

Experimental and computational fatigue strength analysis of typical penstock welds

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Abstract. In the course of a pumped-storage hydro power project executed by ANDRITZ HYDRO GmbH, fatigue tests were carried out on welded high-strength steel specimens made of S500ML and S690QL. The most common used pipe welds of steel penstocks – the longitudinal butt welds and the circumferential backing-strip welds – were investigated by laboratory testing to validate the required material and welding parameters specified for this project. Another aim was to show that the fatigue evaluation of these main welding details corresponds well to the experimentally derived SN-curves based on the tested specimens. In the best case, it should be shown that prior calculation carried out by means of different stress assessment techniques following guideline-based assumptions - in this case IIW’s “Recommendations for Fatigue Design of Welded Joints and Components” - might be conservative compared to the experimental results. In addition, following questions should be clarified: Does material strength and does welding process influence the fatigue life of the welded components, since these factors may be of economic relevance? The former could be clearly verified for the backing-strip specimens made of S690QL, the evaluations of the fatigue tests showed a significantly higher SN-curve.

1 Brief insight into fatigue strength analysis of penstock welds

1.1 General

Penstocks usually comprise several fatigue relevant structures, a huge quantity of welded pipes (welded together both at workshop and at site) and fewer but geometrically more complex structures, e.g., reinforced bifurcations, transitions, or manholes. This paper focusses on the most common pipe welds – the transverse loaded butt welds (longitudinal pipe welds) and the transverse loaded backing-strip welds (circumferential pipe welds) – indicated in Fig. 1.

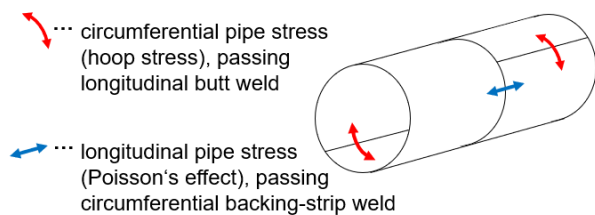


Fig. 1. Characteristic principal stresses passing penstock welds.

1.2 Stress assessment for fatigue evaluation

Analytically based nominal stress assessment is commonly carried out for less complex components by using well-known formulae, like hoop stress formula for circumferential pipe stress and 30% of hoop stress - which corresponds to the stress caused by Poisson’s effect - for axial pipe stress. More geometrically demanding components require finite element analysis (FEA). The latter can be done by using different stress

assessment techniques based on both structural and notch stress concepts, summarized in [1]. The FEA calculations accompanying the present paper are based on the hot spot stress approach or linear surface stress extrapolation technique (refer to [2], [3]) – and on the notch stress or R1-concept (refer to [4]), Fig.2.

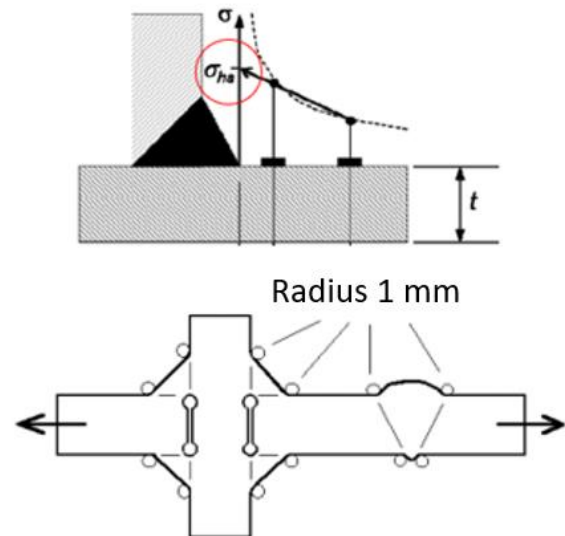


Fig. 2. Top: Linear surface extrapolation (hot spot stress). Bottom: Notch stress concept (R1 concept). Both from [2].

