Fatigue behaviour of a welded I-section under a concentrated compression (wheel) load

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Research highlights

- The paper presents fatigue test results of a welded I beam under a concentrated compression (wheel) loading.
- The tests show that in these test specimens the cracks initiate only at the side without stiffeners and grow to about 50 to 60% of the web thickness and then stop.
- The minimum ratio in life between visually observed crack initiation and maximum crack length for cracks which initiated from the weld or weld toe with the web was about 3. For cracks initiating from artificial defects in the flange it was about 5.
- The codes for wheel loading in compression show large discrepancies in effective length and fatigue classes to be used.

Fatigue behaviour of a welded I-section under a concentrated compression (wheel) load

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Abstract

This paper deals with the evaluation of fatigue cracks under a concentrated compression (wheel) load in an I-section with full penetration welds between the web and flange. The objective is to investigate whether cracks stop or nearly stop when they have grown through the residual tensile stress field.

These experimental investigations are part of a review of a crane runway girder where after 20 years of service fatigue cracks were observed in the flange at the toe of the full penetration weld. The fatigue analysis of the actual crane runway girder is described in [1].

The fatigue tests under a concentrated wheel compression loading show that, for the specimens considered on a scale of about 1:2 with stiffeners at one side, the cracks only initiate and grow at the non-stiffened side to about 50 to 60% of the web thickness and then stop. Based only on the nominal stress range under the wheel, determined according to EN 1993-6 and neglecting the shear stress effect, an equivalent fatigue class of about 160 N/mm^2 was found for crack initiation in the web, whereas the minimum ratio in life between visually observed crack initiation and maximum crack length was about a factor 3.

Comparison of the codes for a wheel loading in compression shows large discrepancies in effective width and fatigue classes to be used.

Key Words

Crane runway girder, compression load, fatigue, fatigue cracks, crack growth, residual tensile stresses.

1. Introduction

This paper deals with the evaluation of fatigue cracks under a concentrated compression (wheel) load in an I-section with full penetration welds between the web and flange. The objective is to investigate whether cracks stop or nearly stop when they have grown through the residual tensile stress field.

These experimental investigations are part of a review of a box type radial crane runway girder with full penetration welds between the web and flange where after 20 years of service fatigue cracks were observed in the flange at the toe of the full penetration weld. The observed cracks in the crane runway girder vary in length from a few mm to 330 mm with a summation of the lengths of all observed cracks being 750 mm, on a total length of 56 000 mm, thus being only 1.3%. The fatigue analysis of this actual crane runway girder is described in [1].

Although the external loading by the crane wheels is in compression, due to the residual tensile stresses in the outer layers of the welds the stress ranges at the critical locations at the weld toes are in tension, resulting in the observed fatigue cracks.

A test set-up with a rolling wheel with relatively high loading would result in a complicated test set-up with a low test frequency and consequently would be extremely expensive. That is why tests on a scale of about 1:2 have been carried out with a fixed wheel compression loading, dealt with in this paper, and with a line loading, described in [2].

Based on these results and those which became recently available from the German AIF/Fosta research program [3] by the University of Stuttgart conclusions are drawn regarding crack initiation, crack growth, end of crack growth and the classification.

To the authors knowledge no other scientific work with quantitative information on the fatigue behaviour of I sections with multi-layered welds subjected to external compression loading has been published.

1.1 Stresses under a concentrated wheel load compared to those under a rolling wheel

As extensively discussed by Kuhlmann et al. [3] and Euler and Kuhlmann in [4] a rolling wheel on a crane runway girder produces as shown in Fig. 1, for a particular location a normal stress range $\Delta\sigma$ and an additional local shear stress range $\Delta\tau_{local} = 2\tau_{local\cdot max.}$ This results for every wheel passing in a shift of the direction of the principal stress. Therefore, Kuhlmann et al. [3] state that the summation of the individual damages for normal stresses and shear stresses as used in EN 1993-1-9 [5] and EN 1993-6 [6] is not appropriate for the non-proportional multi-axial loadings as occurring under a rolling wheel.

