HIGH-STRENGTH STEELS: LOW-CYCLE FATIGUE BEHAVIOR OF LONGITUDINAL STIFFENERS

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Abstract The extensive database of fatigue tests on longitudinal fillet welds, which have been carried out at the Research Centre for Steel, Timber and Masonry at the Karlsruhe Institute of Technology (KIT) in the last years, is now extended by low-cycle fatigue tests. Fatigue tests on plates with longitudinal stiffeners made of S690QL and S960QL were carried out. Three different base plate thicknesses have been investigated: 8 mm, 16 mm and 30 mm. The results of the low-cycle fatigue tests are analyzed and compared to the previous test results for high-cycle fatigue. A shared evaluation of all tests is made, too. The influence of yield strength on the low-cycle fatigue behavior will be further considered. These results are discussed referring to the classification into the detail categories of EN 1993-1-9 [1] as well as the new IIW guideline [2].

1 INTRODUCTION

The growing demand for high load capacity in steel construction together with the need of decreasing total construction weight can be met by the use of high strength steels. Thereby, overall material costs and carbon footprint as well as weld volume can be reduced. Structures, for which high strength steel is preferentially used, are often exposed to very high alternating stresses. Due to the cyclic load behaviour fatigue becomes the decisive factor for design. Low-cycle fatigue, that usually leads to failure at load cycle numbers below 40.000, is barely investigated and especially for high-strength steels there is nearly no information available up to now.

2 GENERAL

In general, the SN-curve is divided into three parts: low-cycle fatigue (LCF) for numbers of load cycles below 40,000, high-cycle fatigue (HCF) between 40,000 and 10 million load cycles, and very high-cycle fatigue (VHCF) with numbers of load cycles above 10 million, see Fig. 1.

