EXPERIMENTAL AND NUMERICAL INVESTIGATION ON THE FATIGUE LIMIT OF BLOCK FLANGES USED FOR STEEL PENSTOCKS IN HYDRO POWER PLANTS

Andreas Lechner, Richard Greiner

Institute for Steel Structures, Graz University of Technology, Lessingstr. 25/3, 8010 Graz, Austria,
Email: lechner@tugraz.at, www.stahlbau.tugraz.at

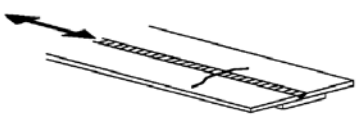
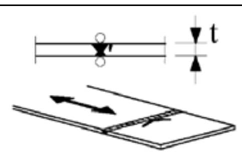
Abstract

In underground installations of hydro power plants nowadays large tunnels with diameters up to 5 – 8 m are being built. Considering such large diameters in connection with pressure heads up to 100 bar and more, pressure shafts are armoured by steel shielding of high strength steel grades in order to withstand the loading. Due to the increased operation in pumped storage mode – in comparison to the previous decades – and the use of high strength steel grades fatigue loading tends to be the governing load case for this type of steel shielding. In a research programme owners, steel fabricators and research institutions investigated the fatigue resistance of existing steel penstocks of hydro power plants in Austria, both experimentally and by means of Finite-Element (FE-)analysis, since specific FAT-classes could not be found in present design codes (Eurocode 3-1-9 [1], FKM [2] and IIW [3] respectively). At special details of openings, which are used for the usual placement of grouting between the concrete backfill and the steel shielding itself, the limiting fatigue resistance is found. The research work focused on the use of high strength steel grades in welded (reinforced) and non-welded (unreinforced) openings. Three different types of reinforced openings were investigated. As reference case tests on an unreinforced type were examined too. In the following, the test programme, FE-results and the fatigue evaluation of two welded cases, *Type A* and *C*, in accordance with the structural hot-spot stress concept are presented. Further results will be published subsequently.

1 GENERAL

In principle, the smooth steel shielding of pressure shafts in underground installations of hydro power plants has to be designed against four different limit states: primary stress state (LS 1), stability (LS 2), secondary stress state (LS 3) and fatigue (LS 4). LS 1 covers the design for the maximum internal pressure loading including water hammer. LS 2 means the design check against the maximum external pressure loading caused by the seepage water respectively the grouting in the erection phase. LS 3 assures that the secondary stress criteria won't be exceeded for the maximum range between internal pressure and external pressure loading including temperature change and Poisson-effects. LS 4 addresses the fatigue check according to Eurocode 3, part 1-9 (EC3-1-9) [1].

Table 1. Relevant fatigue limits of Eurocode 3 for welded details in steel shielding of penstocks

FAT 112 Automatic butt welds made from one side only, with a continuous backing bar, without stop/start positions		**FAT 112** Transverse splices in plates and flats, weld ground flush to plate surface parallel to the direction of loading; welded from both sides, checked by NDT	

As shown by *Table 1*, the fatigue limit is determined by fatigue class (FAT) 112 N/mm^2 for the circumferential butt welds that are manufactured on site by automatic or semi-automatic arc welding. However Eurocode 3 does not provide any fatigue class relevant for the openings used for the placement of the grouting (*Fig. 1* and *2*). In other design recommendations as FKM [2], IIW [3] and AD 2000 [4] more information is given for openings, but its different approaches lead to a large variation in the fatigue limit. FKM and IIW specify FAT 71 for the stiff block flange with full penetration welds regarding the nominal stress approach. However AD 2000 specifies K1 plus the stress concentration factor η = 3.0, which would be approximately FAT 36 in comparison to the safety level of 97.5 % of Eurocode 3 (95 % of IIW).

Regarding the structural hot-spot (HS-) stress approach Eurocode 3, IIW and FKM provide rather similar FAT-classes. In order to overcome these discrepancies – specifically in case of high strength steel grades currently used in steel penstocks, at the Graz University of Technology (TU Graz) an Austrian Research project *"Innovation in the Construction of Steel Penstocks for Pumped Storage Hydropower Plants – INJ09"* was started together with VERBUND Hydro Power AG, TIWAG – Tiroler Wasserkraft AG, Vorarlberger Illwerke AG, ANDRITZ HYDRO GmbH, the Austrian Research Foundation FFG and Oesterreichs Energie Research & Innovation. In the following, the main issues of the first project year are reported herein.