Under a concentrated wheel loading the local shear stresses τ_{local} at both sides of the concentrated load are proportional to the normal stress range σ_z but are not independent. For a constant wheel load the local shear stress range $\Delta\tau_{local}$ will be equal to $\tau_{local,max.}$ which is half of that under a rolling wheel. Since under a concentrated wheel loading the load is concentrated at one location and the crack(s), grow into a lower-stressed area, the crack growth in length direction will be slower than that under a rolling wheel, resulting in a better behaviour compared to that under a rolling wheel.

2. Test specimens

For the experimental investigations the actual crane runway girder in [1] with stiffeners at one side was simplified to an I-beam specimen. Due to the available plate thicknesses the average scale compared to the configuration in [1] is approximately 1:2. The specimens, shown with dimensions in Fig. 2, were made in such a way that both the top side and the bottom side of a specimen could be used.

The welds between the flanges and the web were intended to be made on scale and were made similar for the top and bottom flange with the web (also the same welding position). Thus, each specimen has 2 test locations A and B. To allow better NDT inspection of the welds, a removable rail was provided on the top flange and to the bottom flange of the specimen. Loading of a specimen at the top (at A in Fig. 2), gives in the weld at the bottom flange (at B) stresses below the cut off limit, which therefore do not affect the fatigue behaviour if the bottom part is tested thereafter. The only asymmetrical parts are the two stiffeners c.o.c. 470 mm that are located at one side only.

The welding procedure specification of the full penetration weld between the web and flange (SMAW process, electrodes, layers, preheating temperature) was carefully specified. Since in the actual crane runway girder prefabricated T sections are used, a horizontal down hand position was used for all welds. Welding distortions were limited during fabrication. Further, as in the actual crane runway girder, the flanges were machined flat from 40 mm to 35 mm. No afterwards heat treatments of the welds and surrounding areas have been used. All specimens were carefully MPA and ultrasonically checked by a qualified inspection company on defects but no positive signals of defects were identified. The procedure and acceptance criteria for the ultrasonic inspection were according to the ASME Boiler and Pressure Vessel Code, (procedure N-UT-ASV-01 rev. A and acceptance criteria according to N-UT-AS VIII-A1+rev.A).

However, after fabrication, it was observed that the foot print of the welds at the connection with the flange was larger than in the actual crane runway girder. This resulted, as discussed later on, in governing crack initiation at the weld toe with the web instead of crack initiation at the weld toe with the flange.

Since the crane vessel was built in the 80’s, some steel types [1] were no longer available. However, the steel types for the test specimen were selected in close cooperation with the steel suppliers to obtain steel characteristics (yield and tensile stresses) close to the original types although the way of manufacturing could not be checked. The dimensions, steel grades and steel qualities of the test specimen of Fig. 2 are recorded in Table 1.

3. Test Rig, Testing Procedure and Measurements

3.1 Test rig

The test rig, shown in Fig. 3, consists of 2 welded box section columns provided with holes and supporting blocks to allow heavy welded transverse beam sections to be fixed at the required levels. The test arrangement is positioned “up-side-down” in the test rig, i.e. the test specimen with the half wheel is positioned above the jack. The "bottom" side of the test specimen is at both sides supported by thick plates on the heavy transverse beams. The jack applies a pushing force in upward direction. Further the scaled half wheel is laterally supported and in this way the test specimen is tested.

3.2 Testing Procedure

Since the welds at both sides were not perfectly the same and the flange thickness also varies, positioning of the specimen and the wheel was generally carried out using auxiliary adjusting devices. This was done in such a way that the strains in the web at both sides at approximately $0.5t_w$, $0.8t_w$ and $1.5t_w$ from the web weld toe (with t_w = web thickness) were about the same, taking account of the exact location. Further tuning was performed by increasing the loads in steps and adjusting the wheel position when required. In this way the specimens were loaded at three pre-loading levels of approximately 1/3, 2/3 and 3/3 of the planned maximum compression load level. After this static tuning procedure, on each specimen three dynamic load tuning tests were carried out at a frequency of 0.1 Hz, 1 Hz and 3 Hz, each during about 20 cycles. After this tuning process the specimen was ready for testing.