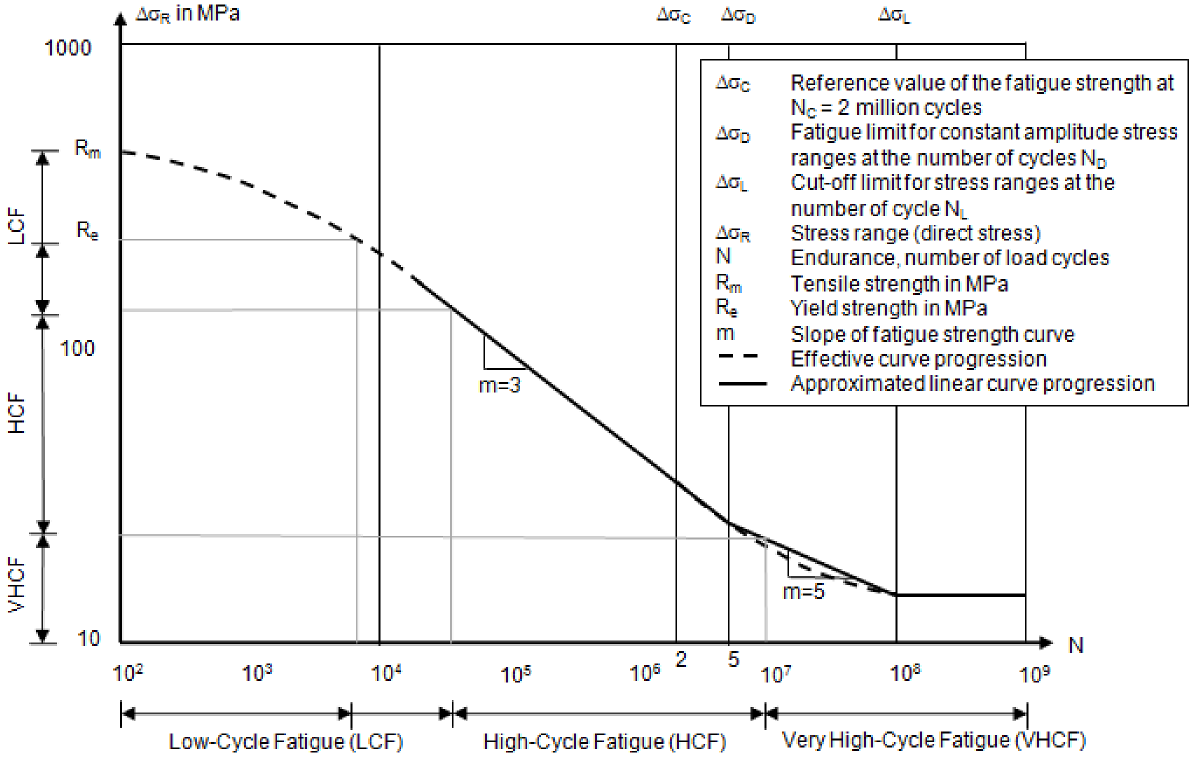

Figure 1. Terms and definitions of fatigue strength

Since in common static analysis, a single stress higher than the yield strength is not allowed, often the yield strength Re is considered to be also the lower limit to low-cycle fatigue [3]. From here on, plastic strains occur.
Another way to separate low-cycle from high-cycle fatigue for ductile materials is by means of deformation criterion [4], which also considers the influence of the stress range ratio.
Conventional standards and recommendations, such as EN 1993-1-9 [1] and the International Institute of Welding (IIW) [2] provide fatigue design S-N-curves starting at 10,000 load cycles. To simplify matters, a linear curve is assumed also below 40,000 load cycles independent of the material yield strength. In recent standards only yield strengths up to 700 MPa are considered.

3 CLASSIFICATION

Longitudinal attachments are often used in crane structures to fix cables or guy anchors. The fatigue behavior of such welded details is dominated by the stiffeners length and the shape of the stiffener and the weld execution. Beneath different shapes of the stiffener, the focus of previous investigation was laid on rectangular shaped attachments, 80 mm and 200 mm long. These research results are now extended by low-cycle fatigue tests, which are presented in the following.
Table 1 shows the classification of rectangular longitudinal attachments according to EN 1993-1-9 [1], IIW [2] and FKM-Guideline [5]5respectively and EN 13001-3-1 [6]. Stiffeners with 200 mm length are classified in FAT 63 according to IIW [2] and EN 13001-3-1 [6], while EN1933-1-9 [1] provides one class below, namely 56 for this detail. For the 80 mm long stiffener all standards provide a FAT class 71.

Table 1. Classification of longitudinal attachments according to recent standards

Detail	EN 1993-1-9 [1]		IIW [2] resp. FKM [5]		EN 13001-3-1 [6]	
Stiffener Length	Length L	Detail Category	Length L	FAT Steel	Length L	$\Delta\sigma_c$
	$L \leq 50$ mm	80	$L < 50$ mm	80	$L \leq 50$ mm	80
11a: 80 mm	$50 < L \leq 80$ mm	**71**	$L < 150$ mm	**71**	$50 < L \leq 100$ mm	**71**
	$80 < L \leq 100$ mm	63				
11b: 200 mm	$L > 100$ mm	**56**	$L < 300$ mm	**63**	$100 < L \leq 300$ mm	**63**
			$L > 300$ mm	50	$L > 300$ mm	56

4 EXPERIMENTAL INVESTIGATION

At the Research Center for Steel, Timber and Masonry, 116 well documented fatigue test results are available for welded longitudinal attachments.