1.3 Determination of equivalent constant amplitude stress range

Since a penstock is subjected to numerous load cycles depending on the operation of the hydraulic machines (here pump-turbines), the determination of an equivalent constant amplitude stress range corresponding to 2 million cycles (refer to [2] and [5])

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simplifies the calculation effort, since a penstock usually extends over hundreds of meters in length. Another approach is the determination of the damage sum in each point and for each welding detail which should be less than 1 for most applications.

The fatigue tests and the calculations of the present study are based on the load spectrum set up for a pumped-storage hydro power project calculated and executed by ANDRITZ HYDRO GmbH. Typical modes of operation are given in Table 1. For each operation mode a certain stress range and its occurring frequency must be obtained – which is sometimes difficult, especially at the beginning of a project, but may be the governing load case scenario for certain structural parts.

Table 1. Penstock load spectrum example.

Load case	Operation mode
1	Start up
2	Shut down
3	Single load rejection
4	Single unit emergency shut down
5	Power plant quick shut down
6	Dewatering

A cumulative stress range is usually determined in the vicinity of the machine's centreline by applying Palmgren-Miner's linear damage hypothesis (explained in e.g. [5]). This equivalent constant amplitude stress range leads to the same damage as caused by the sum of all load cases of a given load spectrum, see Fig. 3. A corresponding pressure variation (Δp) is then determined and distributed linearly along the developed axis of the steel liner, starting at the turbine centreline and approaching in upstream direction along the waterway system.

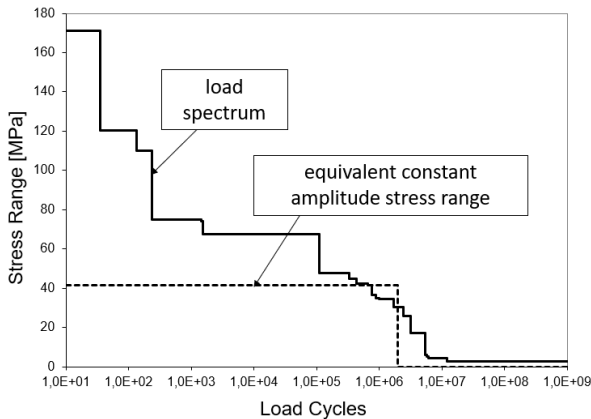


Fig. 3. Graphical example for an equivalent constant amplitude stress range, non-logarithmic scale for load cycles.

1.4 Fatigue verification based on nominal, structural and notch stress

For all points of interest along the penstock axis the equivalent constant amplitude stress range is compared with the corresponding structural welding category or FAT class, see Fig. 4. The common FAT classes ranging from 36 MPa to 160 MPa at 2 million load cycles (compare [2], [5]) are indicated within a rectangle in the SN-curve family ($S \triangleq \Delta\sigma$, $N \triangleq$ load cycles). IIW recommendation [2] defines a “knee point” at $N = 10^7$

for the Palmgren-Miner summation. Above this knee point the SN-curves for welded structures show a slope of $m = 3$ and only for the parent material a slope of $m = 5$. Below this knee-point the curves for welded structures follow a slope of $m = 5$ except for the parent material curve, which follows a slope of $m = 9$ (for variable amplitude loading).

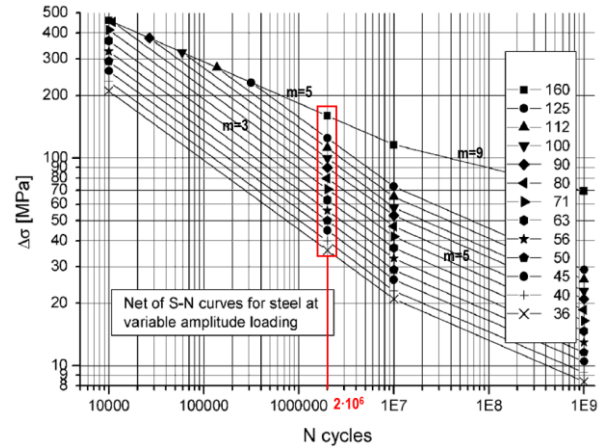


Fig. 4. Fatigue resistance SN-curves of steel for Palmgren-Miner summation, modified from [2].

