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Investigation of Obsolete Structural Elements and Retrofit of Old Steel Structures

Recherche sur des éléments affaiblis et réparation d'anciennes constructions métalliques

Forschung an überholungsbedürftigen Bauteilen und Reparaturen an alten Stahlkonstruktionen

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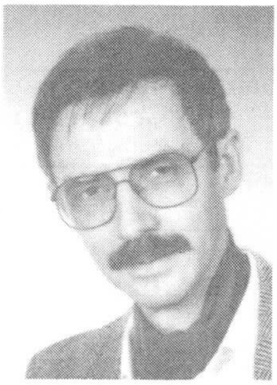

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SUMMARY

Examples of the state-of-the-art of structural safety assessment of old steel elements and obsolete structures are described based on the experience in the research laboratories and field work. Current studies on fracture behaviour of old structures and steels, and repair work are presented to define design and strengthening strategies and quality assurance and testing. This will assist in retrofitting such structures.

RÉSUMÉ

Des exemples illustrent l'état de la technique d'analyse de la sécurité de vieux aciers et de structures dépassées, sur la base d'expériences de laboratoire et de chantier. Des études actuelles sur le comportement à la rupture des structures, des aciers et des réparations sont la base pour élaborer l'étude, les stratégies de renforcement, de l'assurance de la qualité et des essais concernant la réparation de ces structures.

ZUSAMMENFASSUNG

Beispiele für den Stand der Technik der Sicherheitsanalyse an alten, überholungsbedürftigen Stahltypen und Konstruktionen werden vorgestellt anhand von Erfahrungen aus Forschungslabor und Feldarbeit. Aktuelle Bruchuntersuchungen an alten Strukturen, Stählen und Reparaturstellen werden vorgestellt und Entwurf, Reparaturvorgehen und die begleitende Qualitätssicherung und Verfahrensprüfung für die Sanierung erläutert.

1. OBJECTIVES OF REPAIR AND STRENGTHENING OF STRUCTURES AND JOINTS

The scope of this paper is concentrated on the safety and fracture toughness of old steel structures with respect to the influence of static load, strain rate, temperature and influence of weldments and environment. In some cases the influence of fatigue and embrittlement is mentioned. The determinant structural element that initiates repair work are in most cases the connections between main girders or floor beams and specifically tensile elements or strings.
Therefore strategies of repair and retrofitting of structures have to consider multiple parameters influencing the technology of repair beside the criteria for structural safety.
The figures given in a first overview are examples which combine the parameters of mechanics (see fig. 1) with the ones of technology and practise how to repair all kinds of joints with rivets, bolts or high strength bolts (HS) and by welds or other joining techniques.
The last column shows recent examples, if the goal of retrofitting is a fail-safe design. This can be achieved by using additional structural elements as reinforcing plates or sheets (fibres or composite materials) or prestressing tendons as used extensively for concrete bridges.

Method of Retrofit Case,Technology ↓ *service condittions*	**splices „soft repair“**	**welded joints „cut“ and „paste“**	**strengthening, external prestressing („fail safe“element)**
Riveted joint to be reinforced *Static load*	replace by HS-bolts friction type	reinforcing by fillet weld or buttweld	external cables fixed with bolted adapters
Riveted Joint to be reinforced *at low temp.*	replace by HS-bolts fitted or friction type	welding not recommended	external cables fixed with bolted adapters
Riveted joint to be reinforce. *Fatigue load*	replace by HS-bolts fitted or friction type	welding not recommended	external cables evtl. composite laminates
Welded joints to be reinforced	repair (Hi-quality and weldability), NDT	replacement after NDT and new WPS	external cables or composite laminates