The results obtained in this first project year [7] serve both as reference for the endurance limit for the existing types of openings and for the optimization and further development in the continuation during the second research period. In *Fig. 1* a typical cross-section of the steel penstock of *Limberg II*/Austria [6] including the arrangement of welded openings used for grouting is shown. The distance between these welded flanges equals 120° (deg) in circumferential direction and approximately 2.5 m in axial direction of the penstock. In total more than 1000 welded openings have been installed. *Fig. 2* gives an outside view during welding on site (left) and an inside view of a plugged reinforced opening in high strength steel grade after grouting (right).

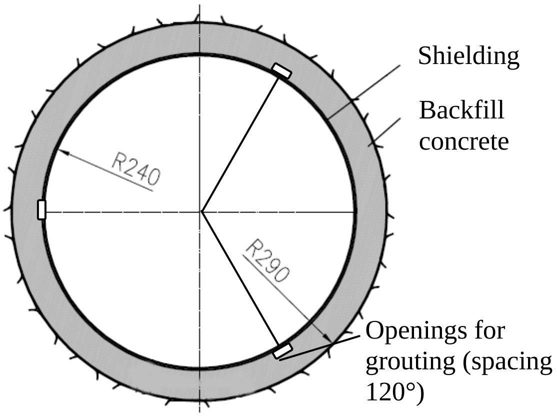


Fig. 1. Cross-section of pressure shaft, Limberg II, Austria [6]

Fig. 2. Typical reinforced opening – outside view (left) and inside view (right), Limberg II, Austria [6]

The loading of the shell - in axial and circumferential direction - is shown in *Fig. 3*. Regarding the structural HS-stress approach for the reinforced openings the corresponding FAT-classes according to EC3-1-9 are shown in *Fig. 4*. Based on the nominal stress criterion openings lower the fatigue limit to 36 to 71 % compared to the welded shielding itself (m = 3). The endurance limit decreases to 0.36^3 resp. 0.71^3*100 = 5 resp. 36 %. Due to the high quality standard for the fabrication of the openings and its welding - welding class "B" according to *EN ISO 5817* [5] - higher fatigue strength was assumed. The test programme focused on validating or possibly raising the fatigue strength as determined by the structural HS-stress approach according to EC3-1-9 and on developing FAT-classes for the nominal stress approach. Further the influence of the cylindrical shielding to the openings compared to the flat plate was investigated.

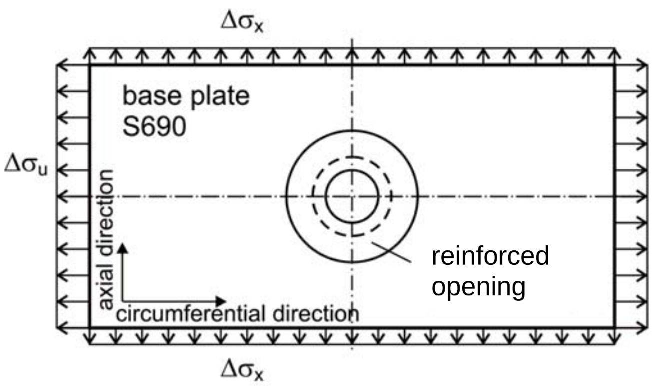


Fig. 3. Actions at openings in cylindrical steel shielding

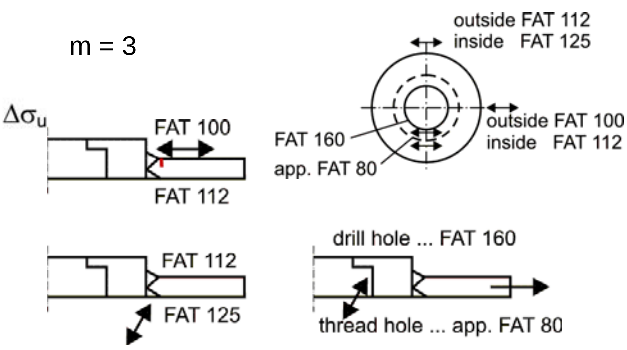


Fig. 4. FAT-classes acc. structural HS-stress approach

2 EXPERIMENTAL TEST PROGRAMME

2.1 Specimen

The focus in the fatigue assessment lied in the appropriate reproduction of the real conditions of welded or non-welded flanges in cylindrical shells. Therefore, large scale test specimens (scale app. 1:2) were realized. The weld quality of the specimens was in reasonable accordance with the existing one in penstocks. The result of the numerical study on the influence of the cylindrical curvature compared to planar specimens is shown in *Fig. 5*.