Similarity is given in [5] but with the difference, that a first knee-point is located at $N = 5 \cdot 10^6$ and a further knee-point at $N = 10^8$, beyond the latter the curves run horizontally, with no further decline.

Moreover, partial safety factors on both resistance and action side and size effects for plate thicknesses exceeding 25 mm must be considered, which leads to a reduced FAT class stress value.

According to IIW [2] a partial safety factor of 1,4 on resistance side (ranging from 1 to 1.4 depending on the damage severity) is considered for penstock weld evaluation in this paper, the factor on action side equals 1.

The most common welded structural details for penstock fatigue evaluation based on **nominal stress approach** are FAT 90 / FAT 112 for non-grinded / grinded butt welds and FAT 71 for circumferential backing-strip welds. The backing-strip welds are mainly used when space around penstock is limited, e.g., when welding from the outside is impossible and hence the pipes must be welded together from the inside against so-called backing-strips (see Fig. 5 for as-built welding details).

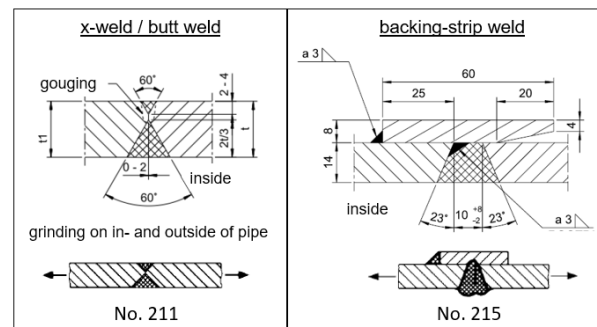


Fig. 5. Project executed main penstock welds and their corresponding FAT class detail.

The corresponding structural details are categorized and described in [2], defined as No. 211 and No. 215, corresponding details can also be found in [5], Table 8.3., with the same stress range value.

The arrows shown in Fig. 6 represent the main or principal stress direction, which is the circumferential pipe stress for FAT 112 and the longitudinal pipe stress for FAT 71 (refer to Fig. 1).

The fatigue resistance category of the backing-strip weld based on **structural stress approach** is FAT 100 according to No. 5 from Table 3.3-1 of [2].

Due to weld improvement by grinding for material yield strength equal or above 355 MPa, the fatigue resistance category for a butt weld and structural stress can be increased to category FAT 125 (see Table 3.5-2b of [2]). Since it is not possible to assess a “structural stress” on a FEA based “flush grinded” butt weld model - because of the absence of any structural discontinuity - the evaluation of this structural detail is only done by analytical nominal stress and FAT 112 (see chapter 3). Otherwise this would lead to fatigue underestimation.

If the stress assessment is carried out on basis of the **notch stress concept**, the applicable FAT class is FAT 225 (refer to Table 3.4-1 of [2]) - independent on the type of the structural detail or on the improvement technique. But one must keep in mind, that the fatigue resistance of the weld toe is additionally limited by the fatigue resistance of the parent material, which is lower than FAT 225 (usually FAT 160 for nominal stress).

The outcome of any calculation based on stress assessment should be, that the existing stress range at any point of interest does not exceed the allowable FAT class stress range which has to be additionally modified by previously mentioned partial safety factors and seize effects.

2 Fatigue tests and test specimens

The Institute of Structural Durability and Railway Technology at Graz University of Technology carried out the laboratory fatigue tests on behalf of ANDRITZ HYDRO GmbH [6] with two universal servo-hydraulic testing machines of the type MFL HUS 60, operating in force control mode. The fatigue tests were based on a constant stress ratio of 0,5. For some weld samples this stress ratio resulted in too much run-outs, hence, in this case the stress ratio was changed to 0,1.

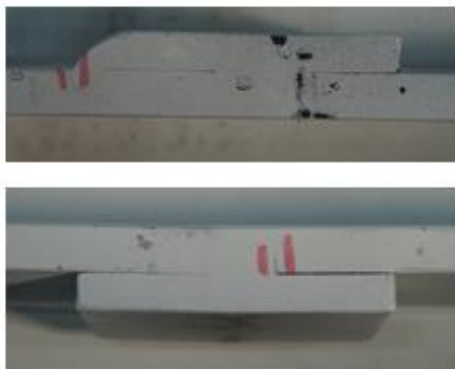


Fig. 6. Test specimens with initiated cracks being marked.