Fig.1. Goals and technology for repair of steel structures

The aims of repair and strengthening of old structures are to extend their lifespan, but especially for old structures the goal is to redesign the structure such that well-defined safety is achieved (see also fig. 2.4). If old iron material is present, a soft reinforcing technology of splices is recommended to avoid the effects of cutting and welding. Melting and metallurgical effects may cause cracks in the lamellar structure of the steel. To avoid load redistribution effects in a non isostatic structure e.g. in a continuos beam repaired by welding, it may be recommended not to change the static system and to do only minor welding work (less internal stresses) in a old structure. In this context old codes may be helpful to study the old design philosophy (e.g. [1]).
It is a must in any redesigned joint and reinforcement, to assess the quality of the old material before and after the repair by means of actual non destructive testing (NDT) and for any new additional structural element as well. One favourable property of old steel is (type Tomes steel or wrought iron), their low sensitivity to corrosion. However, poor maintenance and therefore damage by corrosion are still the main reason for the repair or demolition of most old steel structures. Note, that the cases reported here, are structures manufactured about 100 years ago.

2. PRELIMINARY INVESTIGATIONS, NON DESTRUCTIVE TESTING AND SMALL SCALE EXPERIMENTS

2.1 Preliminary investigation and strategy

An analysis and retrofit program may cover the following items and steps of operations:
- Investigation of damage and extrapolation of risk to the end of the extended service life: cause and degree of damage, remaining period and failure scenario, structural behaviour and consequence of repair for safety, remaining service life, timing, maintenance, inspection.
- Actions of retrofit program, design and technical specifications.
- Environmental studies for adequate corrosion protection of surfaces and strengthening elements.
- Choice of methods "soft repair" or welded joints or strengthening and reinforcing (as fig. 1): Technology of joints with „soft repair“ methods do not affect the ductility and plastic properties and embrittlement is avoided; another case is the effect of welding which often causes reduced toughness in the HAZ or cracks in zones of laminated concentrations of phosphorus (P) and

sulphur (S) (see fig. 2.1 d).
Strengthening by external prestressing or by bonded advanced composite sheets, where experienced methods are available now (see par. 4 and [7] for composites).

- Execution, quality management, non-destructive testing and documentation: Specification of repair, materials and testing, WPS and NDT criteria for welds.
- Consequences for extended service, NDT and inspections by owner and consultants

2.2 Preparation of structures and inspection of critical zones

Accessibility to the specific joints of all tensile members as well as adequate surface grinding before any inspection and non destructive testing are mandatory.
If ultrasonic testing (UT) is used there may be no reliable back-wall signal due to the lamellar structure of old steels. The NDT procedures recommended are visual testing (VT), magnetic particle- (MT) or penetration testing (PT). Experienced inspectors are able to detect small cracks by VT, but the use of a lens and PT may be necessary if steels near rivet heads and bolts are inspected as in fig. 2.1 and 2.3 (lit. [2]). These figs. show other typical damage, corrosion pittings and cracks due to on the site welding, which can be caused by improper repair work. Therefore quality assurance of any repair must include VT, PT or MT and UT inspections if possible.
Investigations and welding qualification programs (as WPS explained in [4]) with fine grain steels for power plants are good examples to pre-qualify any old steel for its fracture and failure behaviour.

2.3 Fracture mechanics analysis (see [3] [4])

An investigation of Swiss Railroad (fig. 2.2 in [2]) including results of EMPA, shows the temperature transition curves of CVN-toughness of wrought iron and mild Tomas-steel (period 1890 to 1940, covered in [1]). This latter steel contains impurities as well and has a typical upper and lower shelf of toughness, compared to the wrought iron with its typical laminated carbon inclusions. The "old iron" shows less temperature sensitivity but low CVN-energy as well. Both steels show low toughness, they are sensitive to strain rate and temperature- and ageing effects may appear, if cold forming is present. Nevertheless due to multiple crack branching the K_{IC} of old steels may be surprisingly high (see fig. 2.3 and [3]). Our results showed, that at increasing load, close