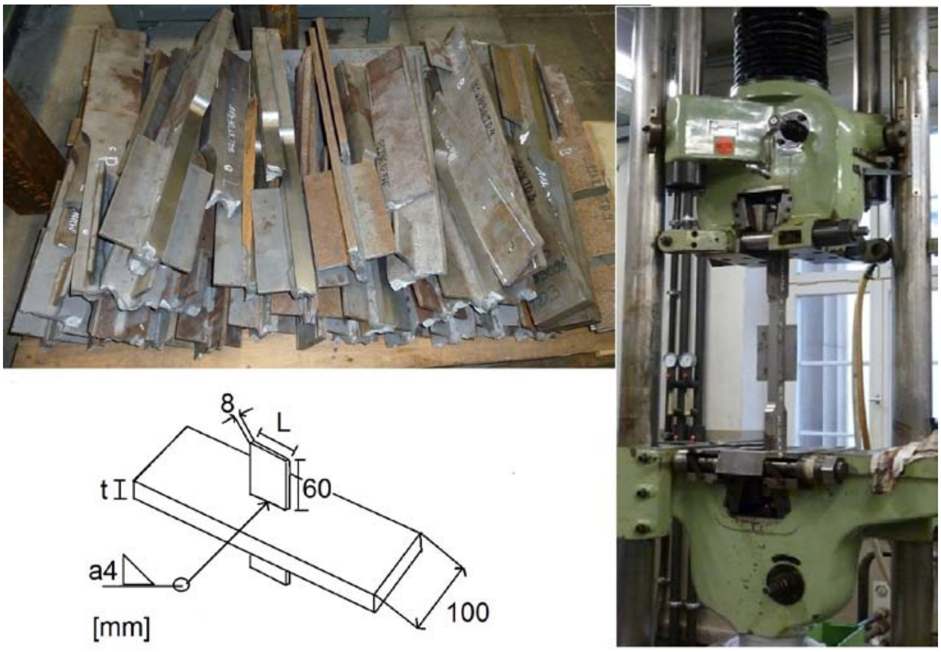

Figure 2. Samples, dimensions and test set-up

Within the research projects P293 [7] and P512 [8], the stiffeners were welded on rectangular hollow sections with wall thicknesses of 4 mm [7] and 5 mm [8] respectively, and tested under 4-point-bending. Stiffeners welded on 8 mm thick plates within LIFTHIGH [9] and on 16 mm and 30 mm thick plates within REFRESH [10] were tested under tension load. To avoid bending in the specimens, the stiffeners were welded on both sides of the base plate.

4.1 Test Program

The samples for the new low-cycle fatigue tests are welded similar to the previous specimens and tested under tension load. Figure 2 shows an overview of failed samples, the geometry of the samples and the test set-up.
On the basis of the available test data, the low-cycle fatigue behavior of two different steel grades (S690QL and S960QL) and three different base plate thicknesses (t = 8, 16 and 30 mm) is investigated. Most of the specimens had a stiffener length L = 200 mm, but also stiffeners with lengths of L = 80 mm are considered. Table 2 gives an overview of the test program. Terex-Demag GmbH, Germany, fabricated all specimens by means of MAG welding. Further information, such as manufacturing instructions and welding procedures, can be found in the final report of P778 [11].

Table 2. Low-cycle fatigue test program

Test series	Dimension [mm]		Steel grade	Number of tests
	Base plate	Stiffener		
11a 16 69	1000x100x16	80x60x8	S690QL	6
11a 16 96	1000x100x16	80x60x8	S960QL	6
11b 8 69	1000x100x8	200x60x8	S690QL	6
11b 8 96	1000x100x8	200x60x8	S960QL	6
11b 16 69	1000x100x16	200x60x8	S690QL	6
11b 16 96	1000x100x16	200x60x8	S960QL	6
11b 30 69	1000x60x30	200x60x8	S690QL	6
11b 30 96	1000x60x30	200x60x8	S960QL	6

4.2 Test Set-up

The presented low-cycle fatigue tests are carried out under alternating tension stress with constant amplitude and stress ratio of R = +0,1. Therefore, a servo-hydraulically test machine (Losenhausen) is used, see Figure 2. The test loads are defined on the basis of previous test results, so that the expected number of load cycles lies between 10,000 and 40,000.

4.3 Test Results

Since for six low-cycle fatigue test results, an extrapolation to the detail category $\Delta\sigma_c$ at two million load cycles is not suitable, the evaluation is made together with high-cycle fatigue test results from previous investigations.
This evaluation is summarized in Table 3. In the first column the name of the test series according to Table 2 is given. In the second and third column the numbers of test results from previous high-cycle fatigue tests and the number of new test results for low-cycle fatigue is given. Bracketed numbers stand for specimens without rupture, so called run-outs. These test results are displayed with an arrow in the S-N-curves. In remaining columns the results of the statistical evaluation is given, where the detail category $\Delta\sigma_c$ at two million load cycles for survival probability P_S at 50% and 95% respectively is given together with the inverse slope m of the S-N-curve. For the evaluation without low-cycle fatigue tests, test results from previous tests of the research projects REFRESH [10], P512 [9] and LIFTHIGH [8] are summarized. In the last columns of Table 3 these results are extended by the new low-cycle fatigue tests and evaluated together.