3.3 Measurements

The following data were recorded:

- the actual dimensions of the welds at both sides (N and S) of the web, i.e. b_w and h_w in Fig. 4 (N = side with no stiffeners and S = side with stiffeners).
- strains in the strain (strip) gauges (see Fig. 4 for the web) for positioning in the test rig, for comparison with the FE data, for extrapolation to determine the geometrical stress at the weld toe in the web and at the flange and for monitoring crack initiation and propagation.
- number of cycles at the visually observed crack length and NDT crack depth measurements
- visually observed crack initiation and crack length measurements.
- number of cycles at end of crack propagation and at end of test.

4. Load range ΔF and stress ratio R considering the effect of residual stresses

4.1 Effect residual stresses

In the tests, the load range with the stress ratio R has to be such that the effect of local yielding does not lead to such a reduction of the tensile residual stress field that part of it will be in compression.

Depending on the electrodes for the last welding layers and the heat input, at both sides of the web (thickness t_w = 30 mm a residual tensile yield stress f_{ywr} (assumed 500 N/mm^2) may exist over a certain depth t_{wr}. According to the simplified model, shown in Fig. 5, this results in a compression stress $\sigma_{res.}$ at the centre, being:

$$\sigma_{res.} = 2t_{wr} x f_{ywr} / (t_w - 2t_{wr}) \quad (1)$$

The residual tensile yield stresses f_{ywr} at the weld toe with the web is assumed to act at both sides over t_{wr} = 6 mm (for the in-situ situation about 13 mm). Fig. 5b shows that for the actual yield stress of 415 N/mm^2 for the steel in the centre and 500 N/mm^2 for the weld at the sides a compression stress range of 160 N/mm^2 would already result in considerable yielding at the centre.

As shown in Figs. 5b and 5c the final stress variation remains elastic at the outer sides between +383 and +223 N/mm^2 and at the inner side between -255 and the yield stress of -415 N/mm^2. The situation at the connection of the web with the flange is considerably more complicated since the residual stresses are in three dimensional directions. Also FE calculations show that due to the three dimensional stress field, yielding occurs first at the weld toe with the flange.

From Fig. 5a it can directly be concluded that the outer part can take a stress of -500 N/mm^2 before it reaches compression, whereas the inner part can take -82 N/mm^2 up to yield. Thus, to remain at the outer side of the cross section in tension, the maximum applied stress on the cross section follows from (18x(-82) + 2x6x(-500))/30 = (-1476 - 6000)/30= -249N/mm^2. The load ranges in combination with the R ratio used, have been determined in such a way that the maximum stress does not exceed this stress.

4.2 Load range and stress ratio

Based on the above considerations with respect to residual stresses, the stress range in the actual crane runway girder, the thickness effect and the required time for testing, it was decided to use initially a load range of 850 kN. Later on two additional tests were carried out with a load range of 1365 kN.

To keep the load ratio ΔF close to the in-situ situation with R = 0 but also to provide sufficient stability during testing, the compression loading was varied between a loading of -0.05 ΔF and -1.05ΔF, giving an actual load ratio R = (-1.05)/(-0.05) = 21.24. As will be shown below, this results in maximum stresses which satisfy the limit determined under 4.1.

5. Nominal stress ranges according to EN 1993-6

Similarly as in [1, 2], in this paper the analysis of the crane runway girder is based on the "nominal" stress range determined according to EN 1993-6 [6]. The effective length l_{eff} in

Fig. 6 and shown in Table 2 is determined according to [6] for the case that the rail and flange are not connected. According to EN 1993-6 [6] a full connection of the rail and the flange would result in an increase of nearly 1.6 in effective length compared to that of the not connected case, thus to stresses which are about 60% of those determined for the not connected rail to flange case.

The first test (3A) showed that the measured extrapolated geometrical strain (according to [8 or 9]) to the weld toe using E = 2.1×10^5 N/mm^2 was 78 % of that determined by calibrated FE calculations for the case that the rail and flange are not connected. For the other tests, even with more grease between the rail and flange, the measured geometrical strains were about 80% of that of the not connected case. These factors for friction are included in the stress ranges in the last two "grey" columns of Table 2 to determine the "nominal" stress ranges $\Delta\sigma_i$ for the weld toe with the flange and with the web.

According to [6] the $l_{eff,\ web}$ used for the web is equal to $l_{eff\ flange}$ of the flange with a 45° spreading to the weld toe with the web, i.e. ($l_{eff\ flange}$ +2h_w).