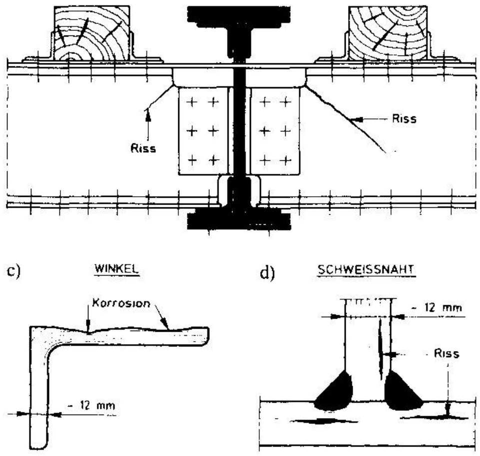


Fig.2.1 Examples of possible cracks and notches
above: cracks in web due to local deformation or service load
below left: corrosion pitting between corner and plate
below right: influence of welding in web and flange due to filet weld
(Stahlbau 58 (1989), Brühwiler, Hirt, Morf, Huwiler)

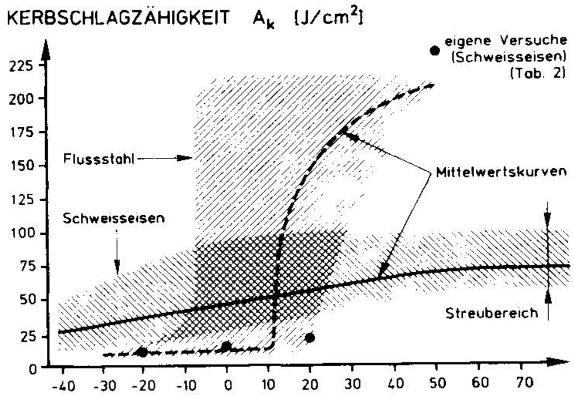


Fig.2.2 Charpy-V-notch fracture toughness Ak(J/cm2) vs.temperature in °C (transition) for wrought iron and old mild steels
Schweisseisen=wrought iron,
Flussstahl=mild steel (1890...1940)

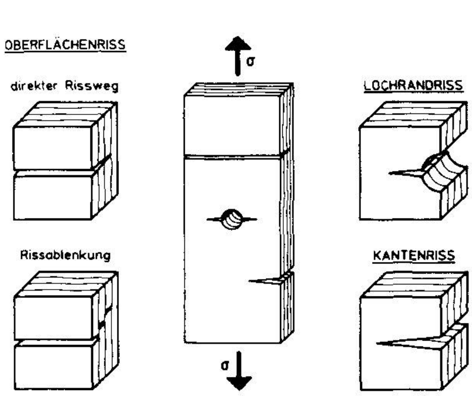
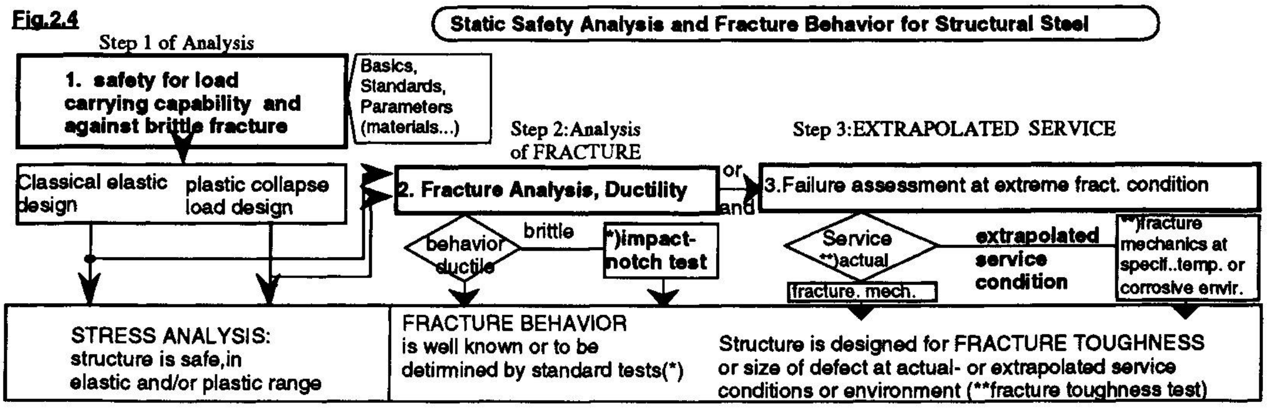


