FATIGUE DESIGN OF CIRCULAR HOLLOW SECTION K-JOINTS WITH GAP

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For high strength steels as well as for sections with large thickness only little information about the fatigue behavior of CHS K-joints with gap is available. It is questionable whether recent design recommendations are valid for the described applications. Therefore, fatigue tests as well as extensive numerical parameter studies are carried out to establish a base for the extension of the application range of common design rules. The nominal stress method as well as the structural stress (hot spot) method are considered. Further instructions for fatigue resistant constructions are given for a safe and an economic design of K-joints with gap.

Keywords: Fatigue; K-joints; circular hollow sections; high strength steels; large wall thickness.

1 Introduction

The typically used joint type in lattice girder design is a K-joint with gap made of circular hollow sections (CHS). To reduce weight and welding costs, also fatigue loaded structures such as jack-up rigs, wind energy converters, cranes or bridges, are more and more made of high strength steels. However, for high strength steels as well as for sections with large thickness only little information about the fatigue behavior is available. The existing and approved design rules have origin in the CIDECT Design Recommendations, which are based on Karamanos et al. (1997) investigations on joints with small wall thickness made of steel with yield strengths of 235 or 355 MPa. It is questionable whether these design recommendations are valid for applications of thick-walled and high strength steels with yield strength up to 700 MPa also.

For this reason, a research project was initiated by the Center of Competence for Tubes and Hollow Sections (CCTH) together with the Research Center for Steel, Timber and Masonry of KIT in Karlsruhe and TNO in Delft (FOSTA P1132 / CIDECT 7AB, 2019). Herein, fatigue tests as well as extensive numerical parameter studies are carried out to establish a base for the extension of the application range of common design rules.

2 Experimental investigations

2.1 *Test program*

Since the publication of CIDECT Design Guide (Zhao et al. 2001), only little further research on the fatigue behavior of K-joints with gap has been published (Schumacher 2003, Kuhlmann et al. 2015). No further systematic efforts have been made to develop new formulae or to extend the validity range of the design graphs and parametric formulae (Herion 2018). Due to that, the experimental investigations of K-joints with gap made of CHS with smaller (“CHS-Small”) and

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with larger sections ("CHS-large") are examined, see Table 1. All K-joints have a brace opening angle of 45°. For the specimens hot-finished, seamless hollow sections (323.9×20 and 244.5×20 in S355 and S700), hot-finished longitudinally welded profiles (193.7×10 and 114.3×6.3 in S355) and cold-formed longitudinally welded sections (193.7×10 and 114.3×6.3 in S700) are used.

Table 1. Test matrix for fatigue tests on CHS K-joints with gap with axial load on the braces

Parameter K-Joints	**CHS - small**	**CHS - large**
Chord $d_0 \times t_0$ [mm]	193.7 × 10	323.9 × 20
Brace $d_i \times t_i$ [mm]	114.3 × 6.3	244.5 × 20
Gap g [mm]	25	40
Eccentricity e [mm]	-3.4	30.9
Width ratio $\beta = d_1 / d_0$	0.59	0.75
Slenderness $2\gamma = d_0 / t_0$	19.4	16.2
Related gap size $g' = g / t_0$	2.5	2.0
Non-dim. eccentricity e / d_0	0.02	0.10
Steel grade	**S355 and S700**	**S355 and S700**

Tests on small CHS K-joints were performed at the TNO Structural Dynamics lab in Delft, Netherlands on a custom produced test frame with single acting jacks at the two braces and at the chord (Hrabowski and Herion 2019).

Large K-joints were tested at KIT Steel and Lightweight structures, Karlsruhe on a Schenck MMC 0105 universal test machine with a dynamic capacity of 5,000 kN.

Here, the test rig acts as a stiff frame, which connects both braces (braces fixed to the frame by bolts and acting as pinned connection). The load is introduced into the chord and similar axial forces in both braces, one in tension, one under compression, is reached.

Due to the high loads and restrictions of the total weight by reason of handling in the lab and smoothly installation and removal of the specimens, the test rig is carefully considered and elaborated.

