FATIGUE BEHAVIOUR OF TUBULAR K-JOINTS WITH THICKWALLED CHORDS

U. Kuhlmann[1], Ö. Bucak[2], I. Mangerig[3], B. Kranz[4], M. Euler[1], M. Hubmann[1], A. Fischl[2], R. Wagner[3], J. Herrmann[4], R. Zschech[4]

[1] Stuttgart University, Stuttgart, Germany/ [2] Munich University of Applied Sciences, Munich, Germany/ [3] Universität der Bundeswehr, Munich, Germany/ [4] Schweißtechnische Lehr- und Versuchsanstalt Halle, Germany

Abstract. Thickwalled tubular trusses with welded uni- or multiplanar K-joints under fatigue loading are frequently used in many infrastructure facilities such as bridges, cranes and offshore structures. Due to the stress concentration around the brace-to-chord intersection, the hot-spot-stress method has to be used in order to verify such structures. As a consequence the fatigue evaluation has to be performed with structural instead of nominal stress ranges. However, this method can only be used efficiently for design purposes if appropriate fatigue strength values are available. Unfortunately, the existing design rules lack these values for the scope of thickwalled trusses with multiplanar K-joints ($4 \leq \gamma = r/t \leq 12$). This paper is going to present the outcome of a still on-going, comprehensive research project where thickwalled K-joints are tested under different basic load cases such as chord axial loading, chord bending, brace axial loading, brace bending. As an innovation the investigation focuses on a particularly efficient weld configuration that consists of a full-penetration weld at the crown toe of the K-joint shifting into a fillet weld at the crown heel.

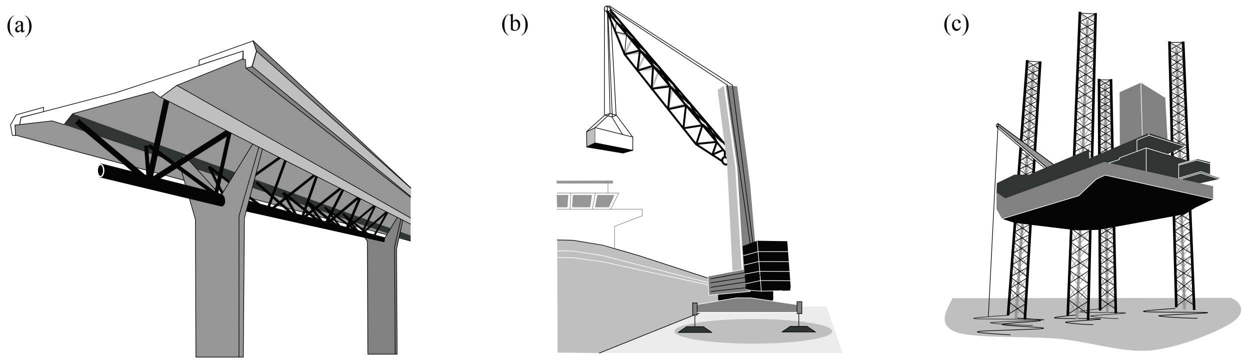
1 SCOPE

1.1 Applications

Thick-walled tubular trusses with welded K-joints under fatigue loading are frequently used in many fields, **Figure 1**. Member intersections in tubular trusses are called uniplanar K-joints if two diagonally oriented, equally inclined braces meet the chord member. If four braces intersect the chord in a symmetric pattern, the joint is referred to as multiplanar K-joint or KK-joint, **Figure 2** a,b.

1.2 Cast joint versus weld joint

Principally, it is possible to fabricate K-joints in tubular structures by means of cast steel elements which all truss members are welded on, **Figure 2** d. A cast steel joint shows a high degree of geometric flexibility. Especially in case of many braces that have to be connected with the chord. Furthermore, the welding of cast steel joints is easier since all connections are plain butt welds. On the other hand, the number of connections within the chord is greater compared with the welded K-joint due to the cutting of the chord before and behind each cast steel element, **Figure 2** c, d. Thus, the chord exhibits more locations of potential failure (redundancy). Additionally, the fabrication of the cast steel elements is time-consuming and expensive.
The direct welding of the braces to the chord member forms an alternative that is supposed to be focused in this paper. Welded K-joints have got some essential advantages over cast steel joints. Firstly, the direct connection of the braces and the chord saves the cast steel elements and, consequently, reduces the costs. Secondly, the fatigue behavior of the