In [1] it was shown that, for the actual crane runway girder, where the rail and flange are fully connected, the effective lengths according to EN 13001-3-1 [7] and IIW-XIII [8] were about 15% lower than that according to EN 1993-6 [6]. However, for the tests considered here with the rail not connected to the flange, the effective lengths of [7, 8] are about 50% higher than those determined with EN 1993-6 [6]. In combination with the about 10 to 60 % higher fatigue classes, as further discussed in 7.4, this needs further attention.

6. Test results

6.1 General

Table 3 (5th and 6th column) shows the number of cycles for crack initiation and end of crack growth for the stress ranges corrected for friction (see last two columns of Table 2) and thickness (in bold). Although EN 1993-1-9 does not specifically indicate that for this detail a thickness correction should be applied, for comparable details loaded in tension it is indirectly included in the class which depends on the flange thickness t_f and the weld depth h_w. Other codes or recommendations, e.g. IIW-XIII [8] and the offshore code of DNV [9] give for comparable details loaded in tension a thickness exponent which varies between 0.2 and 0.3.

Therefore, in Table 3, the correction for thickness is based on a thickness exponent of 0.2 for respectively the flange thickness and the web thickness to the reference thickness of 25 mm; the resulting stress ranges (in bold) are further used for the analysis.

For easy comparison of the results, in Table 3 also the equivalent $\Delta\sigma_2$ for the test results is determined being the equivalent stress range at $2x10^6$ cycles assuming an inverse slope of the $\Delta\sigma$-N line of m = 3.

The initial tests 3A and 1A did not show any cracks when they were stopped (respectively at $1.66x10^6$ and $10x10^6$ cycles). For investigation of crack growth in these specimens two symmetrical artificial large defects were made at the weld toe with the flange after which fatigue testing was continued. These modified specimens are designated as specimens 3A-K and 1A-K respectively.

The two symmetrical elliptical artificial defects (notches) in specimen 3A-K, shown in Fig. 7 were made by grinding. They were 3 mm deep, 42 mm long and approximately 1.5 mm wide under an angle of 30º with the flange. For test 1A-K the more precise electrical discharge machining method was used to make smaller symmetric elliptical artificial defects at the weld toe with the flange. The dimensions were reduced to 2 mm depth, 20 mm length and 0.5 mm wide under an angle of 10º with the flange, see Fig. 8.

For comparison with tests 3A-K and 1A-K which were already loaded in fatigue before applying the artificial defects, tests 1B-K and 4B-K were provided with the same artificial defects as test 1A-K but now before loading in fatigue.

All tests 3A-K. 1A-K, 1B-K and 4B-K have been tested with the same load range -0.05ΔF to -1.05ΔF with ΔF = 850 kN, resulting in the calculated nominal stress ranges at the weld toe with the flange, shown in Table 3.

6.2 Tests 3A and 1A with a load range of 850 kN which did not show cracks

The first test 3A was stopped at 1.66×10^6 although it did not show any cracking but the load cell was not functioning properly. Initially, the loading was varied between -42 kN and -892 kN, however, after 2×10^5 up to 6×10^5 cycles the loading changed to about -342 kN and -1200 kN, thus with about the same load range of 850 kN but the R ratio changed. Based on the model discussed in Fig. 5 it could be assumed that the stress range remained within the residual tensile part, thus it may be expected that the change in R ratio had no effect and the test was later on further used as 3A-K.

For the following test 1A the same load range of 850 kN was applied with a ratio R = -892/-42 = 21.2. The test was stopped at 10.8×10^6 and did not show any cracking.

6.3 Tests 3A-K, 1A-K, 1B-K and 4B-K with artificial defects with a load range of 850 kN

As mentioned above, the test specimens 3A and 1A which did not show cracks were provided with artificial defects after the initial fatigue testing, whereas specimens 1B-K and 4B-K were, for comparison, directly provided with artificial defects. Table 4 summarizes the results with regard to the crack development. The visually observed crack initiation started in all tests in the artificial defect at the weld toe with the flange at the N-side of the specimen (N = no stiffeners). At the S-side with stiffeners and at the weld toes with the web no cracks were observed.