All tests are carried out load and frequency controlled with axially loaded braces using constant amplitude loads with a stress ratio of R = +0.2. The failure criterion for the tests is a through thickness crack, as usually defined for hollow sections. To enable the verification of subsequent finite-element analysis (FEA), statically loaded tests on specimens prepared with strain gauges are carried out, too.

Twenty-two fatigue tests on K-joints with circular hollow sections made of steel grade S355 and S700 have been carried out in four different test series, see Table 2.

Table 2. Fatigue test series and dimension

Series	No. of	Chord [mm]			Brace [mm]			Gap [mm]	Angle [°]	Steel grade
	tests	l_0	d_0	t_0	l_i	d_i	t_i	g	Θ	
K45_193.7_10_114.3_6.3_g25_S355	8	1800	193.7	10	800	114.3	6.3	25	45	S355
K45_193.7_10_114.3_6.3_g25_S700	8	1800	193.7	10	800	114.3	6.3	25	45	S700
K45_323.9_20_244.5_20_g40_S355	4	1950	323.9	20	1000	244.5	20	40	45	S355
K45_323.9_20_244.5_20_g40_S700	2	1950	323.9	20	1000	244.5	20	40	45	S700

2.2 *Nominal stress evaluation*

As the joint geometry influences the secondary bending moments, a rough assumption for this influence is given in EN 1993-1-9 (2010) and by Zhao et al (2001). Accordingly, for braces of K-joints with gap made of CHS, the nominal stress range in the braces must be multiplied by a magnification factor MF = 1.3 for joints calculated as pinned connections. As the test results include the secondary bending effects, MF = 1.3 needs to be applied to achieve the pure axial load in the braces. The test results then are compared to the standard S-N-curves for detail categories (DC) according to EN 1993-1-9 (2010), Figure 1.

The fatigue resistance of CHS K-joints is dependent on the wall thickness and the wall thickness ratio $\tau=t_i/t_0$, where t_0 is the wall thickness of the chord and t_i is the wall thickness of the corresponding brace. In EN 1993-1-9 (2010) and by Zhao et al (2001), the DC for CHS K-joints with gap is 45 for a ratio t_0/t_i= 1.0 (green) and 90 for t_0/t_i= 2.0. So, large CHS K-joints (K45_323.9_20_244.5_20_g40_S355 and K45_323.9_20_244.5_20_g40_S700) with brace and chord thickness t_0 = t_1 = 20 mm, are represented by DC 45 (green). Fatigue test results of these series barley fulfill DC 45, but they also show a large scatter (Fig. 1).

Values between 1.0 ≤ t_0/t_i ≤ 2.0 can be interpolated, so that for the series K45_193.7_10_114.3_6.3_g25_S355 and _S700, DC 71 with t_0/t_i= 1.6 (red) is valid.

The fatigue tests of series K45_193.7_10_114.3_6.3_g25_S700 have three outliers (marked with an arrow). For specimens with early cracking, the first crack on the surface occurred in the middle of the weld. Since the crack initiation usually occurs at the weld toe, a crack in the center of the weld seam suggests a crack initiation from the weld root. When opening these samples for an inspection of the fracture surface, an insufficient weld penetration could be found as the cause of the root cracks. The statistical evaluation of the 13 remaining tests of series K45_193.7_10_114.3_6.3_g25_S355 and _S700 results in a fatigue strength of 95.5 N/mm² at 2 million load cycles with freely calculated inverse slope of m = 3.7 at 95% survival probability (Fig. 1, black line). With a given inverse slope m = 5.0, the notch class 90 is fulfilled. This is two detail classes higher than EN 1993-1-9 (2010) and Zhao et al (2001) predict with DC 71.