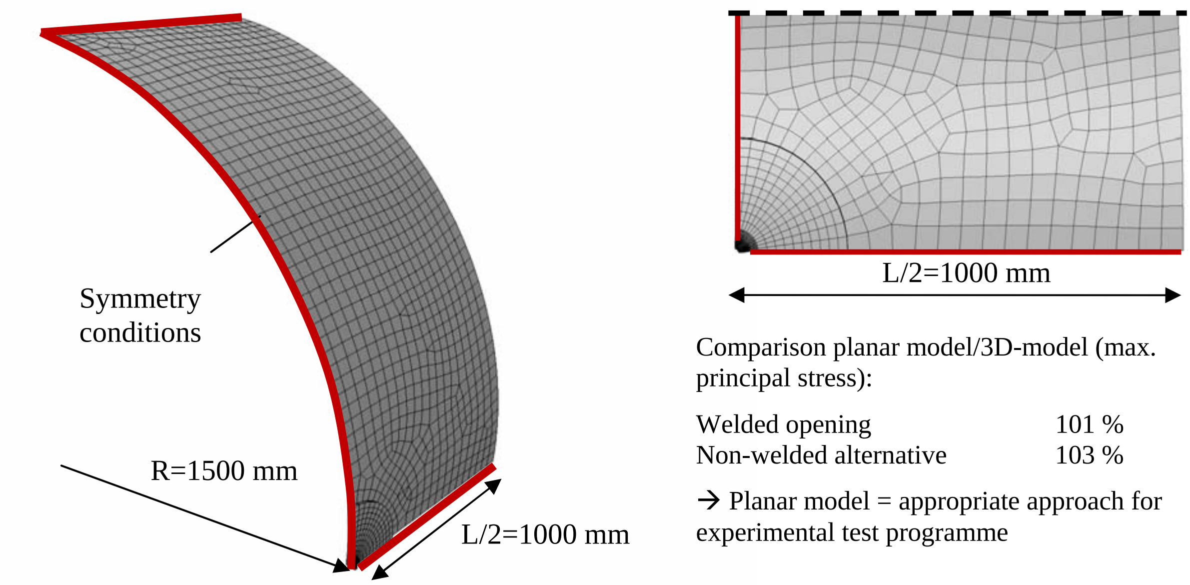


Fig. 5. 3D-shell model of cylindrical steel shielding, diameter D = 3000 mm and length L = 2 m

The comparison between these two models showed, that the planar model always lied on the save side. The maximum difference was 3 % for the max. principal stress, which was acceptable for the decision to adopt only planar specimens for the experimental test programme.

In *Fig. 6* the specimens for the first project period are shown. The flange details *Type A*, *B* and *C* represented different types of reinforced openings, and *Type D* the unreinforced opening. The material grades of the base plate and the welded flange were S 690 as indicated. *Fig.* 6 also indicates the path for the hardness-test of the weld and the onset of the internal thread. The welding was executed in accordance with the welding procedure and the inspection plan [7]. In total 13 specimens were investigated (three pieces per type plus one reference plate with a simple hole). The rolling direction was documented too.

