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A Current Problem for Steel Bridges: Fatigue Assessment of Seams´ Repair

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***Abstract*—**The paper describes the results from a research project about repair of welds. The repair was carried out by grinding the flawed seams and re-welding them. The main task was to determine the FAT classes of original state and after repair of seams according to the assessment procedures, such as nominal, structural and effective notch stress approach. The first part shows the results of the tests, the second part encloses numerical analysis and evaluation of results to determine the fatigue strength classes according to three assessment procedures.

***Keywords*—**Cyclic loading, fatigue crack, post-weld treatment, seams' repair.

I. Introduction

In dynamically loaded components, weld transitions often are the reasons for cracking with subsequent crack growth. They restrict in many cases the life of the components and structures. There are also deviations that could not be taken into account in the design of the construction, for example, larger loads and the desire for prolonged use.

According to the authors, no design concept for the load capacity of the weld after the repair is known to this day. In a research project [1], [2], in which not only the Department of Steel Construction of the BTU but also the Institute of Joining and Welding Technology at the TU Braunschweig (both Germany) and the Institute of Engineering and Materials Science of the University Innsbruck Austria took part, FAT classes for renovated welds are developed for the first time.

II. Research Schedule

Since welds contain significantly higher stress concentration than in butt ones, in the following paper, the experimental investigations were carried out by using specimens with fillet welds under tensile stresses. The fatigue strength of whole structure decisively depends on details, which are mostly welded joints. Weld transitions are the most critical locations where fatigue cracks are more likely to occur and later grow. Quite often it comes to fatigue failure even at non-load carrying details e.g. transverse attachment of a bridge girder. It was a reason for the choice of specimens in this research. The examined in the following paper specimen are transverse non-load carrying attachment with fillet welds manufactured from steel grade S355J2N (Fig. 1).

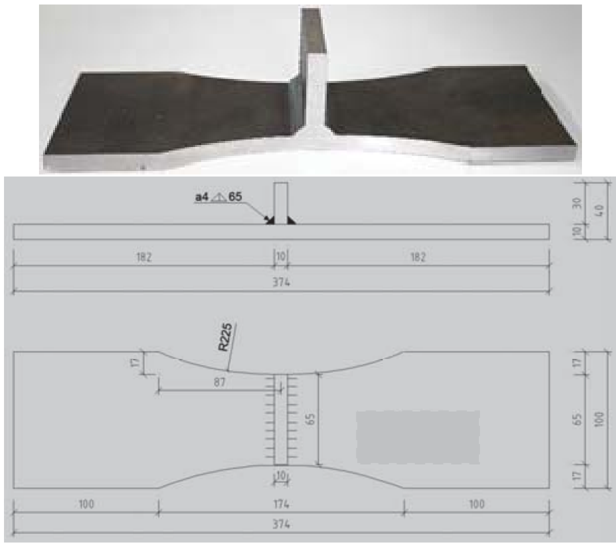

Fig. 1 Geometry of specimen [1]

For such geometry of specimen, a fatigue crack is expected to occur at weld toe and is mostly caused by concentration of notch stresses (Fig. 2). To make possible a comparison the results of fatigue strength for the welds after seams' repair and additionally seams' re-working methods, the fatigue strength test analyses were divided into three groups:

- Group I: fatigue strength tests for defect-free weld seams;
- Group II: fatigue strength tests for seams' repair scenario, i.e. flawed weld seams renovated by grinding the existed crack and re-welding;
- Group III: fatigue strength tests for analogous to group II but supplemented by post-weld treatment methods.

The test schedule is given in Table I, whereas Table II shows parameter of welding.

TABLE I
Test Schedule – Seams' Repair with the Existed Crack (Prior Damage)

Group I Original state	1. with MAG (135) welded; 2. each pieces were separately cut; 3. fatigue strength test.
Group II Seams' repair	1. with MAG (135) welded; 2. each pieces were separately cut; 3. grinding the existed cracks till 30% of plate thickness; 4. E-welding (3 layers); 5. fatigue strength test.
Group II Seams' repair	1. analogous to group II but with supplemented by weld-seam reworking methods (high frequency hammer treatment).