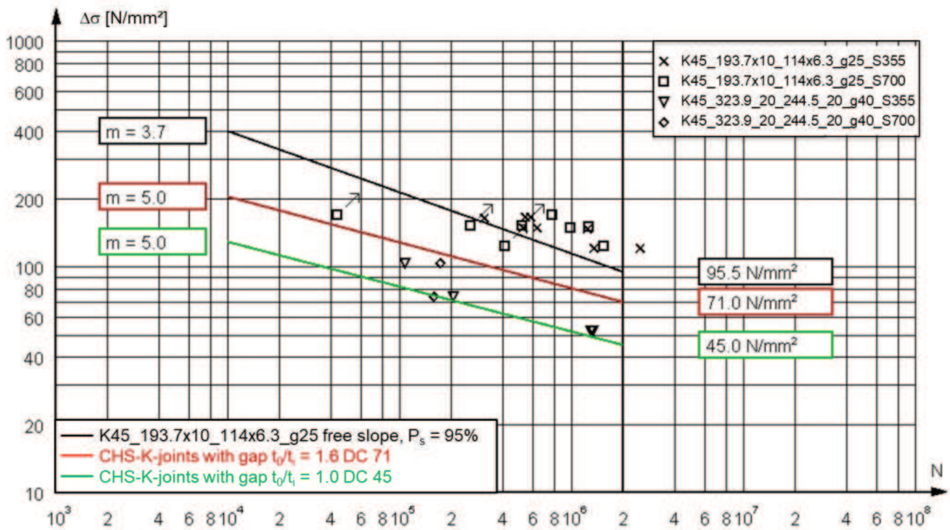

Figure 1. Nominal stress evaluation of fatigue test results on small CHS K-joint with t_0 / t_1 = 1.6

The welds of the specimens for test series K45_193.7_10_114.3_6.3_g25_S355 and _S700 were, in contrast to recommendations in EN 1090-2 (2018), see Fig 2a), not passed around the brace. But as shown in Fig. 2b), the welding starts at the crown heel and runs in one pass over the saddle and the crown toe over the gap and over the crown toe and saddle and ends at the crown heel of the second brace.

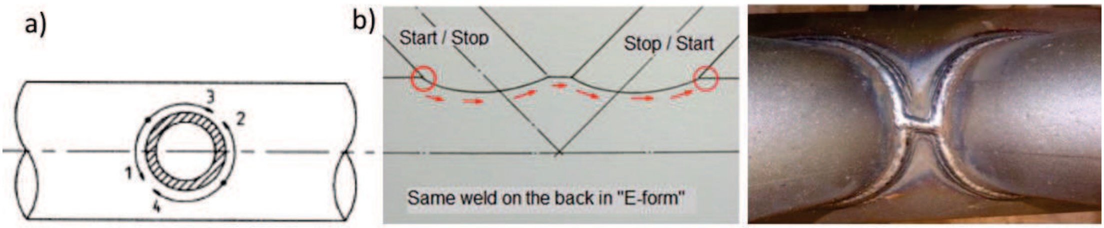

Figure 2. Weld execution for CHS-joints a) recommendation EN 1090-2 (2018) b) implementation.

The welding of the 10 mm thick braces is executed with one root pass and three top layers and weld preparation according to EN 1090-2 (2018). The advantage here is that in the gap region no start- or stop position of the weld is needed. In addition, the highly stressed gap area is reinforced by the multi-layer weld. This results in a shift of the crack initiation from the weld toe on the chord to the weld toe at the brace, as the plot of the von Mises-stresses in Fig. 3 (left) shows. The crack initiation on the brace starts later, as it would do without over-welded gap, but then in the chord. The crack initially moves along the weld seam transition of the brace. After about 25 degrees around the brace circumference the maximum stresses in the chord occurs. At this point, the crack migrates through the weld seam into the chord, see Fig. 3 (right). As a result, the criterion "through-thickness crack" is fulfilled much later and the lifetime of the joint increases.