The evaluation of the fatigue tests follows IIW recommendations [2]. The fatigue life of the test specimens was determined by the sum of the elapsed cycles required to initiate a fatigue crack (Fig. 6) by monitoring an increase of the piston stroke over approximately 5%. Run-out was set at 10 million load cycles.

The characteristic values for the evaluation of the test data originating from the test series are calculated following the procedure from [2]. The stress range is taken as the independent variable. The output of the test series are curves with the stress range $\Delta\sigma$ (in MPa) plotted against the bearable load cycles N in double-logarithmic scale, which are then compared with the IIW SN-curves.

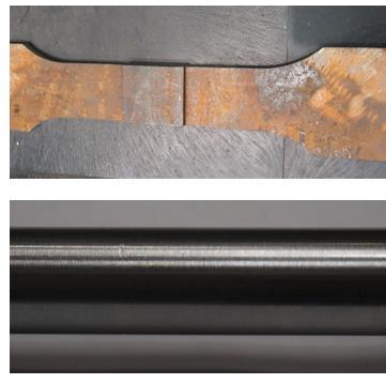


Fig. 7. Backing-strip weld (top) and butt weld (bottom) specimens.

The geometry of the specimens depends on what should be tested and the testing machine. Here, fatigue tension was required (application of axial force). Counter effects are eliminated by an adequate width and length of the samples. For the backing-strip weld samples two flat plates were welded together against a backing-strip and the specimens were cut off (Fig. 7, top). The round specimens for representing the butt welds were made up of circular bars taken from the critical part of the weld of the reference assembly (two plates welded together by X-weld, Fig. 7, bottom). The plate thickness for the backing-strip weld samples (flat plates) equalled 10 mm. The butt welds were represented by round specimens with a diameter of 12 mm.



Fig. 8. Roof formation of 9 mm for round specimens, from [6].

Some round specimens were tested with intentional roof formation (Fig. 8) to include possible calibration effects caused by the bending machine, which is commonly used to bend the flat steel plates to cylinders before welding the longitudinal butt-welds (X-welds).

The steel grades of the plates used for fatigue testing were S500ML (thermomechanical rolled weldable fine grain structural steel) and S690QL (high yield strength structural steel in the quenched and tempered condition, fine grain).

Steel grades and welding processes of all test specimens are summarized in Table 2.

Table 2. Steel grades and welding processes of test samples.

Steel grade	Sample	Nos. tested	Welding process
S500ML	Backing-strip weld	10	FCAW ¹
S500ML	X-weld	10	FCAW
S500ML	X-weld with roof effect 9mm	10	SAW ²
S690QL	X-weld	10	GMAW ³
S690QL	X-weld	10	SAW
S690QL	Backing-strip weld	10	GMAW
S690QL	X-weld with roof effect 16mm	10	SAW

¹: Flux cored arc welding; ²: Submerged arc welding; ³: Gas metal arc welding

3 Computational results

It should be clarified what impact different calculation techniques (nominal, structural and notch stress concepts) have on the safety against fatigue and how much the results scatter with regard to the evaluation technique. In [7] a round-robin study was performed to map scatter (among other things) in fatigue life estimation by predominantly using nominal and notch stress approach. The results scattered tremendously. This behavior was also shown in [1], where the stress assessment techniques combined with different standards or guidelines produced a scatter in results for some structural details.

One problem in terms of fatigue assessment by using notch stress approach on the grinded butt weld detail is the presence of very mild to none notches, for which the R1-concept is not suitable. Because of a missing notch and the consequent absence of any forced stress increase, the surface extrapolation technique is also pointless. Therefore, the computational evaluation of the grinded butt weld is purely analytically based and follows the so-called nominal stress approach.