Fig.2.3 Orientation of cracks found in anisotropic steels as wrought iron or old mild steels
left side: surface cracks with multiple deviation
right side: edge crack or corner crack in hole

to the yield point (R_p), small cracks may not trigger spontaneous fracture. Wrought iron plates have been tested up to R_p with 10mm edge-cracks at holes. To redesign such structures a combined „Static safety and fracture behaviour analysis" is necessary according to fig. 2.4 (complete flow chart see [4] and design curve in [5]). For extrapolated behaviour at extreme service and environment fracture mechanics testing could be worthwhile, since inexpensive small– sample CVN-test methods (HR6-method in [5]) are available in practise.
To reach the optimal load capacity in a cracked plate—that means the status of plastic collapse starts before unstable crack growth—the rule described in [5] for the required fracture toughness is: (1) $\mathbf{K_{req}=1.38\ R_p\sqrt{t}}$ where
- R_p is the actual yield point of the representative element (thickest representative flange or wall) at extreme service conditions as local strain rate and lowest service temperature,
- t is the thickness of the same structural element.

2.4 Mechanical testing with small samples
In any case we suggest full size testing , if scale factor problems (t >>10mm) are present; in such tests extreme thickness and strain rate and lowest temperature may be simulated. In the case of a riveted structure it is realistic to use a choice of the thickest representative elements, corners and plates and design a testing program similar to the WPS for pressure vessels (SVTI 505, Swiss board for techn.Inspections or ASME in USA). In this test plate, sets of small specimens are used as for WPS. In our case precracked CVN samples are used to check whether the condition of fig. 2.4 for step 3 is fulfilled, means if for a given crack situation the stress intensity is below K_{IC}:
(2) $\mathbf{SIF < K_{IC}}$ This safety equation for the fracture toughness requirement (formulas (1) and (2)) SIF < K_{IC} < K_{req}) is traditionally replaced by the simple check of „ductile behaviour" (step 2 in fig. 2.4) by means of welded bend test specimens and CVN-tests at the lowest service temperature. For actual applications we recommend here to apply Eurocode 3 (1994) Annex C. In this provisional code for structural steel, the minimum temperature for service T_S(°C) is given for minimum fracture toughness (K_{IC}), test temperature and temperature shift due to shock:
(3) $\mathbf{T_S(°C) = 1.07\ T_{CVN\ 27J} + \beta + \Delta T[de/dt]}$ where $\beta = 100(\ln(K_{IC}) - 8.06)$
- The term $\Delta T[de/dt]$ is negligible since it depends on the global strain rate [de/dt in s^{-1}] which is usually close to zero. For medium shock loads use $\Delta T[de/dt]=2100(de/dt)$.
- $T_{CVN\ 27J}$ is the test temperature at which the CVN-energy is 27J. In the case of some old steels the result for T_S (°C) may be such, that retrofit by welding is not possible!

Fig.2.4



3. ENGINEERING OF IMPROVED JOINTS AND REPAIR TECHNOLOGY

3.1 Methodology for specific repair of old steels
The analysis of old steel structures and possible repair strategies combines the methods of inspecting damaged structures and procedures of production as WPS for bridges and pipelines. For concrete structures a RILEM draft [6] covers special questions about corrosion in this context.
In cases of damage to steel structures, a checklist for some types of connections is shown in fig.1.