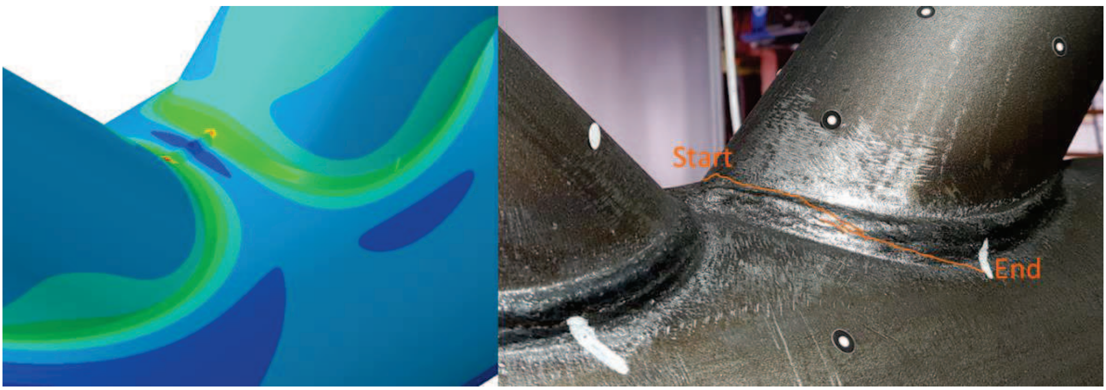

Figure 3. Stress distribution (left) and crack (right) in an CHS K-joints with over-welded gap.

2.4 *Structural stress evaluation*

The nominal stress approach often cannot meet the complex behavior of hollow section joints and the available detail catalogues do not provide enough categories for hollow sections. Therefore, the structural stress method is often preferred, which also accounts for the unequal stress distribution in hollow section joints. The structural stress at the decisive position, the so-called hot spot, includes effects from joint geometry and stiffness and the load case.

The stress concentration factor (SCF) is defined as the structural stress σ_{hs} divided by the nominal stress σnom in eq. (1).

$$SCF = \sigma_{hs} / \sigma_{nom} \tag{1}$$

Zhao et al. (2001), ISO 14347 (2008) or DNV GL-RP-C203 (2016) provide formulae or diagrams for determining SCFs, which can then be used to calculate the structural stress.

In Fig. 4 the load cycles to failure N_f reached during the tests are compared with the load cycles calculated by means of the formulae and diagrams for CHS K-joints with gap and axial load on the brace given in ISO 14347 (2008), which are the same as given by Zhao et al. (2001).

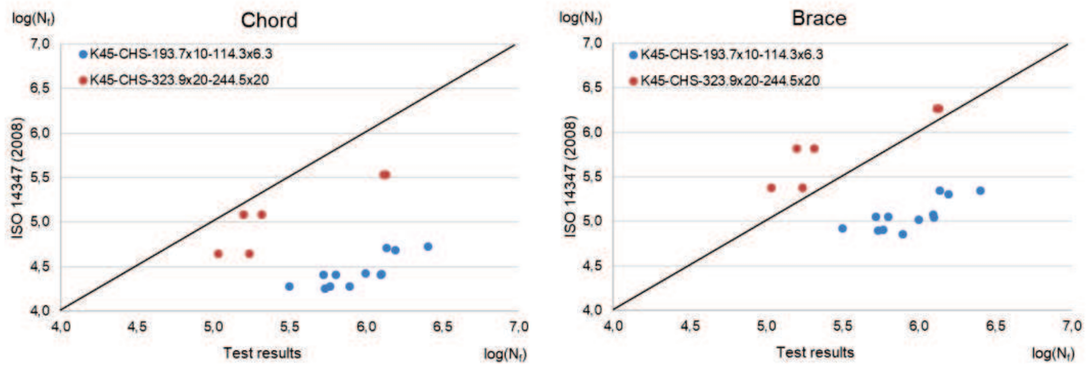

Figure 4. Structural stress approach evaluation acc. ISO 14347 (2008) vs. test results

For the chord, clearly higher load cycles are achieved in all tests than predicted according to ISO 14347 (2008), see Fig. 4, left. For the brace, tests on large samples (red) reached a lower number of load cycles than ISO 14347 predicts, see Fig. 4 right. In principle, these are on the unsafe side, but as all tests showed the crack started not in the brace, but in the chord. So, the chord is decisive for the evaluation of the joint resistance.

The fact that the tests on smaller samples with a chord wall thickness of 10 mm perform much better, can be attributed to better weld seam guidance with over-welded gap, less than to an influence of wall thickness, see chapter 2.2.

3 Numerical investigation

3.1 *Procedure*

Based on the structural stress approach, stress concentration factors (SCF) are calculated via finite element analysis (FEA) by linear extrapolation with finite element package ABAQUS 6.11-1. Parametric studies are carried out to enlarge the investigated dimensional range.