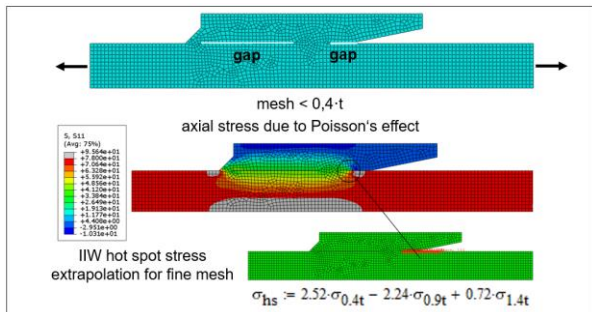


Fig. 9. FEA model for the structural stress analysis.

The backing-strip weld is analyzed by all three techniques. The FEA models for the backing-strip weld are 2D-planar parts. The geometry of the main plate and its backing-strip correspond to the dimensions of the project's penstock section being investigated.

The loading of the models is the axial stress due to Poisson's effect, which equals 30% of the hoop stress at the point of interest.

The maximum principal stresses (S11 in the structural approach model, Fig. 9, and Max. Principal in the notch stress model, Fig. 10) are then taken as basis for scaling the stress ranges for each load case of the load spectrum before the equivalent constant amplitude stress range at 2 million load cycles is determined.

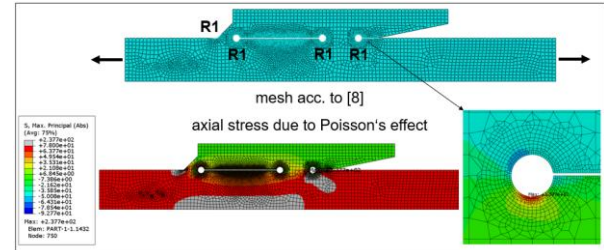


Fig. 10. FEA model for the notch stress analysis.

For each stress assessment technique, the values for the equivalent constant amplitude stress ranges of the backing-strip weld are calculated and added to the SN-curves diagram (Fig. 11). The index "mod" stands for the modified SN-curve including a partial safety factor of 1.4.

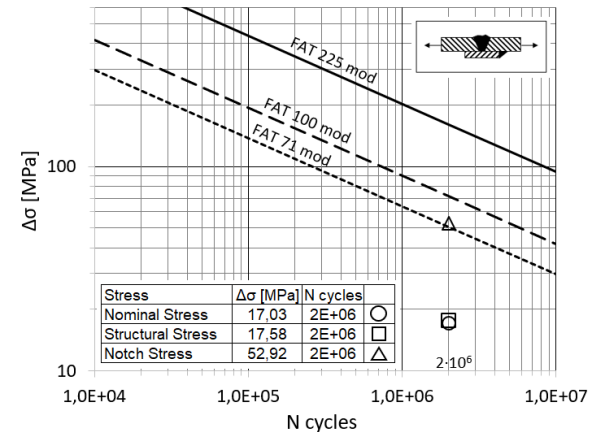


Fig. 11. Calculated equivalent constant amplitude stress ranges within SN-curves for backing-strip weld.

The application of the structural stress concept leads to the least conservative results in terms of safety against modified FAT and is in the range of the nominal stress concept according to its quantity. The safety against modified FAT category is more or less equal for nominal and notch stress concept with 2.98 against modified nominal stress range FAT 71 and 3.04 against modified notch stress range FAT 225.

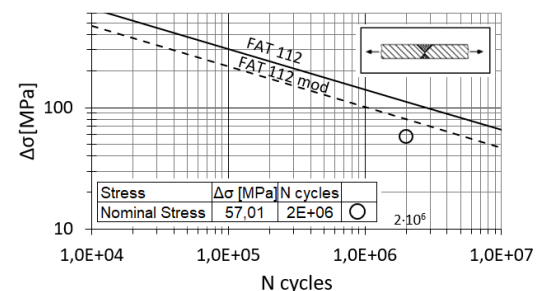


Fig. 12. Calculated equivalent constant amplitude stress range within SN-curves for butt weld.

All three stress assessment techniques fulfil the fatigue verification of the backing-strip weld – with nominal stress assessment being the most effective one since it has the least computational afford.