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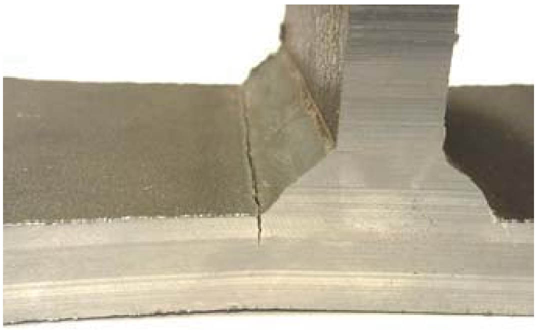


Fig. 2 Crack at weld toe [1]

III. Manufacturing of Test Specimens

A. Original State

The original state is given on Fig. 1 and Table II.

B. Seams' Repair

TABLE II
WELDING PARAMETERS OF SPECIMENS DURING MANUFACTURING

Symbol	Quantity
I [ampere]	320
U [volt]	30.8
v_S [cm/min]	40
v_D [m/min]	11
process of welding	135
position of welding	PB
wire electrode	G4Si1

In repair state, the potentially existing cracks were removed by grinding of weld toe area. It was proceeded by using a milling machine. In order to get an adequate fusion in the HAZ, the excavated groove of the flawed material was performed in V-shape (Fig. 3). A stage of re-welding was carried out by using arc welding and supplemented in three welding layers (Fig. 4). These weld seams are characterized with much flatter shape in comparison to the ones in original state.

C. Seams' Re-Working Method

In order to explore the effects of mechanically treated weld toes on the fatigue strength, the high frequency hammer treatment with a frequency of 230 Hz was applied.

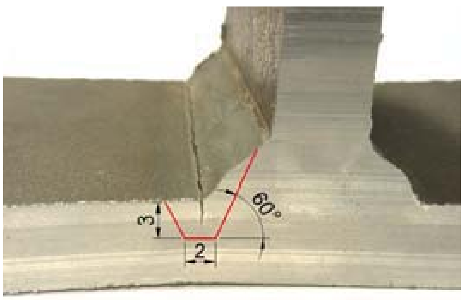


Fig. 3 Grinding of crack [5]

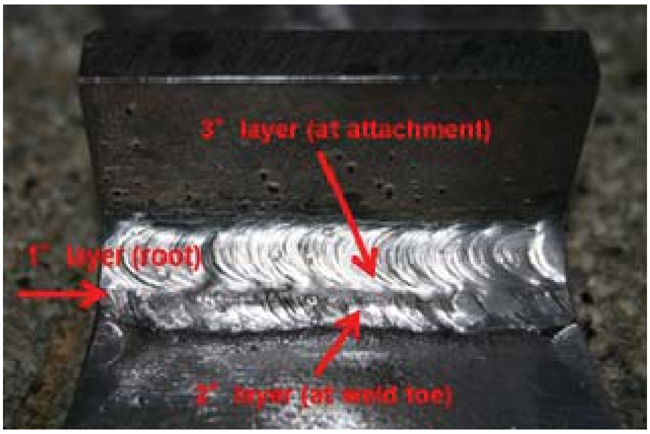


Fig. 4 Repair welding layers [1]

IV. Experimental Investigation and Results

The fatigue tests were carried out with frequency of loading 30 Hz by using a servo hydraulic fatigue test machine (Fig. 5). According to recommendation for fatigue tests the specimens were loaded in five different load levels. To determine a Wöhler (S-N) curve, just the specimens with the crack at weld toe were taken into consideration. The run-out samples were indicated on diagrams by data points with arrow marks. The fatigue loading was alternating the axial tensile with the assumption of stress radio R = 0.1 and fixed slope of Wöhler curve m = -3.

Fig. 5 Hydraulic fatigue test machine [1]

The following numbers of specimens were investigated: 29 for group I (original state), 13 for group II (after seams' repair) as well as 13 for group III (with post-weld treatment). The data points were presented in Wöhler diagram (Fig. 6). For the group I the fatigue strength has a value of 104 N/mm^2, for the group II 124.5 N/mm^2 and accordingly for group III 116.5 N/mm^2. It concerns a probability of survival of 50 %, i.e. regression line. The results show that the weld seams after repairing process could easily achieve the fatigue strength of those in initial state. In some cases, even the considerable enhancement of fatigue life is observed. But, it should be mentioned that such repair procedures can lead to the increase of misalignments of specimen geometry. The post weld treatment, i.e. the high frequency hammer delivered in this case negligible effects on the fatigue strength to compare with the original ones.