Table 3. Results of fatigue tests

Series	Number of tests		Probabilistic evaluation without LCF-results, $\Delta\sigma_C$ [N/mm²]			Probabilistic evaluation with LCF-results, $\Delta\sigma_C$ [N/mm²]		
	HCF	LCF	P_S=50%	P_S=95%	m	P_S=50%	P_S=95%	m
11a 16 69	7 (1*)	6	79,5	53,9	3,1	75,3	55,9	2,6
11a 16 96	6	6	63,6	57,9	1,9	69,4	59,3	2,3
11b 8 69	31	6	86,4	63,9	3,3	84,9	63,4	3,2
11b 8 96	12	6 (2*)	58,2	43,6	2,2	58,6	47,0	2,3
11b 16 69	19 (3*)	6	86,6	78,5	2,7	88,8	78,4	2,9
11b 16 96	19 (3*)	6	86,6	78,5	2,7	88,9	79,9	3,0
11b 30 69	8	6	88,0	81,2	2,7	89,3	84,4	2,8
11b 30 96	8	6	88,0	81,2	2,7	88,2	83,3	2,7

*Run-outs

4.4 Discussion

The fatigue behavior of longitudinal stiffeners is dominated by the stiffener's length L. Up to 300 mm, the detail category decreases with an increasing length of the stiffener, see Table 1. Additional parameters investigated here, such as base plate thickness t and steel grade, do not apply to the fatigue design of longitudinal attachments. The test program given in Table 2 facilitates conclusions on the influence of wall thickness and material on the fatigue behavior of longitudinal attachments under high load amplitudes.

4.4.1 Influence of base plate thickness t

In Figure 3 the low-cycle fatigue test results of series 11b, with 200 mm long stiffeners made of S690QL and different base plate thicknesses t = 8 mm, t = 16 mm and t = 30 mm are illustrated. Recent standards classify this detail in category 56 or 63 respectively, independent from wall thickness t, see Table 1. As can be seen in Figure 3, the fatigue test results fulfil the requirements of detail category 63 with inverse slope m = 3.0. In direct comparison of the test series, samples with thicker base plates provide at least the same fatigue resistance than samples with smaller base plate thickness.

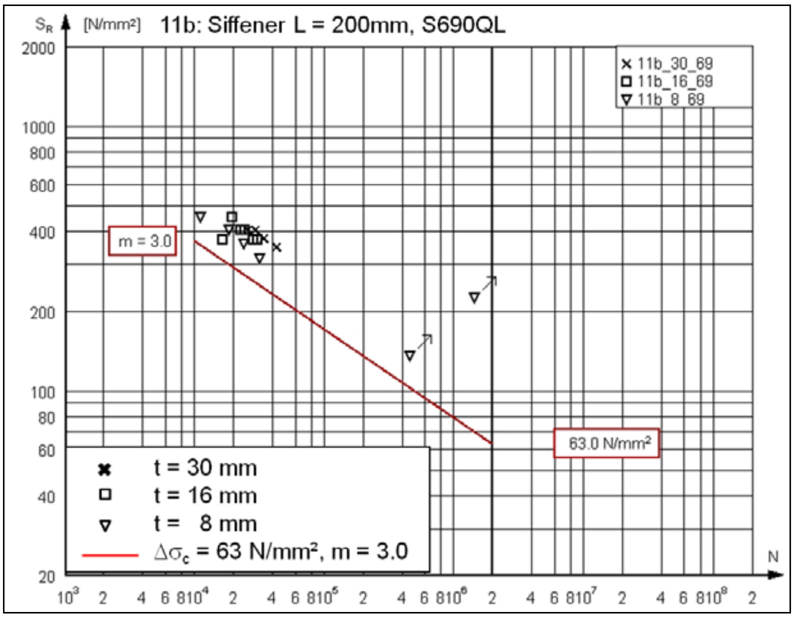

Figure 3. Influence of base plate thickness t of detail 11b (L = 200 mm), S690QL

4.4.2 Influence of length L of the stiffener

The test results of the two investigated different lengths of the stiffener, 80 mm and 200 mm, are compared in Figure 4. Both stiffener types are welded on plates with thickness t = 16 mm and S960QL. As already mentioned above, a stiffener length L = 200 mm is classified in detail category 56 or 63 respectively, stiffener length L = 80 mm in detail category 71. The fact that longer stiffeners provide a lower fatigue resistance is also valid for the low-cycle fatigue tests, see Figure 4. The S-N-diagram in Figure 4 also shows, that both test series fulfil detail category 71 as illustrated in the red curve.