The number of cycles at which the crack did not grow any further in depth direction could not always be determined accurately with the NDT measurements from the side. As an example, Fig. 9 shows for test 1B-K a maximum depth, measured from the surface of the web, between 15 and 20 mm which was reached at about $1x10^6$ cycles. The other tests showed a similar crack pattern. As shown in Fig. 10, the visually recorded crack lengths did not grow anymore after 2.0 to $2.2x10^6$ cycles.

Specimens 3A-K, 1A-K, 1B-K and 4B-K were also cut in slices to measure the final crack depth accurately, see as an example Figs. 11 and 12 for test 1B-K. Fig. 12a shows that the crack depth is nearly constant over a long length which agrees with the NDT measurements in Fig. 9 and the crack grew from one side to about 50 - 60% of the web thickness. Fig. 12b shows that at the ends the crack tends to go deeper in the flange following a path perpendicular to the principal strain, with a maximum depth of 18 mm measured from the side of the web.

6.4 Tests 2B and 4A with a load range of 1365 kN with cracks in the welds and web

Since the tests 3A and 1A did not show any cracks at a load range of 850 kN and additional measurements and analyses indicated that a higher load range could be used with the stress range remaining in the residual tensile field, it was decided to do two additional tests (2B and 4A) at a load range of 1365 kN, see Table 5. Both tests showed crack initiation at a start-stop position of a weld layer.

In test 2B crack initiation started at $0.62x10^6$ cycles, only at the N side but as shown in Fig. 13 the crack propagated at one side through the weld into the web and at the other side through the weld into the flange. In this test there was a certain eccentricity that resulted in actual measured stresses at the N-side which were about 25% higher than those at the S-side, which explains the somewhat lower result compared to test 4A. After N = $2.28x10^6$ cycles the cracks, with a total length of 290 mm, did not grow further. From this test specimen no slices were made to determine the exact crack depth because the other side has not yet been tested.

In test 4A crack initiation started at $0.85x10^6$ cycles at the weld toe of the web, only at the N side. The crack propagated at one side into the web and at the other side through the weld into the flange, see Fig. 14. After N = 2.4x10^6 cycles the cracks with a total length of 145 mm and a depth of 17 mm did not grow further.

7. Evaluation of test results

7.1 Weld toe at the flange

The test results of tests 3A, 1A, 2B and 4A in Table 3 can be used for evaluation of a lower bound for the crack initiation at the weld toe of the flange and are shown in Fig. 15. For tests 3A with a stress range corrected for thickness of 141 N/mm2 with 1.66x10^6 cycles and 1A with a stress range corrected for thickness of 158 N/mm^2 with 10.8x10^6 cycles no cracks were observed at the weld toe of the flange.

In tests 2B and 4A the cracks initiated in the welds and grew at a later stage into the flange. Thus using the number of cycles for crack initiation in the welds also for the crack initiation in the flange will be a conservative lower bound. The lowest equivalent stress range for crack initiation $\Delta\sigma_2$ for 2x10^6 cycles is >162 N/mm^2 which can be considered as a conservative lower bound for the flange.

7.2 Weld toe at the flange with artificial defects

For the crack initiation and propagation at the weld toe of the flange with artificial defects the test results of tests 3A-K, 1A-K, 1B-K and 4B-K given in Tables 3 and 4 are used. The tests 3A-K and 1A-K had before the artificial cracks were applied, already been subjected to fatigue loading. That is why they show an earlier crack initiation than tests 1B-K and 4A-K. Further, test 3A-K had a much larger artificial defect, thus as expected, crack initiation started earlier. The maximum observed crack lengths in case of artificial defects, shown in Fig. 10, were in all cases 225 to 240 mm and were reached for all four tests in the range of 2.0 - 2.2x10^6 cycles. The measured maximum crack depths were between 16 and 18 mm and reached at about $1x10^6$ cycles. The results in Fig. 16, show that there is more than a factor 5 between the number of cycles at crack initiation and that at reaching the maximum crack length.

7.3 Weld toe at the web and in the weld

The results for the tests with no cracks (3A and 1A) and those with cracks in the weld (2B) or at the weld toe with the web (4A) given in Tables 3 and 5 are indicated in Fig. 17. This shows that tests 2B and 4A have a somewhat comparable behaviour. Compared to these test results it is surprising to see that test 1A did not show any crack initiation, suggesting a fatigue limit for this case at about $2x10^6$ cycles. The two tests 2B and 4A with nominal stress ranges $\Delta\sigma_i$ at the weld toe with the web of 237 and 241 N/mm^2 give a lowest equivalent stress range $\Delta\sigma_2$ for $2x10^6$ cycles for crack initiation in the weld or web of 160 N/mm^2; test 1A even reaches more than 10^7 cycles without crack initiation, suggesting a fatigue limit close to $2x10^6$ cycles.