The numerical model was verified by strain gauge measurements carried out on the specimens during the experiments.

Within the parametric study, the weld seam is realized with nominal dimensions depending on the wall thickness of the brace according to the recommendations of CIDECT (Zhao et al, 2000). At the toe and the flank of the braces a HV seam and at the heel a fillet weld is modelled.

The model for CHS K-joints is generated using linear hexahedral elements of type C3D8R and the joint is modeled in its entirety. The connection between the brace and the chord is generated using tie constraints.

3.2 *Parametric study*

Table 3 gives the parameters and their application limits for using the SCF formulas according to Zhao et al. (2001) and DNV GL-RP-C203 (2016) for CHS K-joints with gap. Zhao et al. (2001) is valid for the load case balanced axial loads on the brace (AX). The load cases in-plane bending (IPB) and out-of-plane bending (OPB) of the braces are not included in the CIDECT design guide 8 (Zhao et al., 2001), but part of DNV GL-RP-C203 (2016). IPB and OPB have been also investigated within the parametric study (FOSTA P 1132 / CIDECT 7AB, 2019).

Table 3. Parameter range for SCFs of CHS K-joints with gap

Parameter		Application acc. Zhao et al. (2001)	Application acc. DNV GL-RP-C203 (2016)	Parameter range FEA
Chord slenderness	$2\gamma = d_0 / t_0$	24 – 60	16 – 64	6.5 – 30.7
Thickness ratio	$\tau = t_1 / t_0$	0.25 – 1.0	0.2 – 1.0	0.4 – 1.67
Width ratio	$\beta = d_1 / d_0$	0.3 – 0.6	0.2 – 1.0	0.39 – 0.75
Brace angle	θ	30° – 60°	20° – 90°	35° – 55°
Non-dimensional eccentricity	e / h_0	0		-0.02 – 0.25

In Fig. 5 the SCFs determined by finite element analysis (FEA) are compared to the SCFs determined according to Zhao et al. (2001). The SCFs for the chord (left) are far on the safe side. The comparison of the SCFs for the brace on the right side in Fig. 5 shows a pronounced horizontal scatter resulting from the minimum value for the brace SCF as a function of the brace angle Θ (SCF_{Min} = 2.3 for Θ = 45°). The outermost point with $SCF_{br,AX,FEA}$ = 2.91 of the brace by FEA is determined for a joint with eccentricity of e/d_0 = 0.25, which is outside the application range of the CIDECT recommendations (Zhao et al., 2001).

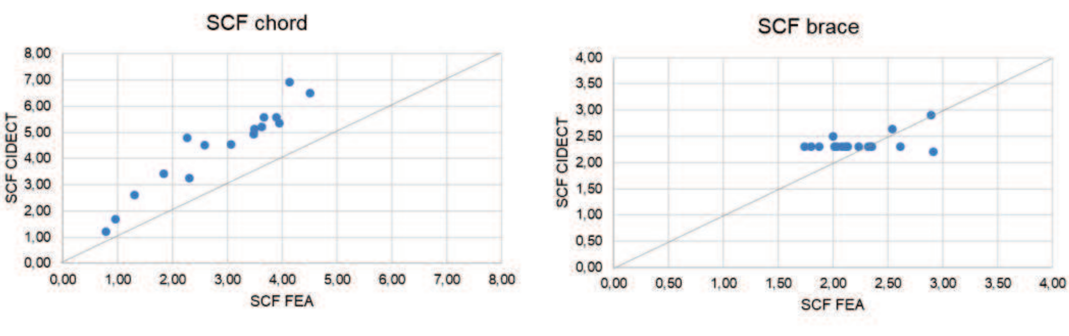

Figure 5. Comparison of SCFs by FEA with SCFs according to CIDECT (Zhao et al., 2001) for balanced axial load on the braces

The comparison of the chords SCFs by FEA to SCFs from DNV GL-RP-C203 (2016) in Fig. 6 shows a much better match, with the values still on the safe side.

Comparing the FEA SCFs with SCFs according to DNV GL-RP-C203 (2016) for the brace at the right side of Fig. 6, also some variability can be seen, but with values mostly on the safe side. The two outliers represent CHS K-joints with large wall thicknesses and a chord slenderness of $2\gamma << 16$, which is not covered by the application range of DNV GL-RP-C203 (2016).