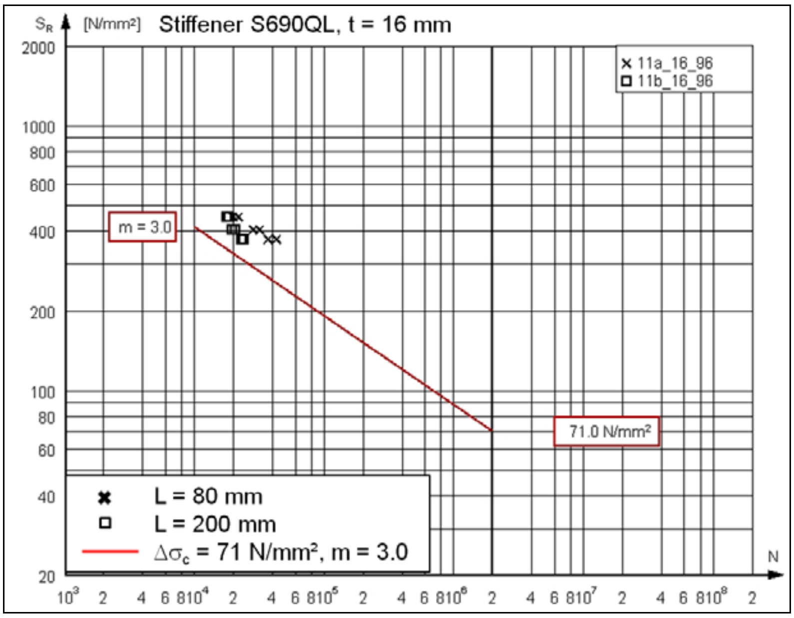

Figure 4. Influence of stiffener Length L for base plate thickness t = 16 mm and S960QL

4.4.3 Influence of steel grade

In the most standards the steel grade does not directly contribute to the fatigue analysis. In EN 1993-1-9 [1] steel grade with yield strengths up to 690 N/mm² are considered. EN 13001-3-1 [6] prefers steel grades with yield strengths up to 700 N/mm. The use of higher strengths steels is not excluded, but the weldability of such steels must be proved and checked. The IIW-recommendations [2] contain steels with yield strengths up to 960 N/mm². The red curve in the S-N-diagram in Figure 5 represents the detail category 71. The given test results all lie above the red curve and therefore fulfill detail category 71. Also for low-cycle fatigue, specimens made of S960QL do not show an advantage in comparison to the ones made of S690QL.

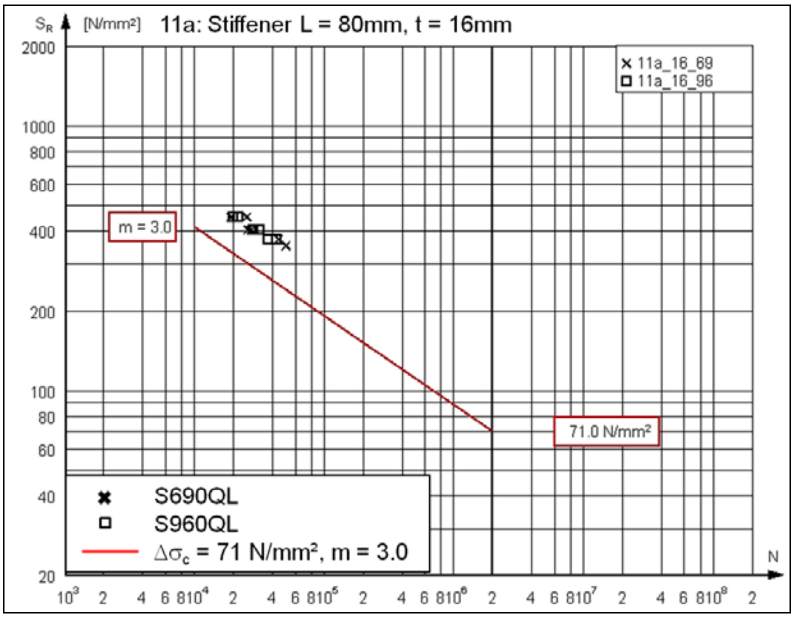

Figure 5. Influence of steel grade of detail 11a (l = 80 mm) with t = 16 mm

4.4.4 Effect of low-cycle fatigue tests on S-N-curve

For the S-N-curves given in Figure 6 test results from REFRESH [10] on 200 mm long stiffeners on base plates with thickness t = 16 mm made of S690QL are taken as a basis. The statistical evaluation of the high-cycle fatigue tests within REFRESH [10] lead to $\Delta\sigma_c$ = 78.5 N/mm² at two million load cycles with free determined slope of m = 2.7. Taking into account the new low-cycle fatigue tests, the detail category at two million load cycles stays constant with $\Delta\sigma_c$ = 78.4 N/mm², while the curve gets flatter with free determined inverse slope of m = 2.9. The low-cycle fatigue test results lie within the scatter of the S-N-curve from REFRESH [10], but all together they are below of the 50% percentile, as can be seen in Figure 6.