$4{,}0 \leq \gamma = r_0/t_0 \leq 10{,}0$ $5{,}0 \leq \gamma = r_0/t_0 \leq 9{,}0$ $\gamma = r_0/t_0 \leq 8{,}0$

Figure 1. Applications of tubular K-joints with thickwalled chords: highway bridge (a), mobile harbour crane (b), leg structures of jack-up platforms (c)

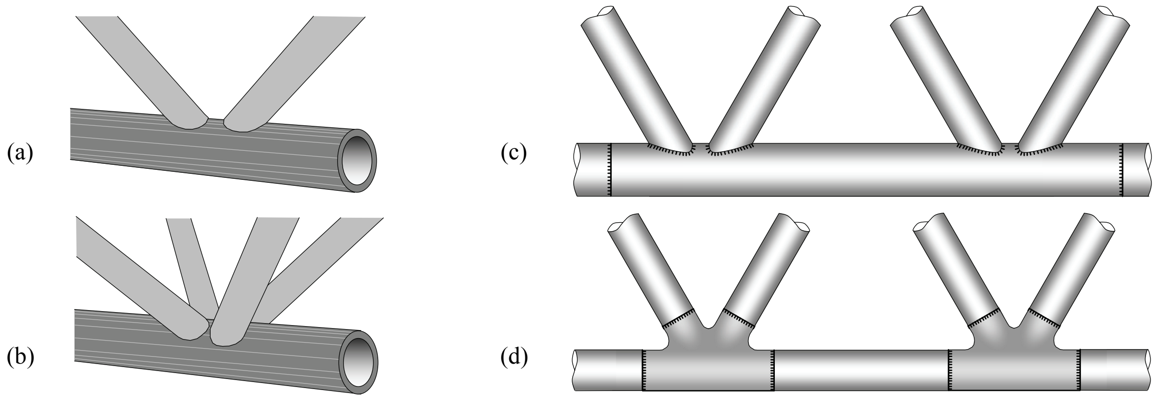


Figure 2. Uniplanar (a) and multiplanar K-joint (b), welded K-joints (c), cast steel joints (d)

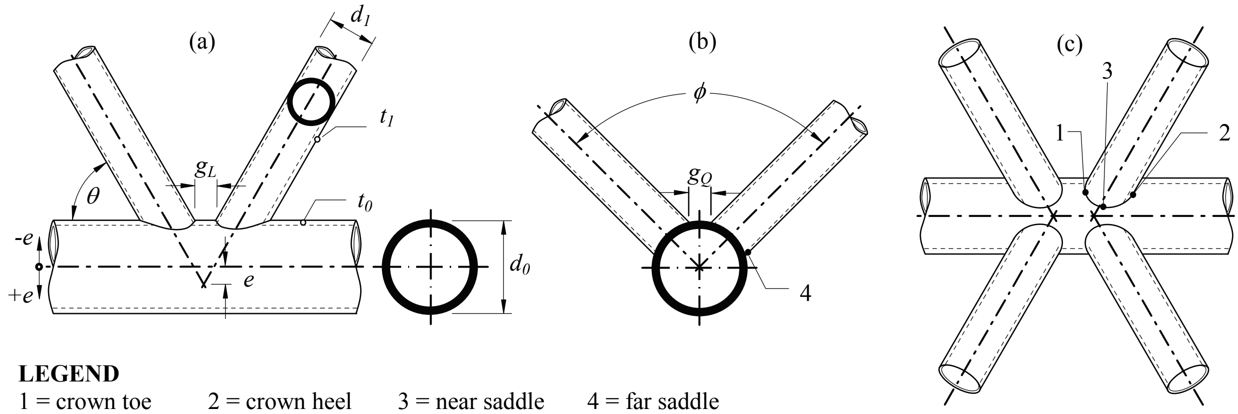


Figure 3. Geometrical parameters of K-joints: longitudinal view (a), cross section (b), top view (c)

weld joints has to be considered quite good-natured since the fatigue cracks do not start on the inner surface of the tubes. Normally, they are initiated on the outside of the truss members, especially at the chord crown. Therefore, the cracks are well detectable through permanent inspections. Furthermore, the fatigue resistance of the potential crack locations can be improved by post-weld treatment. Lastly, the design and the fabrication process are accelerated since the fabrication of the cast steel elements still needs months and interruptions and delays caused by flawed cast steel elements are eliminated.

