used. Truss members were dimensioned (inclusive buckling checks) in the static calculations with the help of tables, which offered a clear identification of relevant load combination (see Figure 9).

The stability proofs of uniform built-up members in the early static calculations only checked the whole member as a rigid connected section. Later, with the introduction of the Prussian regulations of 1925, there were occasional proofs of the single components with the \( \omega \)-method. Normally there were no proofs of connections in the historic calculations. For the design of riveted connections, tables were available in historic literature with which the required number of rivets could be determined. These tables can be found for example in (Stahlwerksverband 1924 p. 91).
Special caution is advised at historic craneways: The loads of the craneways do not comply with today’s requirements, since often only vertical loads were applied. There were no horizontal loads applied, although there were recommendations in historical literature for lateral forces in craneways (Gregor 1924 pp. 9-10). Moreover, it can be assumed that for historical craneways no fatigue checks were made, because they could not be found in the analysed historic static calculations. The problem of fatigue checks was found by Wöhler at axes of trains (Wöhler 1863). His research work led to fatigue assessment with “Wöhler-curves”, which were introduced in steel design of railway bridges in the 20th century. Despite of the knowledge on fatigue, it is not mentioned in detailed historic literature on craneways. Only in the German standard for craneways from the year 1936 (DIN 120: 1936), which regulated the dimensioning of craneways, fatigue checks made with the $\gamma$-method can be found. The $\gamma$-method was unsafe compared to today’s requirements, because only loads, which caused a change between tension and compression, were regarded as significant loads. In addition, the notch cases were not important for the fatigue check according to DIN 120.

**Structural analysis of historic carrying structures and recommendations**

In addition to the investigations on the separate aspects, selected roof constructions from the projects of the GHH were structural analysed according to today’s criteria, for the integral appraisement of the safety of the carrying structure. As recommended in the literature (Käpplein et al. 2001 p. 71), material properties of a current steel S 235 were used for these approximate calculation.

It became evident, that sufficient resistance of most links of lattice trusses could be proofed under today’s criteria. This is due mainly to the lower snow loads on the roofs for the appropriate locations, compared with historic regulations (see Figure 3). Sufficient resistance of several truss members could not be proofed. In addition to errors or inaccuracies in the historical analysis, mainly compressed truss members did not meet the proofs. Truss members in historic structures were usually uniform built-up members made of angles or C-section. In historic analysis built-up sections had been checked for buckling as a single integral member. That does not comply with the current rules of (DIN 18800-2: 1990) for closely spaced built-up members due to the usual high distance of interconnections. The real load carrying behaviour in ultimate limit state is a combination of local buckling of single members and overall buckling of the whole section. This may lead to significant lower carrying capacity, which can be calculated according to (DIN 18800-2: 1990) or Eurocode 3 (DIN EN 1993-1-1: 2005). Taking the effect of shear stiffness of the interconnections into account, the members did not offer enough buckling resistance. In other cases, truss members, which were dimensioned in the historical analysis as tension members were loaded with pressure at today’s analysis. Reasons for this were revised load situations (wind suction instead of wind pressure), inaccurate determination of internal forces or too strongly simplified statically undetermined systems in the original dimensioning. Due to inadequate construction as pressure members resulting in high slenderness, the buckling proofs failed. Figures 10 and 11 present examples of typical tension and compression members. The result of the structural analysis of historical trusses was, that the members, which were dimensioned according to the historical regulations usually have enough resistance, assumed material properties of today’s steel S 235. However, there are sporadic members with insufficient load carrying capacity by different reasons. This is valid for buildings located in snow load zone 1 or 2. A final appraisement of the load carrying capacity of steel structures is only possible with a structural analysis considering the real material properties and cross-sectional areas also taking corroding and damages into account.