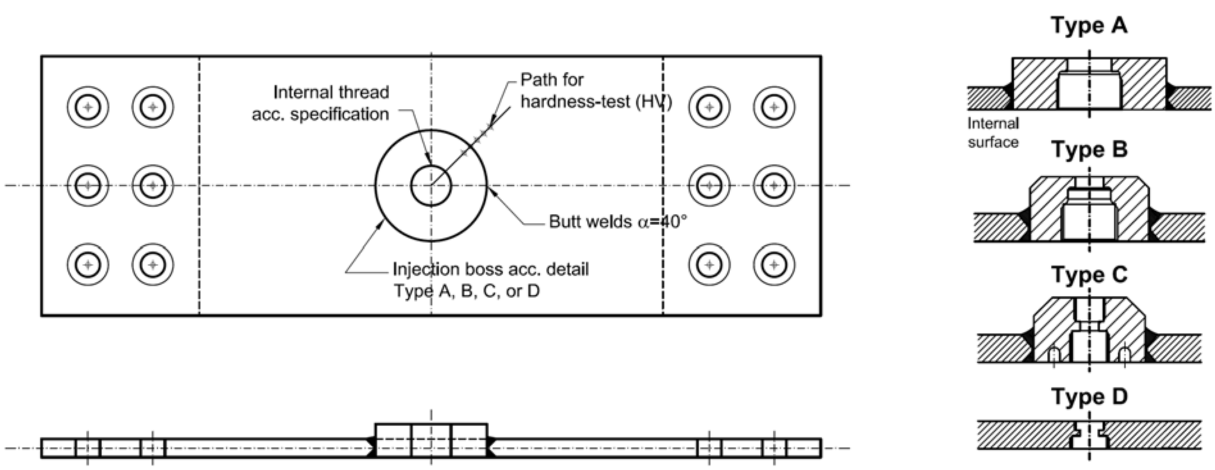


Fig. 6. Specimens used for the test series in the first year

2.2 Laboratory Equipment

In the *Laboratory for Structural Testing* at TU Graz (*LKI*) the cyclic testing was performed on a 1 MN test rig with hydraulic MTS-actuator, see *Fig. 7*. In each test, first static loading with one hysteresis (P_{max} = 930 kN, P_{min} = 30 kN) was applied, then the dynamic loading with constant stress range and frequency 3 Hertz was continued. The maximum load range varied between ΔP = 550 and 705 kN. In total 17.8E+6 load cycles were applied with a stress ratio of R = 0.05. Thereby, one cyclic test (*Type C1*) was investigated with R = 0.2.

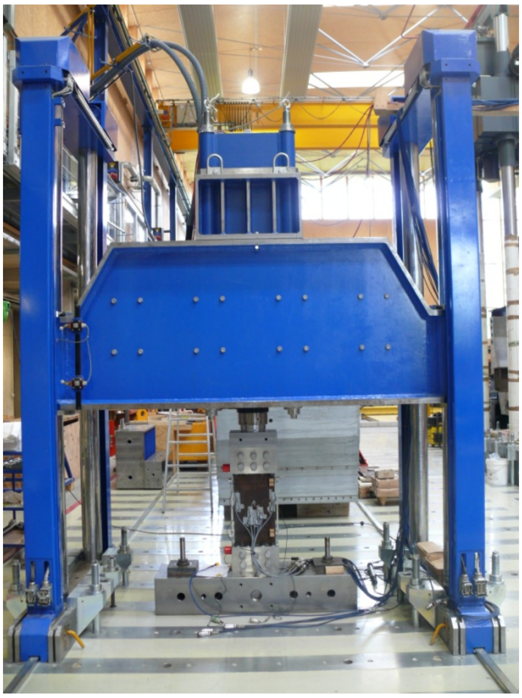


Fig. 7. Test configuration, LKI/TU Graz

Fig. 8. Top and bottom supports

In *Fig. 8* the frictional supports used for the load introduction are shown. Vertical displacement transducers were needed in order to measure the slip (*Fig. 8*). Thereby a maximum slip of 0.2 mm was encountered at P_{max} for the first loading, in the second loading the slip disappeared which confirmed the functionality of the frictional supports. In certain static tests, sliding occurred during the static loading. In such case the surfaces of the frictional supports had to be renewed by sand-blasting SAE 2.5 and then these static tests were repeated without any difficulties.

To detect the crack-opening during the cyclic tests several strain gauges were placed. In *Fig. 9* five strain gauges on the internal surface close to the stress peaks in the circular butt weld (*DMS 4, 5* and *8*) and at the internal thread (*DMS 6, 7*) are shown. The strain gauges in the vicinity of the stress peaks for the outside weld (*DMS 9, 10, 15*) can be seen in *Fig. 10*. All strain measurements refer to a gauge length of 1.5 mm.

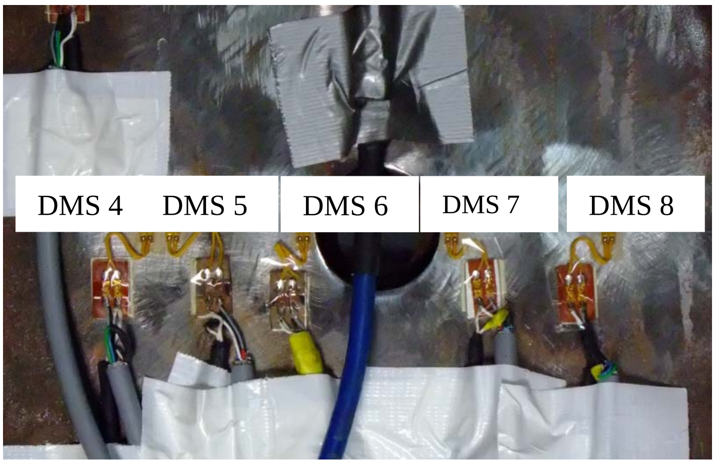


Fig. 9. Strain gauges close to stress peaks at thread and butt welds, internal surface