3.2 Case studies of repair technologies for buildings and bridges
•The first example of an old low carbon iron **arch string bar** (35mm*52mm), manufactured in the 17th in Engadin/Switzerland, was to be repaired in a church. The objective was to design a fail safe

splice, in addition to the repair by butt welding. The latter was successfully accomplished. Details, material data and welding procedure specification are given below:

description of steel: low carbon iron with high contents of manganese and phosphorus (P:0.1%) tensile strength: 230 to 330 N/mm^2, CVN-energy (in HAZ): 50 and 220J

welded specimen : high variation of hardness HV 100...260 (in the HAZ: HV100...180)

WPS (see fig.3.1): electric arc welding with basic electrodes 2.5/3.25, 13 passes. Some cracks in the HAZ had to be repaired in zones of high contents of P and S.

•**Riveted joints transformed in slip resistant joints** with high strength bolts are good examples of retrofitting methods and typical for railroad bridges. Two cases reported from Swiss railroad are old truss systems made of wrought iron in 1875 with additional elements of mild steel. In most cases gusset plates spliced with diagonals or beams had to be reinforced. The aim was to replace rivets by slip resistant high strength bolts. Based on German tests, the improvement of fatigue strength and of the slip behaviour is evident (Fisher [8] p.238).

Below the joint or splice is described first and then the method of strengthening and inspection with points to observe (slides by E.Brühwiler Swiss Rail/ETHL):

<u>Non symmetric bow-truss bridge "Linth":</u>

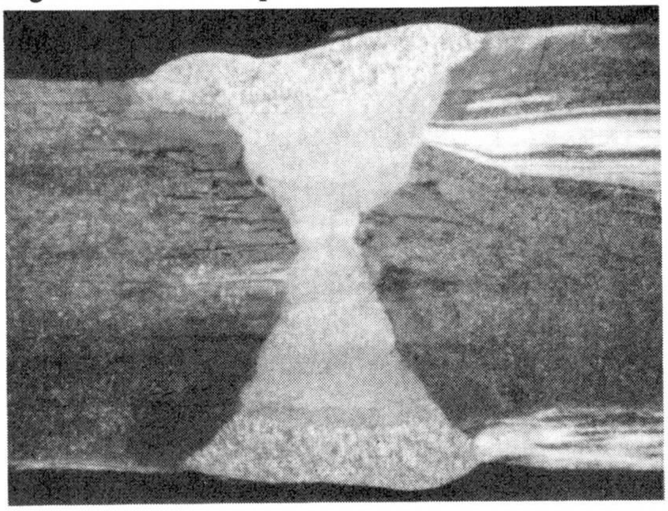
steel / splices: bow with wrought iron flange / reinforced by lateral filet welding in 1930 and attachments of new wind bracings.
Some secondary elements fixed by filet welding on surface of riveted bow.

inspection, observation: In the case of wrought iron, welding between edges of plates is possible, but welds on surfaces are likely to produce lamellar cracks and tearing.. Ribs on plates (as rain drains) should be checked for cracks in HAZ next to the fillet welds. Welds between edges of plate material loaded by shear seemed to behave well.

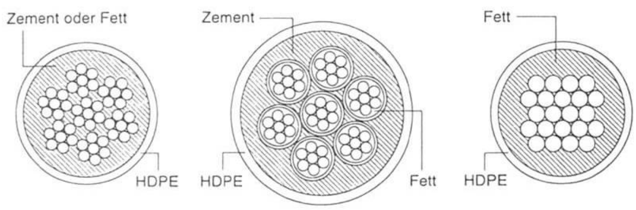
<u>Continuous truss beam "Rhine":</u>

steel / splices: wrought iron / extension of gusset plate with combined action of rivets and new high strength bolts. Extensions of diagonals (attached to gusset plate) by lateral but welding.

inspection, observation: Butt welding was avoided if possible. Load transfer between elements and fillet welds was designed such that shear along edges of plates was predominant. The main points to check or retrofit were obsolete and locally corroded splices and gusset plates. Experience of old road bridges in Basle showed, that the safety and stability of corroded plate girders (wave shaped deformation) is reduced due to expanding corrosion products.