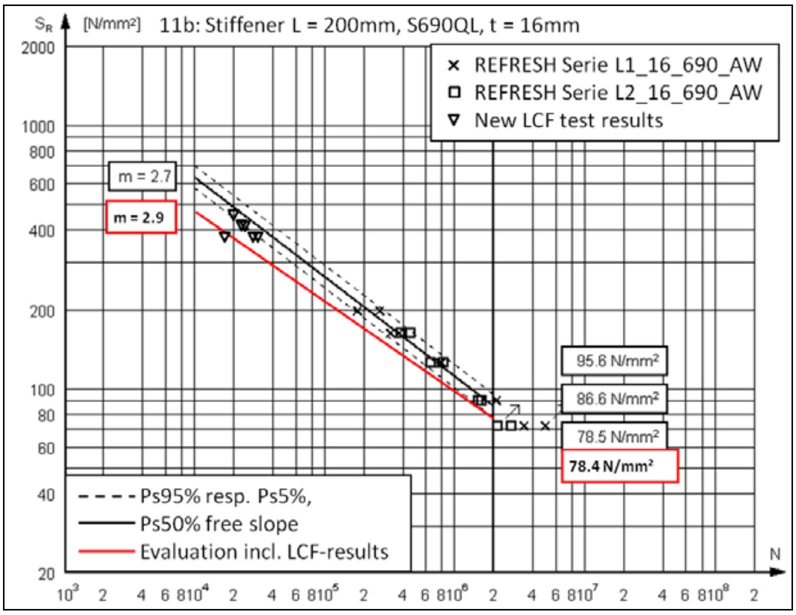

Figure 6. Effect of low-cycle fatigue test results on S-N-curve progression

4.5 Summary

The presented investigations show, that the base plate thickness t, as well the steel grade does not influence the fatigue resistance of longitudinal stiffeners. The fatigue behavior is rather dominated by the stiffener‘s length L. Therefore, in Figure 7 and Figure 8 a summarized evaluation of all test series is made, only divided into the different lengths L = 80 mm and L = 200 mm. To cover the full width from 10,000 up to 2 million load cycles, test results of former research within P512 [8], LIFTHIGH [9] and REFRESH [10] are included.

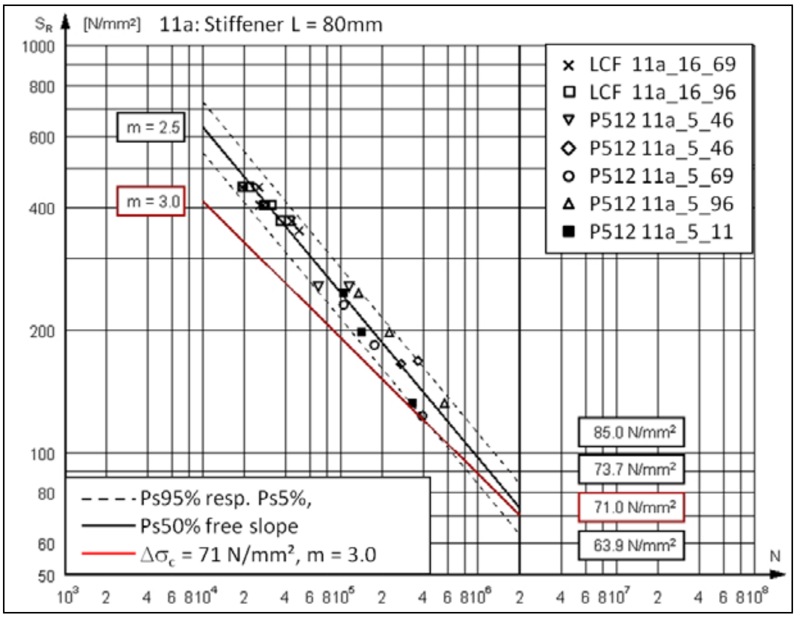

Figure 7. Summarized evaluation for stiffener length L = 80 mm

Fatigue tests on 80 mm long stiffeners results in a fatigue resistance of $\Delta\sigma_c$ = 63,9 N/mm² at two million load cycles. The comparatively low value can be explained by the very steep curve with inverse slope m= 2.5. The red curve for detail category 71 shows, that all test results lie above the detail classification according to recent standards.