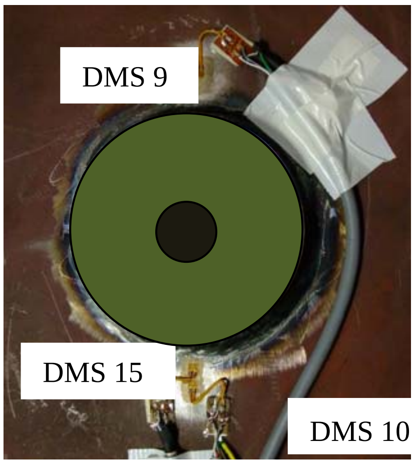


Fig. 10. Strain gauges at butt welds, outside surface

2.3 Crack identification

In the present fatigue investigation the crack initiation was determined by the evaluation of the strain measurements of the gauges closest to the crack openings (*Fig. 11*) and by visual observation using scale magnifier to some extent (*Fig. 12*).

The determination of the initial crack-opening was based on the Δε-N-diagram and by the first derivation of Δε in relation to N of the measured data. Thereby the initial crack-opening could be clearly evaluated. As shown in *Fig. 11* the cyclic test was continued after crack initiation to observe the crack propagation rate for the investigated types. In case of the reinforced openings a crack propagation rate of 1.0 mm/1000 cycles was observed (crack growth outside the flange). The unreinforced openings achieved a rate of 0.8 mm/1000 cycles.

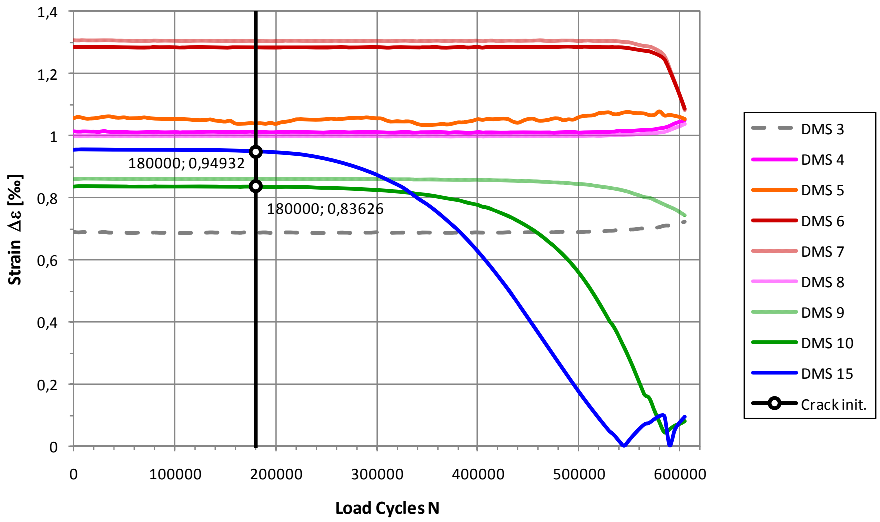


Fig. 11. Δε-N-diagram with crack identification, specimen Type C

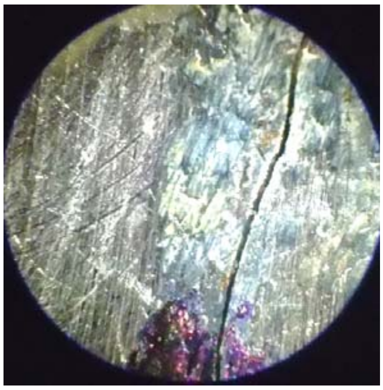


Fig. 12. Crack initiation, opening approximately 0.03 mm

3 FINITE-ELEMENT ANALYSIS

In the present research Finite-Element analysis is indispensable. FE-analysis was adopted to investigate the stress state in the openings by *ABAQUS* [8]. The peak stresses of each type of opening were compared and evaluated. Concerning the HS-stress approach at the welds a stress intensity factor (SIF) of about 1.3 was obtained at the significant positions on the outside surface. Concerning the stress concentration at the internal thread values between SIF = 2.0 and 3.1 were achieved, at other locations without thread values between SIF = 2.3 and 4.4 were found.