With respect to the butt weld and its evaluation based on nominal stress only (Fig. 12), the safety against modified FAT 112 category is 1,40.

4 Fatigue test results

The fatigue test results for the backing-strip specimens are presented in Fig. 13 for materials S500ML and in Fig. 14 for S690QL. For comparison reasons the guideline-based category FAT 71 is also added to the diagram.

A new SN-curve with a survival probability of 95%, a slope of $m = 3.5$ and a stress range of approx. 68 MPa at 2 million load cycles can be derived (Fig. 13). This more or less confirms the recommended FAT category of IIW, with a slight tendency to underestimate.

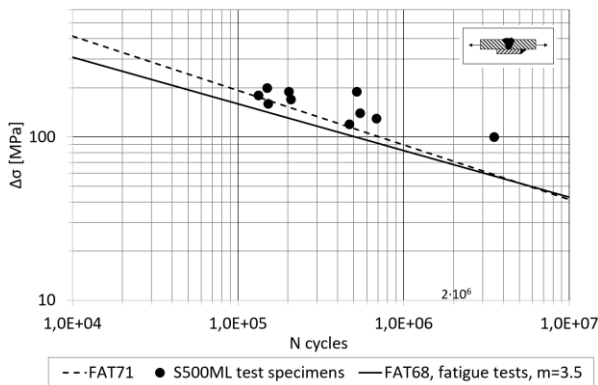


Fig. 13. SN-curve for backing-strip specimens made of S500ML.

For the S690QL test specimens a higher SN-curve can be established, with a slope of $m = 4.09$ and a stress range of 100 MPa at 2 million load cycles. In this case, the experimentally achieved FAT category is well above the guideline-based FAT class (Fig. 14).

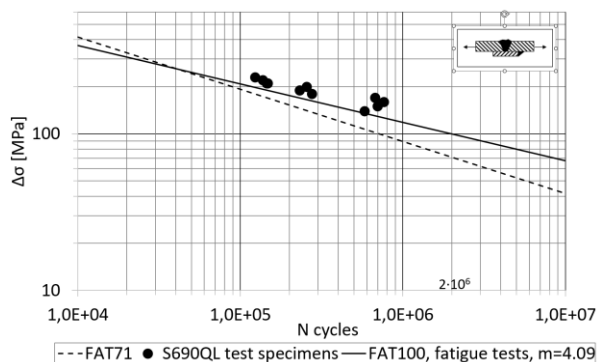


Fig. 14. SN-curve for backing-strip specimens made of S690QL.

As a conclusion, high-strength steel grade S690QL apparently leads to a high achievable FAT 100, whereas the results for S500ML test specimens seem to confirm FAT 71 and are with 68 MPa indeed slightly below. Experiments in [8] on S690 and S1100 butt weld specimens showed a similar behavior – specimens made of higher steel grade achieved higher fatigue strength.

The fatigue test results for the experimentally tested butt weld specimens are presented in Fig. 15 for S500ML and in Fig. 16 for S690QL. Since the parent material fatigue strength might become decisive, the guideline-based FAT 160 category is added to the SN-curve diagrams. The test specimens also include examples with roof formation of 9 mm and 16 mm, without showing significant impact on the fatigue test results, except that higher imposed and impressed bending stress leads to higher stress utilization.

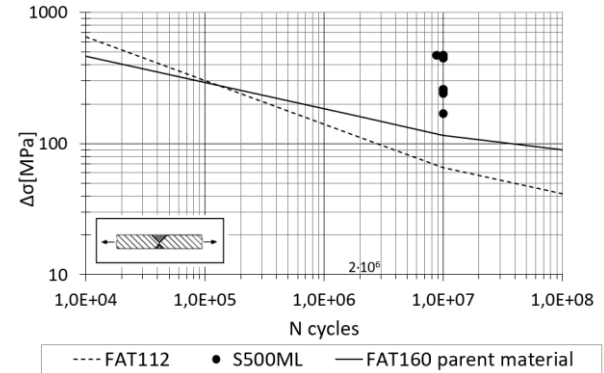


Fig. 15. SN-curve for butt weld specimens made of S500ML.