The probabilistic evaluation of 200 mm long stiffeners results in a fatigue resistance of $\Delta\sigma_c$ = 70.1 N/mm² at two million load cycles with free determined inverse slope m = 3.0. So, the fatigue test results provide a detail category 63 according to IIW [2] and EN 13001-3-1 [6] and lie remarkably above detail category 56 as required according to EN 1993-1-9 [1].

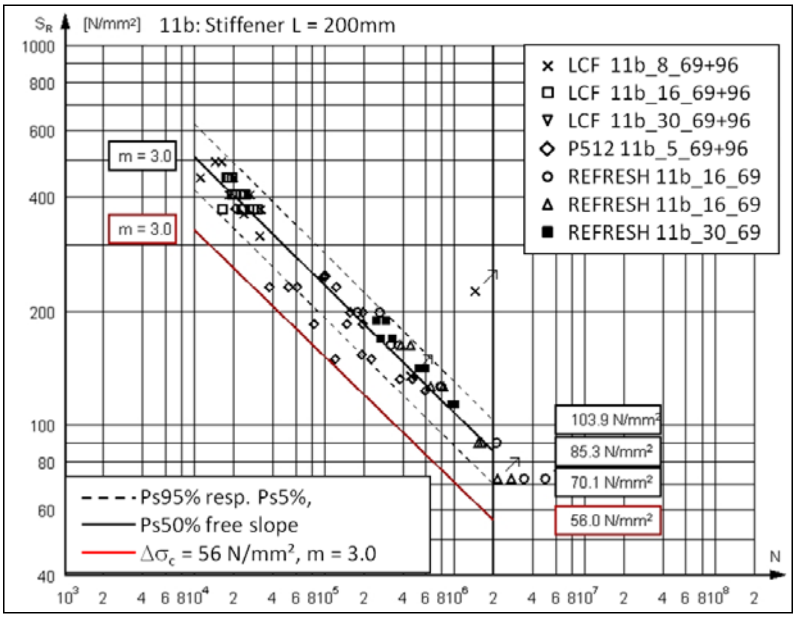

Figure 8. Summarized evaluation for stiffener length L = 200 mm

5 CONCLUSION

The new low-cycle fatigue test results complete previous fatigue test data for the welded detail of longitudinal stiffeners. The fatigue test results confirm requirements of recent standardization, where longer stiffeners provide lower fatigue resistance. Often the test results exceed the standard specification by far.

Also for low-cycle fatigue, no significant influence of the steel grades on fatigue behavior can be detected. The presented investigations allow an equal normative treatment for longitudinal stiffeners made of higher strength steels.

The fact that the new low-cycle fatigue test results lie in the lower scatter band of previous S-N-curves indicates a flatter S-N-curve for high load amplitudes, as shown in Figure 1. Recent test results do not facilitate the determination of a defined range.

As already declared for previous test series on longitudinal attachments, also for low-cycle fatigue the wall thickness of the base plate does not influence the fatigue behavior negatively. New low-cycle fatigue test results do rather indicate a higher fatigue resistance for specimens with thicker base plates. This is due to the fact that larger member sections provide a larger plastic deformability, which gains influence for higher load amplitudes. In addition, the time period from crack initiation to failure is longer for larger wall thicknesses and gains influence for low numbers of load cycles. Furthermore, it is assumed that with larger base plate thicknesses less load is transferred through the stiffener and therefore the stress concentration at the weld toe is smaller. This is also confirmed by accompanying numerical investigations, which can be referred in the final report P778 [11].

The presented evaluation allow a detail classification of the 80 mm long stiffener into category 71 and of the 200 mm long stiffener into category 63 from 10,000 load cycles on for base plate thicknesses up to 30 mm and for yield strengths up to 960 N/mm².