First of all, parametric FE-studies were elaborated, and then FE-analyses of the individual specimen types were carried out on basis of nominal geometry. The results of the parametric studies can be found in [7]. The comparison between FE-analyses of the specimens and the measurements during the tests are shown herein, see *Fig. 13*. Due to the effect of welding residual stresses in *Types A*, *B* and *C*, the comparisons were based on the strain amplitudes of the second loading during the static test. As illustrated in *Fig. 13* the relations between the strains of the FE-results and the experiments were in close accordance (max. 8 %), that confirm the appropriateness of the meshing in connection with the chosen element type C3D8R. Due to the fine meshes similar accuracy was found for all four types of specimens.

So, it was achieved that FE-modelling and experimental strain measurements can be used independently for the evaluation of the fatigue limits. This was supported by the fact, as the fabrication tolerances of the specimens were within a limit of 0.1 mm only for the machined surfaces and within 0.2 mm for the thickness of the base plates.

In order to compare the fatigue test results with the structural HS-stress concept, it was decided to refer the evaluation of test results to the relevant numerically derived HS-stresses.

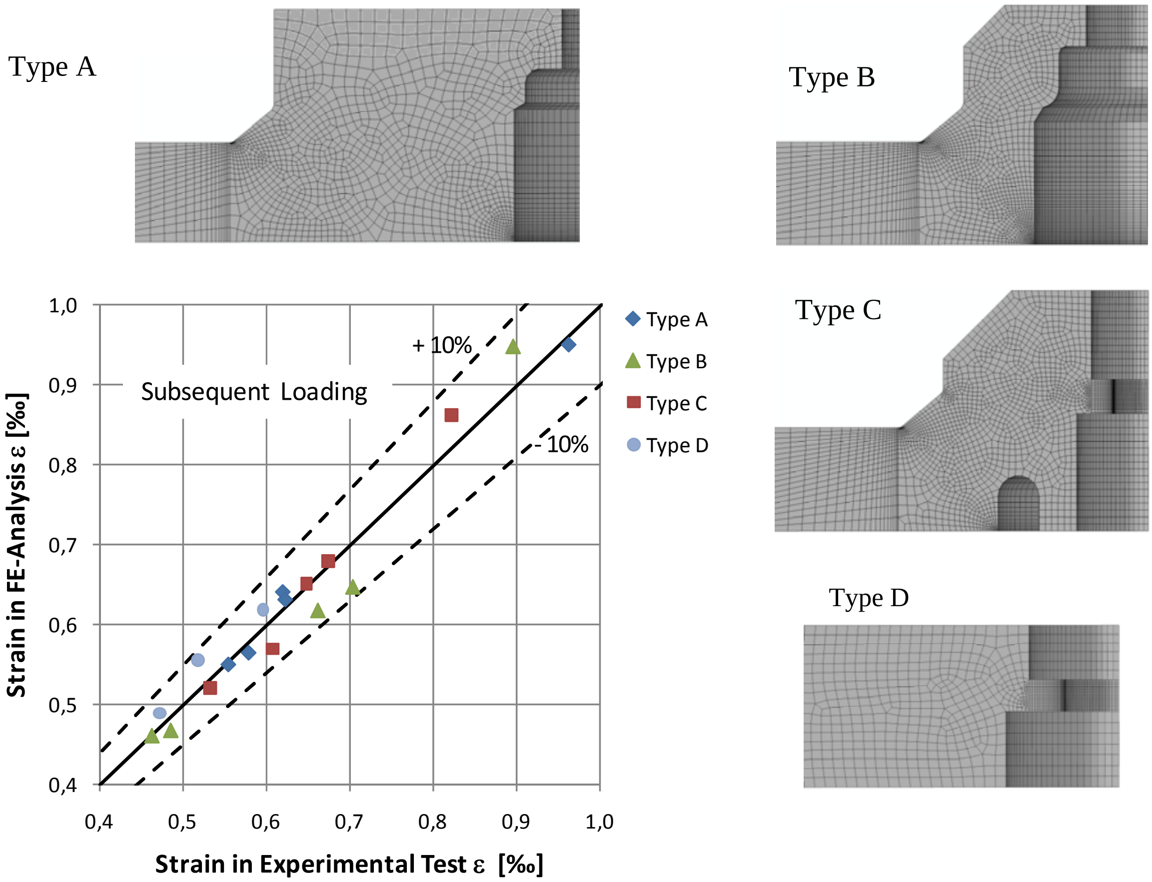


Fig. 13. Comparison of strain gauges with FE-analyses; illustration of mesh for Types A, B, C and D

4 EVALUATION OF TEST RESULTS

4.1 Structural HS-stress – Type A and C

In this section test results of specimen *Type A* and *Type C* are reported. Herein the evaluation is done on basis of the structural HS-stress concept [1], [3]. For each type three fatigue tests were executed with constant amplitude range. As shown in *Fig. 14* and *Fig. 15* the decisive HS-stress at the weld toe exhibits σ_S = 202 N/mm^2 for *Type A* and σ_S = 209 N/mm^2 for *Type C*. The determination of the HS-stress followed the IIW-concept for fine mesh [3]. Further, the effective notch stresses σ_k = 457 N/mm^2 respectively σ_k = 468 N/mm^2 based on r = 1 mm are also shown in *Fig. 14* and *15*. On basis of the stress states it may be estimated, both specimen types will lead to similar fatigue test results.