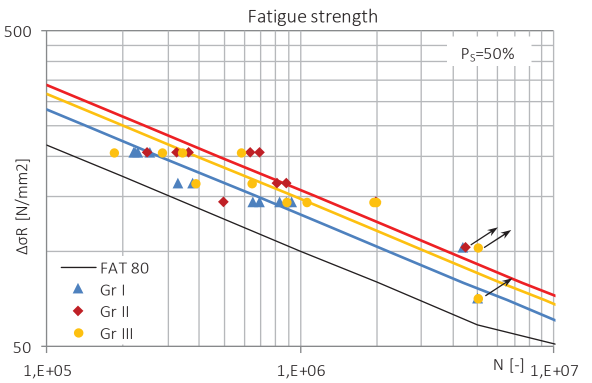
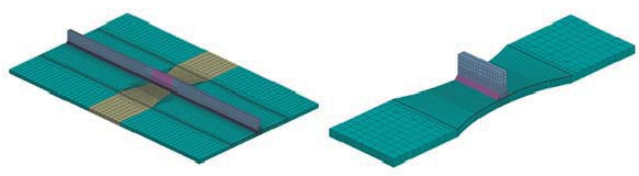


Fig. 6 Comparison of results from three states [5]

V. Numerical Investigation

A. Welding Simulation

The welding simulation should be carried out as realistically as possible. In order to realize this, the structure transformation of material, material properties as well as temperature dependence of the material were taken into account in analyses. The residual stresses of the specimens were calculated by using the software package SYSWELD [1]. For this simulation, especially thermo-mechanical coupling in the material and the geometric preparation of the seam matter. Therefore, the temperature field and macro section were experimentally measured. It was necessary to calibrate accordingly the moving heat source of the welding simulation. To meet the test conditions as closely as possible, these analyses considered in advance simulation of welding the transverse attachment to the base plate and afterwards cutting out every sample separately (Fig. 7).

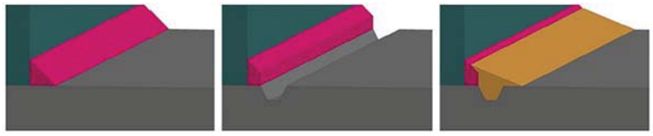


(a) (b)

Fig. 7 Base plate with transverse attachment (a) and separate specimen (b) [1]

The operation of repairing occurred also quite realistic. A flawed part of fillet weld and material was "numerically" removed and re-welded (Fig. 8).

Besides a purely experimental determination, the fatigue resistance can be verified according to three analytical concepts. They based on nominal, structural, and notch stresses. Particular attention is paid to the local approaches (i.e. structural and notch stress approach) since they are recommended due to better efficiency for welded joints [3], [4].

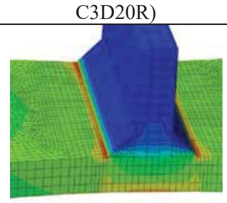
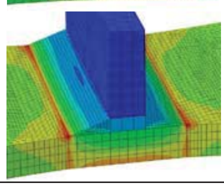


(a) (b) (c)

Fig. 8. Schematic drawing of seams' repair. Fillet weld (a), milled part (b) repaired seam (c) [1]

B. Fatigue Strength Assessment Concepts

TABLE III
Comparison of FE Calculation of Structural Stress

State	Model (Volume elements C3D20R)	Calculated k_t
Original state (group I)		**k_t=1.15**
Seams' re-pair (group II)		**k_t=1.21**

The nominal stress approach concerns stresses calculated in the sectional area of potential crack initiation region by using simple beam theory. The local stress concentrations of the welded joints are disregarded. The fatigue verification occurs in form of relation of stress ranges towards FAT classes, which generally were delivered from the fatigue tests. The local stress peak is covered in resistance side.

The structural stresses include both nominal stresses and the effects of structural discontinuities due to structural detail of welded joint, but excluding the notch effects of the weld profile itself. These fictive stresses are calculated through extrapolation to the weld toe stresses from two or three reference points taken from certain distances from the weld toe.

The basics of the notch stress concept relate to the principle of Neuber at location of potential crack initiation (either at the weld toe or the root). This concerns a theory of macro- and micro-support, with basic assumption that not the full notch stress at the weld toe affects fatigue failure. According to this approach, all edges at weld toe were rounded with the fictitious radius r_t = 1 mm and for such geometry the effective notch stresses were calculated. A master S-N curve for this concept has a value of FAT 225. To determine the effective notch stress are FE calculations required.