The ratio in life between visually observed crack initiation and maximum crack length of about 3 for the weld and web weld toe is considerably shorter than that observed for the flange weld toe with artificial defects.

If according to EN 1993-6 [6] the damage for the shear stress ranges $\Delta\tau_i = 0{,}2\Delta\sigma_i$ would have been considered separately with a fatigue class 80 at $2x10^6$ cycles for 25 mm and an inverse slope of 5 then only the shear stress in the tests 2B and 4A with a high wheel load would have contributed to the damage, resulting in $\Sigma\ n_i/N_i = 0{,}06$.

7.4 Comparison of codes

In this paper the life for visually observed crack initiation is compared with the fatigue class 71 of EN 1993-1-9 [5] with the effective length l_{eff} based on EN 1993-6 [6]. As shown in

Table 6, comparison of these codes with e.g. EN 13001-3-1 [7] and IIW-XIII-XV [8] shows large differences for the effective length l_{eff} to be used and the fatigue class at 2.10^6 cycles.

From the comparison the following conclusions can be drawn:

- For this case with a not connected rail and flange EN 1993-6 gives a very low effective length l_{eff} compared to [7, 8], being about a factor 1.5 lower.

- In case the rail and flange would be connected the effective length l_{eff} according to [6] will increase by a factor 1.58 to 192 mm, being about the same as that according to refs. [7, 8].

- In Ref. [7] and [8] the effective length l_{eff} is independent on the connection of rail and flange.

- The relevant S-N curves in the above codes all have an inverse slope of m = 3.

- The change in slope from m = 3 to m = 5 in all codes is at $5x10^6$ cycles.

- The recommended fatigue classes in EN 13001-3-1 [7] are up to 58% higher and those in IIW-XIII-XV [8] are up to 26% higher than those in EN 1993-1-9 [5] and EN 1993-6 [6].

- Combination of the favourable effects in effective length and fatigue class leads to excessive differences in the analysis and needs further attention.

8. Summary and conclusions

8.1 Visual crack initiation

Although the number of test data is small (3 for the web and 3 for the flange), for the weld toe of the web the lowest equivalent stress range $\Delta\sigma_2$ for crack initiation at $2x10^6$ cycles is 160 N/mm^2 and for the weld toe of the flange 160 N/mm^2 can be considered as a conservative lower bound. This is based on an effective length according to EN 1993-6 and reducing conservatively the calculated stresses for friction by only 0.8.

8.2 Maximum cracks

- All the specimens had stiffeners at one side. The cracks only initiated and grew at the non-stiffened side to about 50 to 60% of the 30 mm web thickness and then stop. The FE calculations, considering the extrapolated geometrical stress, showed that at the non-stiffened side a higher SCF is present.

- The cracks at the weld toe with the web reached the maximum crack lengths between $2.25x10^6$ and $2.40x10^6$ cycles. The cracks at the weld toe with the flange, which had artificial defects, reached the maximum crack depth at about 1.10^6 cycles, whereas the maximum crack length of 225 to 240 mm is reached between $2.0x10^6$ and $2.2x10^6$ cycles.

- The ratio in life between visually observed crack initiation and maximum crack length for the weld and web weld toe was about 3 and that observed for cracks initiating from the artificial defects at the flange weld toe was about 5.

- The crack growth from the artificial defects in test 1B-K with a nominal stress range according to EN 1993-6 of 153 N/mm^2 at the weld toe of the flange showed that after crack initiation, it takes more than $0.6x10^6$ cycles to reach the maximum crack depth at $N \approx 1x10^6$ cycles.

- All crack shapes followed in a certain way a pattern perpendicular to the principal stress.

- The main conclusion is that the fatigue crack growth in multilayered welds due to external compression loading may stop when the cracks have grown to a certain size (this relaxes the residual tensile field). However, the crack depth for cracking at one side only is larger than initially expected for cracks at both sides. This conclusion should be used with care because of the small number of tests per loading case. Cases with cracking from both sides have not yet been observed for the specimens tested.