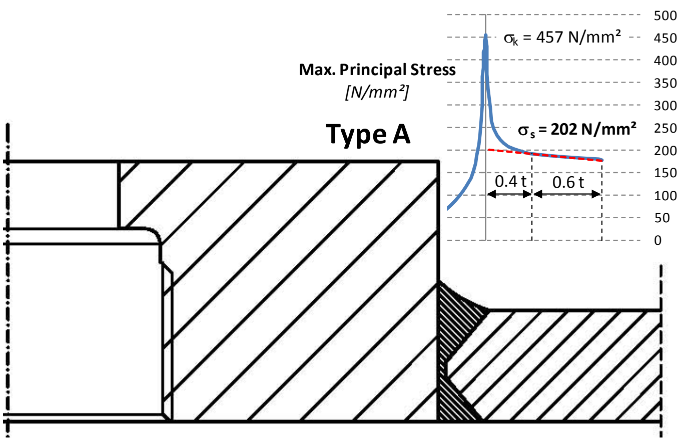


Fig. 14. Structural HS-stress at onset of weld –Type A

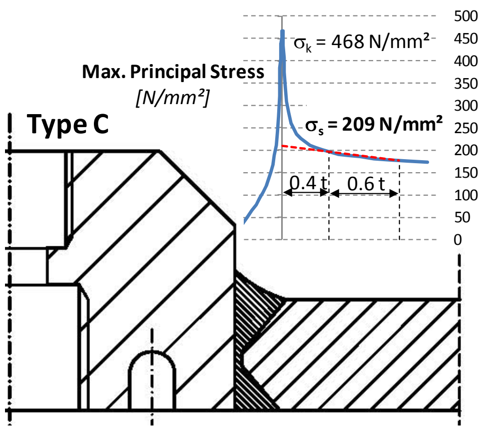


Fig. 15. HS-stress at onset of weld – Type C

4.2 Results of specimens Type A

Similarly to all specimens of *Type A*, crack opening initiated at the stress peak at the onset of the weld, as shown for one specimen by *Fig. 17*. The peak stresses at the internal thread were not decisive for specimens of *Type A*. Thereby crack initiation was documented within a very small scatter between N = 5.4E+5 and 5.7E+5 load cycles (*Fig. 16* and *Table 2*).

It was obtained, that two of the three specimens started crack opening simultaneously at both opposite locations of its maximum HS-stress (*Type A2* and *A3*).

The evaluation of test results on basis of the HS-stress concept led to the minimum fatigue class of $\Delta\sigma_{C,min}$ = 130.7 N/mm^2 for specimens *Type A*, based on m = 3 and N_C = 2.0E+6, which is 30 % higher than the design limit of 100 N/mm^2.

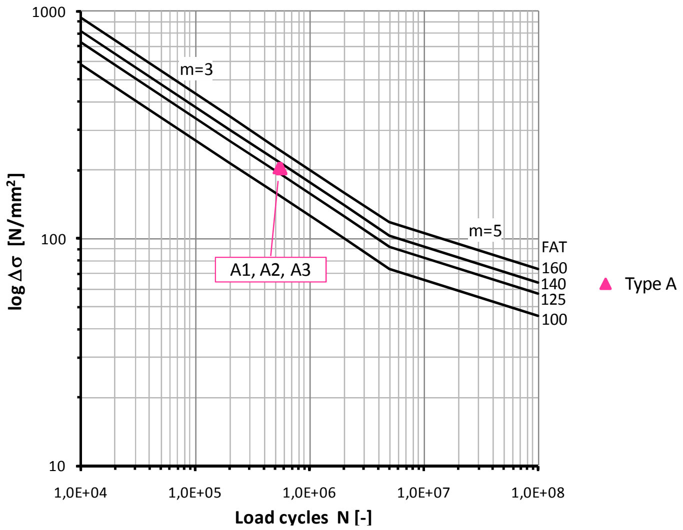


Fig. 16. FAT-classes for structural hot-spot stress, Type A

Fig. 17. Fatigue crack, Type A

Table 2. Table of results, fatigue assessment according to HS-stress concept; Type A