The result of the structural analysis of historic industrial halls was confirmed in the constructive analysis of existing industrial halls. During the exemplary analyses of still existing building stock, built between 1880 and 1940 a survey of the condition of the steel construction was made. It was found out, that the supporting structure was in good condition. Damages or greater deformations resulting of excessive load could not be found. There were no cracks or breakages, which could indicate a brittle, crack sensitive material behaviour. Steel parts within the halls were only corroded slightly at the surface, also applying to structures whose corrosion protection has never been renewed completely. Strong corrosion was found at construction members that were exposed directly to environment for a longer period.
Material analysis and tensile tests of historic steel was made with steel taken from a typical industrial hall built during the nineteen-thirties in the Ruhrgebiet. The material analyses presented typical historic steel with predominantly ferritic structure, which - compared to today’s steel - contained severe impurities by manganese sulphide, oxides and slag inclusions. The high oxygen concentration is a sign of unskilled steel. The high nitrogen concentration indicates that the steel was produced with an air blowing converter. Because of its high nitrogen concentration, aging of the material must be expected. As expected from the literature research, the present historic steel was not weldable because due to impurities, the high oxygen concentrations and the sensitivity to ageing. In tensile tests, the mechanical properties yield stress, ultimate strength and elongation at failure were determined and compared to the requirements of (DIN EN 10025-2: 2005) (Figure 12). The mechanical properties of the tests fulfilled the requirements of (DIN 10025-2: 2005) to steel S 235, there was only a little discrepancy to the strength of one test specimen. The elongation at failure of the historic steels exceed today’s minimum requirements, even though the ageing of the material.

Recommendations for the repairs of historic steel structures can be given by the results of the research project as a support of the planning of the renovation of historic industrial halls. Due to the particularities of each building (different construction types and damages), no general solutions for restoration can be given. The corrosion protection is crucial for the permanent maintenance of historic steel structures. For the restoration the steel structures must be derusted and coated newly with anti-corrosive paint. If insufficient load-carrying capacity of the steel structure is detected by static calculations, reparation or strengthening of the carrying structure is necessary. This requires a decision about the type of connection. The possibility of welding essentially depends on the basic material: wrought iron should not be welded, if the mild steel is suitable for welding can not be predicted categorically. Essential for the weldability of mild steel are the material structure, the composition and the position of the welds, which must be outside of segregation zones (Lüddecke et al. 2006). Thus, the weldability of historic steel must always been determined by a material analysis. The exchange of rivets is possible but laborious; furthermore building companies have little experience in erecting of riveting constructions. A good alternative are bolts which give the visual appearance of rivets.
CONCLUSIONS

Historic steel buildings are an important part of the industrial buildings of the 20th Century. This building stock is worth keeping for economic as well as historic preserving reasons. Essential for the preservation of historic buildings is the verifying capacity of the steel structure according to today’s requirements.

The results of the research project clearly show that it is worthwhile and promising to restore historic steel structures. The exemplary structural analysis of historic industrial halls generally reflected good building structure, which is a good basis for the renovation of structures with a reasonable effort. The appraisement of historical dimensioning and the exemplary dimensioning of historic roof structures showed that it can be successful to verify sufficient load carrying capacity of historic structures. Through this an impetus is given to all involved persons (owners, architects and engineers) to recondition historic buildings, to obtain the future usability and to preserve these useful buildings in this way.

The analysis of the historic design calculations, the appraisement of the historic regulations regarding to design loadings and design methods and also exemplary static calculations of roof constructions provide indications of critical structural members. Thus the research results sensitise engineers and other involved to the identification and appraisement of critical structures. The identification of weaknesses and the knowledge of the historical static constructional characteristics help, that during the repair of historic industrial halls reasonable methods are performed, which really help to improve the structure.

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REFERENCES

Literature

Mang, F., 1979: Stahl im Altbau und Wohnungsbau, Abschlußbericht zum Forschungsprogramm. Im Auftrag des Ministeriums für Landes- und Stadtentwicklung NRW.
Prussian Regulations and German standards


Prussian regulations 1890: Bestimmungen über die durchschnittliche Beanspruchung und Berechnung von Konstruktionsstählen aus Flussstahl und hochwertigem Baustahl sowie aus Gusseisen, Stahlguss (Stahlformguss) und geschmiedetem Stahl im Hochbau. In: Zentralblatt der Bauverwaltung, Jahrgang 45 (1925), Nr. 16, S. 193 ff.