6 FUTURE PROSPECTS

Within the scope of the research project P900, “Erweiterung des örtlichen Konzeptes zur Bemessung von LCF-beanspruchten geschweißten Kranstrukturen aus hochfesten Stählen, (*Enhancement of the local concept of fatigue assessment of welded crane structures of high strength steels in the low cycle fatigue regime*) funded by the AiF German Federation of Industrial Research Associations e.V., an assessment method which is based on the cyclic material behaviour of welded joints under arbitrary functions of load and time and confirmed by way of experiment will be developed. The concept of the reference radius which has been developed for the high cycle fatigue regime may serve as basic principle and it is based on a local approach. But to meet the requirements of the low cycle fatigue regime, it has to be expanded to include elasto-plastic material behaviour. Therefore cyclic material behaviour has to be assessed under constant and variable amplitude loading. By means of stress and strain controlled fatigue tests under constant and variable amplitude loading cyclic material behaviour is assessed in the low cycle fatigue regime and randomly complemented by experiments to determine the influence of TIG-welding finishing treatment and high frequency hammer peening.

7 ACKNOWLEDGEMENT

The authors like to thank FOSTA Forschungsvereinigung Stahlanwendung e.V. for funding, Mr. Heise for administration, Terex Demag GmbH for the fabrication of the specimens and the working team of the research project P778 for support and discussion of the presented investigations.

8 REFERENCES

[1] Eurocode 3: Design of steel structures –Part 1-9: Fatigue; German version EN 1993-1-9:2005 + AC:2009, Beuth Verlag GmbH, Berlin 2010

[2] Hobbacher, A.: Recommendations for Fatigue Design of Welded Joints and Components. IIW document IIW-1823-07 ex XIII-2151r4-07/XV-1254r4-07, December 2008.

[3] E. Haibach, Betriebsfestigkeit – Verfahren und Daten zur Bauteilberechnung, Springer Verlag Berlin Heidelberg, Germany, 2006

[4] H. Gudehus, H. Zenner, Leitfaden für eine Betriebsfestigkeitsrechnung: Empfehlung zur Lebensdauerabschätzung von Maschinenbauteilen, published by Verein zur Förderung der Forschung und Anwendung von Betriebsfestigkeits-Kenntnissen in der Eisenhüttenindustrie (VBFEh) im Verein Deutscher Eisenhüttenleute (VDEh), Düsseldorf, Germany, 2000

[5] FKM-Richtlinie: „Rechnerischer Festigkeitsnachweis für Maschinenbauteile aus Stahl“, Eisenguss- und Aluminiumwerkstoffen. 5. Auflage, Frankfurt/M, VDMA Verlag GmbH, 2003

[6] EN 13001-3-1: Cranes – General Design – Part 3-1: Limit States and proof competence of steel structure; German version prEN 13001-3-1:2010

[7] F. Mang et al., Bemessungsregeln zur Beurteilung des Ermüdungsverhaltens von Krankonstruktionen – Klassifizierung kranbauspezifischen Kerbdetails, (*Design rules for the estimation of the fatigue behavior of crane structures – Classification of crane specific notch details*), Final Report P293, Verlag und Vertriebsgesellschaft mbH, Düsseldorf, Germany, 2000

[8] R. Puthli et al., Beurteilung des Ermüdungsverhaltens von Krankonstruktionen bei Einsatz hoch- und ultrahochfester Stähle, (*Estimation of the fatigue behavior of crane structures when using high strength steels*), Forschungsvereinigung Stahlanwendung e.V., Final Report P512, Verlag und Vertriebsgesellschaft mbH, Düsseldorf, Germany, 2006

[9] O. Lagerquist et al., Efficient Lifting Equipment With Extra High Strength Steel (LIFTHIGH), Final Report ECSC Project 4553, European Comission, Brussels, Belgium, 2006

[10] T. Ummenhofer et al., REFRESH - Lebensdauerverlängerung bestehender und neuer geschweißter Stahlkonstruktionen, (*Extension of the fatigue life of existing and new welded steel structures),* Final Report D761, Verlag und Vertriebsgesellschaft mbH, Düsseldorf, Germany, 2010

[11] T. Ummenhofer et al., Bemessung von ermüdungsbeanspruchten Bauteilen aus hoch- und ultrahochfesten Feinkornbaustählen im Kran- und Anlagenbau”, *(Design of members for crane surtctures made of high-strength fine grained steels under fatigue load),* Final Report P778, Verlag und Vertriebsgesellschaft mbH, Düsseldorf, Germany, to be published 2012