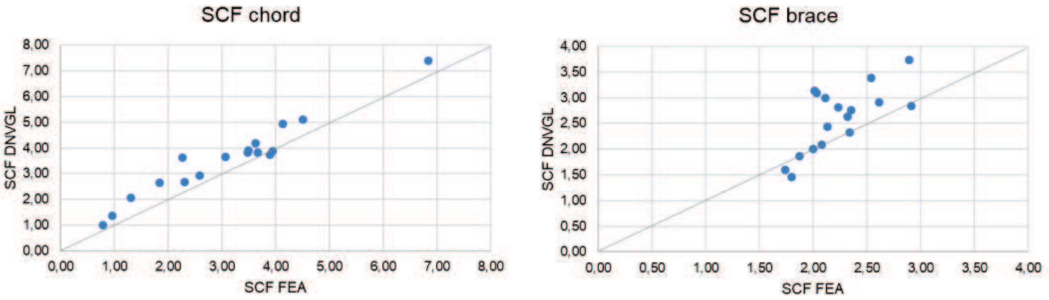

Figure 6. Comparison of SCFs by FEA with SCFs according to of DNV GL-RP-C203 (2016) for balanced axial load on the braces

4 Design Recommendations

The evaluation of the parameter study on CHS K-joints under axial load on the brace shows that the CIDECT recommendations by Zhao et al. (2001) provide conservative SCFs compared to DNV GL-RP-C203 (2016) and the SCFs of FEA. Since DNV GL-RP-C203 (2016) has a larger scope of application, it is reasonable to use these formulae.

The recommendations for the selection of the geometry parameters for CHS K-joints are summarized in Table 4.

Table 4. Recommendation for the design of CHS K-joints with gap.

Parameter	Chord		Brace	
Brace loading	AX	IPB and OPB	AX	IPB and OPB
$\tau = t_i / t_0$	small 1)	small 1)	small 1)	small 1)
$\beta = b_i / b_0$	(large) 2)	(small) 2)	(large) 2)	(small) 2)
$2\gamma = b_0 / t_0$	small 3)	small 3)	small 3)	small 3)
Θ	small	small	small	small

1) thin t_i and thick t_0 2) minor influence 3) thick t_0

For the structural design of the CHS K-joints under fatigue loading, it is recommended that the wall thickness of the brace is chosen thin (small τ-value) in relation to the chord wall thickness, and the chord section should be thick-walled (small 2γ value). The smaller the parameters τ and 2γ are, the lower are the SCFs and thus more favorable for the fatigue design for the three load cases AX, IPB and OPB. Regarding the width ratio β, which has rather small influence, it is advisable to select large β-values for the load case AX and small β-values for the load cases IPB and OPB. In addition, the SCFs decrease with decreasing brace angle θ, so a small angle between the brace and chord is more advantageous, but under consideration of the eccentricity, which should be chosen as small as possible.

5 Conclusions

The fatigue test results for hollow section K-joints are in good accordance with the detail classes given in Eurocode 3-1-9 (2010), which is also valid for joints made of higher strength steel grades S500 and S700 and wall-thickness up to 20 mm.

Beneath the dimensions and the geometrical parameters, the fatigue resistance of CHS K-joints with gap is also depending on the weld execution and shape. This is not considered in the design rules but can be used to build fatigue loaded structures with higher resistance. So, for the CHS K-joints with over-welded gap, the fatigue resistance could be increased by two classes from DC 71 to DC 90.

The structural stress evaluation of CHS K-joints under axial load on the brace shows that the recommendations by Zhao et al. (2001) are partially conservative. Since DNV GL-RP-C203 (2016) has a larger scope and provides SCF-formulae for the load cases in-plane and out-of-plane bending of the braces, this is recommended for design.

The fatigue strength of hollow section joints strongly depends on the dimensionless parameters, what should already be considered in the planning by selecting appropriate parameters. By careful planning and execution, fatigue-proof hollow-section constructions can be realized, which is also valid when using high strength steels.

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