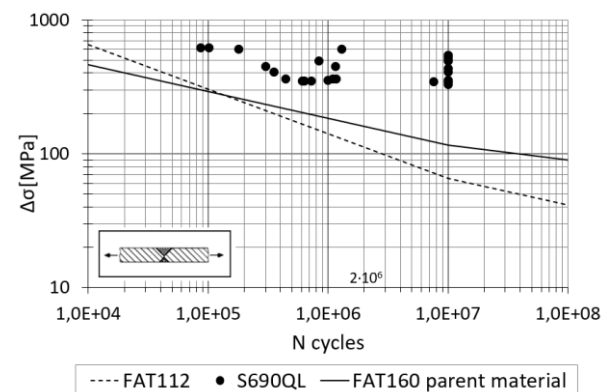


Fig. 16. SN-curve for butt weld specimens made of S690QL.

Although many run-outs do not allow proper SN-curve set up, one conclusion from the tests carried out on the butt weld specimens is that all the results, regardless of material grade, are well above IIW recommended FAT 112. Parent material FAT 160 would become decisive. A slight tendency of S690QL specimens showing higher fatigue strength than S500ML specimens seems noticeable.

Another question needs to be clarified: Is there a connection between fatigue strength and the welding process? Unfortunately, the evaluation depending on the welding process (as indicated in Table 1) scattered too much, a conclusion cannot be drawn.

5 Conclusion and outlook

A clear impact of the material strength on the fatigue resistance is noticeable for the experimentally tested backing-strip specimens. In [9] it is recommended to raise guideline-based FAT classes to a higher level for longitudinal load-carrying welds in beams made of very high-strength steel (S960MC). This also applies to the backing-strip pipe welds made of S690QL of the present

paper. But based on the results of the S500ML test specimens the author would still recommend the application of IIW recommended FAT 71 for this structural detail. This is further emphasized when compared with EN 13445-3 [10], where the backing-strip weld is rated only 63 MPa based on principal stress evaluation.

In a study presented in [11] weld toes of partial penetration welds (e.g., weld toes of lateral stiffeners, cruciform joints) were improved by grinding and experimentally tested. This study confirmed that grinding the weld toe leads to a significant improvement in fatigue strength, even higher than proposed in [2] for improved welds. In [12] butt-welded joints improved by flush grinding are investigated and recommendations for increasing the related FAT category for both EN 1993-1-9 and IIW are given. The authors of [12] further suggest using FAT 125 instead of FAT 112 as recommended by the guidelines. This suggested approach can also be substantiated by the test results of the grinded butt weld specimens of the present study. The results of experiments carried out on longitudinal welds in [13] and [14] also raise the question whether to reclassify certain fatigue details.

A dependence of fatigue strength on the welding process could not be confirmed in the present work.

All three stress assessment techniques applied for the evaluation of the backing-strip weld led to more or less the same results regarding safety against fatigue. A comparison calculation with through-thickness linearization also resulted in similar safety against fatigue (for this assessment technique refer to [15]). This is of great importance since several publications (e.g., [1], [7]) showed a huge discrepancy between the application of different evaluation techniques on several structural details. Not only how to assess the correct stress but also which guideline to be taken for fatigue evaluation may contribute to the scatter in results, as [1] pointed out. And, of course, the geometry of the investigated structural detail contributes more or less to scatter. Although certain guidelines give their preferable stress assessment technique ([2] prefers hot spot stress technique for structural stress assessment, [15] prefers through-thickness linearization technique, [5] makes no recommendation, [10] references to several different structural stress assessment methods) there is still no clear guidance with respect to calculation technique in combination with different guideline safety concepts.

It would be extremely advantageous if both the longitudinal and the circular penstock weld categories were defined too conservatively in the well-known standards and guidelines. If, as is often the case with pumped-storage hydro power plants, the verification against fatigue becomes decisive for certain penstock sections, this would lead to steel weight reduction. Unfortunately, this was not the case for the backing-strip weld specimens. These must be provided wherever it is not possible to weld the pipes from the outside and this is often the case with penstock linings in concreted tunnels.

6 References

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