C. FAT Classes According to Structure and Notch Stress Concept

The structure stress was determined using 20-nodes volume elements of type C3D20R. Table III contains various models with the calculated stress concentration factors. The value of this factor for original state was $k_t = 1.15$ and after seams' repair $k_t = 1.21$ [5].

The notch stress for original state was analyzed both with shell and solid elements. For the shell model, 8-nodes elements of type S8R and for volume model the same elements like in the structural stress concept were used. Table IV shows a comparison of the calculated stress concentration factors for the original state. The values of this factor are a little higher by model using volume elements. For this reason, just volume model was analyzed in case of seams' repair. The value of stress concentration factor for original state was $K_t = 2.3$ and after seams' repair $K_t = 2.2$ [5]. The lower value by repaired welds results from considerably flatter seams shape after repairing.

Fig. 9 shows determined FAT classes for three assessment concepts. For each approach, the value of calculated FAT notch detail is considerably higher than in the currently valid guidelines [3] or standards [6]. Additionally, the results confirm a conservatism of notch class according to EC3 [6] for detail of transverse attachment with fillet welds. This applies in particular to the nominal and structural stress concept, whereby value of improvement reaches even till 20 %.

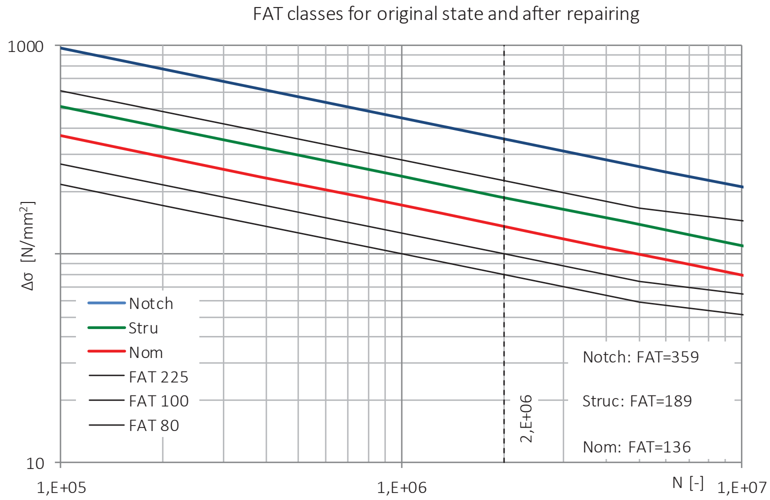


Fig. 9 FAT categories of original state and after seams' repair [5]

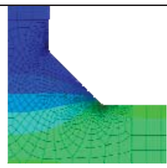
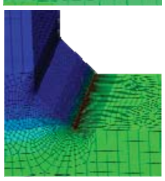
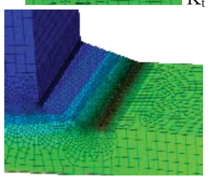
VI. Conclusions

As it was shown in experimental and numerical investigations of steel plates with welded transverse attachment, these repair procedures can lead to considerable improvement of fatigue strength in comparison to original state. In this case, using the post treatment methods with the high frequency hammer is rather no advisable.

The following procedure of cracks repairing by steel bridges is recommended: At first the flawed part of weld seam and material should be removed. It was assumed that grinding reaches till maximal 30 % of plate thickness. The prepared form is afterwards re-welded by using arc welding method. Since the excavated groove is relatively large, it is recommended to use the 3-layers welding. In that case, such repaired weld seam does not match the dimensions of seam from original state.

The following conditions must be noticed: stress ratio $R = 0.1$, assumption of imperfection according to IIW-Recommendations; T-joints detail geometry; steel grade S355, seam thickness 5 mm and plate thickness 10 mm.

TABLE IV
Fe Calculation of Notch Stress for Seams' Repair

State	Model	Calculated K_t
Original state (group I)	 $K_t = 2{,}17$  $K_t = 2{,}36$	**K_t=2,3**
Seams' re-pair (group II)	 $K_t = 2{,}24$	**$K_t = 2{,}2$**

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Prof. Dr.-Ing. habil. Hartmut Pasternak has participated in numerous research projects (e.g. on thin-walled members, welding stresses and adhesive bonded joints). Under his supervision 11 PhD´s were completed. He has more than 130 publications in Journals and at Conferences and is co-author of books in German (4) and English (1) on steel structures. He is member in several National and International Committees (e.g. full member of the ECCS Technical Committee 8 “Structural Stability”).

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