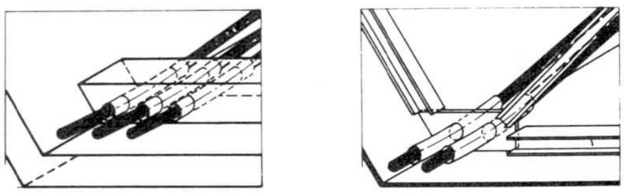


<u>Fig.3.1</u> Repair of a Arch String in a Church 17th
Material: low carbon iron w.inpurities (high contents P, Mn)
WP Spec.(accord. EN287): electric arc weld, manual (111)
type and pos.: but weld, X-shape 35mm (BW)/ vertical (PF)
electrode /diam.: Oerlikon Spec. /2.5...3.25mm at 70...90A



bundle of strands protected by cement or grease | bundle of individually greased and plastic-sheathed strands | bundle of wires protected by cement or grease

<u>Fig.4.1</u>
Cross-sections of three types of exterior cables
(SI+A 21/94, T.Vogel)



<u>Fig.4.2</u>
Saddles and deviations in concrete and steel girders
(VSL news letter II/89)

4. RETROFIT OF STEEL STRUCTURES BY EXTERNAL PRESTRESSING

External prestressing was used since the beginning of prestressed concrete in 1936, later also as a tool for strengthening of structures. For special cases of retrofitting old steel bridges any type of ropes and locked coil cables have been used as the Swiss example of Aarwangen shows. The scope of applications is wide, especially if today's possibilities of external prestressing technologies and the specific cable sheathings (see fig. 4.1) are applied (draft doc. FIP [9]). The external tendons are advantageous for strengthening steel structures, beams and trusses, below beams or inside of structures as in the recent example of the "Bois de Rosset" bridge (see fig. 4.2). Particular solutions are possible if the external tendons are prestressed such that stresses in tension in the main structure are minimised (against brittle fracture) and the external tendons are counteracting the live loads.

Requirements for structure and materials of external tendons:
Tendons exposed to live loads and environment are to be protected against corrosion and damage.
In order to gain full advantage from exposure and easier accessibility the following is important:
- Design of structure, cables and attachment of fittings shall allow inspection and monitoring
- In special cases tendons and anchorages must be restressable, detensionable and replaceable.
- To obtain reliable quality of the protection, three examples of well known permanent corrosion protection methods are shown in fig.4.1 which are state of the art of the respective producers.
- The steel (according to prEN10138) may be supplied with a permanent corrosion protection in the factory, depending on the product as galvanised wire or strand, greased waxed or otherwise soft protected and plastic-coated monostrand or Epoxy-coated wire, strand or bar.
- In the deviators high lateral pressure occurs. Test with strands have shown, that linear pressure of 600kN/m can be reached without noticeable reduction of tensile strength of the prestressing steel. However, the influence of fretting corrosion between steel and pipes (if used as sheathing) should be investigated in a specific fatigue test. In this respect locked coil bridge cables, investigated by EMPA, also showed this sensitivity between the outer and the second layer of wires.
- In case of riveted structures it is recommended to design special adapters to be bolted to the main structure or use symmetrically welded anchorage devices, if weldable gusset plates are present.

DEFINITIONS

CVN Charpy-V-notch impact bend specimens (if precracked basis for evaluation of K_{IC})
HAZ heat affected zone in welds (problems arise if impurities are melted by weldment)
HR6 assessment according to Cent. Electricity Generating Board, CEGB 1986 doc. R, HR6
K_{IC} fracture toughness (crit.factor of stress intensity)
K_{req} required fracture toughness
NDT non destructive testing (for definitions of MT, PT and UT see chapter 2.2)
WPS welding procedure specification (e.g. according natl. codes or standards)
SIF stress intensity factor

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