Type/No.	$\Delta\sigma_{S,weld\ (crack)}$ [N/mm^2]	N_{test} [-]	$\Delta\sigma_{C,test(m=3)}$ [N/mm^2]
A1	200.8	570,000	132.1
A2-top	202.9	570,000	133.5
A2-bottom	202.9	535,000	130.7
A3-top	203.2	540,000	131.3
A3-bottom	203.2	560,000	132.9
Minimum	**202.6**	**-**	**130.7**

4.3 Results of specimens Type C

Crack opening initiated at the stress peak at the onset of the weld, as shown for specimen *C1* by *Fig. 19*. However the other two specimens of *Type C* were run outs, one was stopped at N = 2.0E+6 and the other was stopped at N = 8.3E+6 cycles (*Fig. 18* and *Table 3*). Concerning crack initiation a large scatter was found. It may be assumed that different start/stop positions of the circular butt welds and different residual stress states were responsible for the different fatigue results.

The evaluation of test results on basis of the HS-stress concept led to the to the minimum fatigue class of $\Delta\sigma_{C,min}$ = 93 N/mm^2 for specimens *Type C*, based on m = 3 and N_C = 2.0E+6, which is 7 % lower than the design limit of 100 N/mm^2. However the other results (two run-outs for *C2* and *C3*) indicate that a higher fatigue limit can be assumed in general.

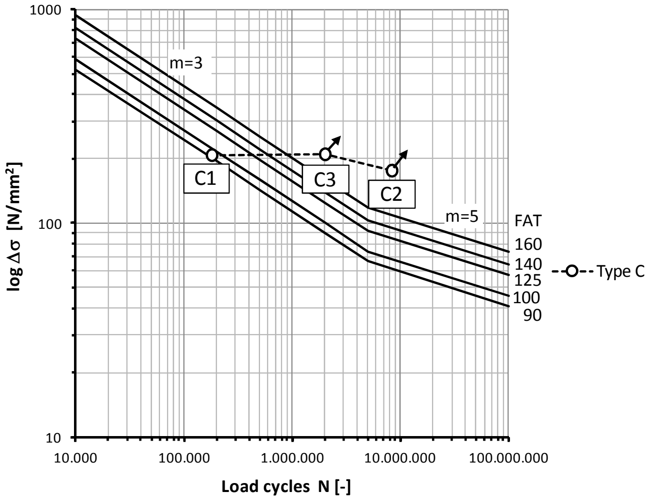


Fig. 18. FAT-classes for structural hot-spot stress, Type C

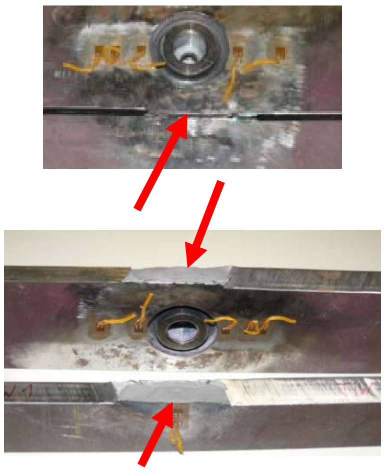


Fig. 19. Fatigue crack, Type C

Table 3. Table of results, fatigue assessment according to HS-stress concept; Type C

Type/No.	$\Delta\sigma_{S,weld\ (crack)}$ [N/mm^2]	N_{test} [-]	$\Delta\sigma_{C,test(m=3)}$ [N/mm^2]
C1	207,4	180.000	93,0
C2* - run out (*..Miners rule)	175,5	8.317.632	282,3
C3 - run out	209,4	2.005.000	209,5
Minimum		**-**	**93,0**

5 CONCLUSION

A report summarizing the outcomes of the entire research project *INJ09* will be published after finalisation of the second-years period by Oesterreichs Energie Research & Innovation. It may be stated, that the given fatigue details on welded flanges made of high strength steel grade S 690 – *Type A* and *C* – reached significantly higher fatigue strength than given by Eurocode 3, however further test results and comparisons with other tests found in literature are needed in order to draw any conclusions for future applications. Further it has to be mentioned; these test results are connected with the applied welding procedure, the specified quality of the base material and the welding, and last but not least with the geometrical properties of the openings and the base plates.

6 REFERENCES:

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