8.5 Comparison with the line load tests in [2]

- In the line load tests [7] two tests, corrected for thickness a $\Delta\sigma_i$ = 173 N/mm^2 at the weld toe with the web and a $\Delta\sigma_i$ = 112 N/mm^2 at the weld toe with the flange could sustain more than 1x10^7 cycles without cracking in web, welds or flange. However, not sufficient data exist to define a reliable equivalent $\Delta\sigma_2$ for 2x10^6 cycles.

- In case of cracks, nearly all cracks initiated from one side grew to a maximum depth of about 50 to 60% of the 30 mm web thickness and then stop, which agrees with the observation for the wheel load tests.

- The smallest observed ratio between crack initiation and maximum crack was 1.2 for the flange which is considerably lower than the observed factor 3 for the web and welds in the wheel load tests. This is logical considering the stress gradient in length direction.

- The test data of the line load tests [2] also suggest that the fatigue limit under external compression loading is below 5x10^6 cycles which is also shown in the tests with the compression wheel load tests.

- Compared to the line load test data for crack initiation the fatigue class 71 in EN 1993-1-9 [5] and EN 1993-6 [6] seems to be too conservative for multi-layered welded girders loaded in compression.

8.5 Comparison with other codes

Comparison of the codes for a wheel loading in compression shows large discrepancies in effective length and fatigue classes to be used. This can lead to excessive differences in design of welded I sections subjected to compression fatigue loading.

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Abbreviations used

DNV: Det Norske Veritas

IIW: International Institute of Welding

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Fatigue behaviour of a welded I-section under a concentrated compression (wheel) load

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Table 1 Dimensions, steel grades and steel qualities of the test specimens

		Dimension mm	**Steel grade/quality**	**actual f_y** N/mm^2	**actual f_u** N/mm^2
1	half wheel	d = 420	30CrNiMo8 + QT	754	905*
2	rail, top & bottom	185x35	DILLIDUR 400V	792	925
3	flange top & bottom	300x35**	S460G2+M-Z35 (EN 225: 2009)	484	550
4	web	450x30	EH36 (Lloyd Register)	415	550*
5	stiffener	450x135x20	DH36 (Lloyd Register)	417	535*
6	end stiffeners	480x300x20	DH36 (Lloyd Register)	417	535*

**) -average value*
***) - machined from 40 to 35 mm*

Table 2: separately at the end

Concentrated wheel loading; rail and flange separate													corrected for friction	
test	Rail		flange		web		EN1993-6	weld	1993-6	flange	1993-6	web	**flange**	**web**
	b_r	h_r	b_f	t_f	t_w	load range	$b_{f,eff}$	$b_{wl}+t_w+b_{wr}$	$l_{eff\ flange}$	$\Delta\sigma_i$	$l_{eff\ web}$	$\Delta\sigma_i$	$\Delta\sigma_i$	$\Delta\sigma_i$
	mm	mm	mm	mm	mm	kN	mm	mm	mm	N/mm2	mm	N/mm2	N/mm2	N/mm2
3A	185	35	300	34.4	30.3	850	254	41.8	120	169	158	177	**132**	**138**
1A	185	35	300	33.7	30.3	850	254	38.3	119	187	157	179	**149**	**143**
2B	185	35	300	34.4	30.7	1365	254	40.5	120	280	156	284	**224**	**227**
4A	185	35	300	34.0	30.2	1365	254	42.2	120	271	156	291	**216**	**232**
3A-K	185	35	300	34.4	30.3	850	254	41.8	120	169	158	177	**135**	**142**
1A-K	185	35	300	33.7	30.3	850	254	38.3	119	187	157	179	**149**	**143**
1B-K	185	35	300	35.1	30.0	850	255	39.0	122	179	152	187	**143**	**149**
4B-K	185	35	300	34.5	30.2	850	255	43.2	121	163	157	180	**131**	**144**

Table 3 Survey of test results

		$\Delta\sigma_i$ corrected for friction			$(t/t_{ref})^{0,2}$ corrected to 25 mm					
test	load	flange	web	crack init.	end	**flange**	**web**	flange	web	Cracks
	range	$\Delta\sigma_i$	$\Delta\sigma_i$	n_i	n_i	$\Delta\sigma_i$	$\Delta\sigma_i$	$\Delta\sigma_2$	$\Delta\sigma_2$	
	kN	N/mm2	N/mm2	$x10^6$	$x10^6$	**N/mm2**	**N/mm2**	N/mm2	N/mm2	
3A	850	132	138	>1.66	>1.66	**141**	**143**			no
1A	850	149	143	>10.8	>10.8	**158**	**149**	>>158	>>149	no
2B	1365	224	227	0.62	2.28	**239**	**237**	>162	160	weld
4A	1365	216	232	0.85	2.40	**230**	**241**	>173	182	web
3A-K	850	135	142	0.127	2.04	**141**	**143**			flange
1A-K	850	149	143	0.265	2.00	**158**	**149**			flange
1B-K	850	143	149	0.370	2.12	**153**	**155**			flange
4B-K	850	131	144	0.350	2.20	**139**	**149**			flange

Table 4 Test results for tests 3A-K, 1A-K, 1B-K and 4B-K with artificial defects at weld toe flange

Test	Load range	$\Delta\sigma_i$ flange	Crack		Crack at n_i x10^6		Number of cycles	
	(kN)	Corrected for thickness (N/mm^2)	max. depth[1)] (mm)	max. length (mm)	initiation N-side n_i	no crack S-side	at max. depth at	at max. length at n_i x10^6
3A-K	850	**141**	16	240	0.127	-	about 1x10^6 cycles	2.04
1A-K	850	**158**	16	243	0.265	-		2.00
1B-K	850	**153**	18	228	0.370	-		2.12
4B-K	850	**139**	17	227	0.350	-		2.20

Note [1)]: distance from the web surface

Table 5 Test results for tests 2B and 4A with a load range of 1365 kN and cracks in the welds and web

Test	Load range	$\Delta\sigma_i$ in web	Crack		Crack at n_i x10^6		Number of cycles	
	(kN)	Corrected for thickness (N/mm^2)	max. depth[1)] (mm)	max. length (mm)	Initiation N-side n_i	no crack S-side	at max. depth at	at max. length at n_i x10^6
2B	1365	**237**	..	290	0.62	-	not available	2.28
4A	1365	**241**	17	145	0.85	-		2.40

Note [1)]: distance from the web surface

Table 6 Comparison of the effective length l_{eff} of various codes [5, 6, 7, 8] for the specimens used in this investigation.

	EN1993-1-9	**EN 1993-6**	**EN 13001-3-1**	**IIW-XIII-XV**	b_{rail}	t_{rail}	t_{flange}	t_{web}	$l_{eff,f}$	D wheel
Ref.	[5]	[6]	[7]	[8]						
l_{eff}	122*	122*	182**	190**	185	35	35	30	255	420
class	71	71	100 or 112	80 or 90						

* If the rail and flange are connected the effective length will increase by a factor 1.58 to l_{eff} = 192 mm.

** In Ref. [7] and [8] the effective length is independent on the connection of rail and flange.

Table 2 Stress ranges according to EN 1993-6 with the rail and flange not connected

Concentrated wheel loading; rail and flange separate														**corrected for friction**	
test	**Rail**		**flange**		**web**		EN1993-6	weld	1993-6	flange	1993-6	web		**flange**	**web**
	b_r	h_r	b_f	t_f	t_w	load range	$b_{f,eff}$	$b_{wl}+t_w+b_{wr}$	$l_{eff\ flange}$	$\Delta\sigma_i$	$l_{eff\ web}$	$\Delta\sigma_i$		$\Delta\sigma_i$	$\Delta\sigma_i$
	mm	mm	mm	mm	mm	kN	mm	mm	mm	N/mm2	mm	N/mm2		N/mm2	N/mm2
3A	185	35	300	34,4	30,3	850	254	41,8	120	169	158	177		**132**	**138**
1A	185	35	300	33,7	30,3	850	254	38,3	119	187	157	179		**149**	**143**
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1B-K	185	35	300	35,1	30,0	850	255	39,0	122	179	152	187		**143**	**149**
4B-K	185	35	300	34,5	30,2	850	255	43,2	121	163	157	180		**131**	**144**