In contrast, the fabrication of the weld joints is more challenging and requires skilful welders. The welding is difficult in terms of the weld profile and the welding position varying around the brace-to-chord intersection. In contrast to the cast steel joints, where the welds can be positioned outside the structural discontinuity zone of the joint by optimizing the joint's geometry, the welds of the weld joints are situated in an area of high stress concentration. This fact has to be critically considered in terms of fatigue.

1.3 Defintion of thickwallness

The thickwallness is usually related to the chord member of the K-joints. Generally, one differentiates between an absolute and a relative definition of thickwallness. The design guide of CIDECT [5] classifies usually the tubular joints in fatigue class 114 (acc. to the systematics of Eurocode 3) in connection with the structural stress concept. This classification holds for joints with a wall thickness of 16 mm and has to be corrected if thinner or thicker wallthicknesses are used.

The reference wall thickness of CIDECT [5] is kind of arbitrarily chosen and does not correspond with the reference wall thickness of 25 mm in Eurocode 3 [1]. Within this paper K-joints with a wall thickness greater than 16 mm are called thickwalled. The influence of the absolute wallthickness on the fatigue strength can be attributed to the increased probability of a defect with growing material volume and the higher amount of residual stresses.

On the other hand there is also a relative definition of thickwallness. The relative thickwallness means that the chord indicates a low ratio of radius and wall thickness also referred to as γ-value. Joints showing values of $\gamma < 12$ are referred to be thickwalled.

In case of welded tubular structures the relative rather than the absolute geometry of the K-joint members has a great influence on the fatigue strength. In terms of welded K-joints the brace-to-chord intersection is a location of high stress concentration. Within the elastic range (that holds for high-cycle fatigue) the stress concentration depends dominantely on the joint geometry that is sufficiently described by the geometrical parameters β, τ, γ , and the brace angles θ and ϕ, see (1), (2), (3) and **Figure 3**. The angle ϕ is only necessary for multiplanar K-joints.

$$\beta = \frac{d_1}{d_0} \qquad (1)$$

$$\gamma = \frac{d_0}{2 \cdot t_0} = \frac{r_0}{t_0} \qquad (2)$$

$$\tau = \frac{t_1}{t_0} \qquad (3)$$

From the standpoint of reliability, K-joint geometries are favourable that ensure visual inspection of all welds (crack detection), **Figure 3**a,b. Since this is a major concern in bridge design, the research project focused on joints with non-overlapping braces, i. e. gapped joints. Furthermore, only configurations with equal braces are considered.

2 STATE OF THE ART

2.1 Fatigue evaluation concept

The fatigue evaluation of all tubular joints including K-joints is complicated due to the stress concentration at the brace-to-chord intersection that leads to an increase of the nominal stress, σ_{nom}, at the joint region, **Figure 4**. The stress concentration has basically two reasons: (i) the sudden shift of geometry, (ii) the metallurgic and geometric notch of the weld toe itself. While for static applications the stress concentration is normally relieved by local plastifying and therefore negligible, it has to be considered for structures with repeated loading.

For several reasons such as calculation efforts, the fatigue evaluation is usually based on the structural stresses, σ_{hs}, (also called hot-spot stresses) rather than on the actual notch stress, σ_{notch}. One fundamental characteristic of the structural stresses is that they include the increase in overall structural stiffness due to the weld (macro effect) but exclude the local stress rising effect due to the shape of the weld toe and the material inhomogeneity caused by the welding process (micro effect).

The fatigue evaluation of K-joints according to Eurocode 3, Part 1-9 [1] and the design guide of CIDECT [5] has the format of (4) with $\Delta\sigma_{FAT}$ as fatigue resistance based on structural stresses and depending on the weld detail, and γ_{Ff}, γ_{Mf} as partial safety factors.

$$\gamma_{Ff} \cdot \Delta\sigma_{hs} \leq \frac{\Delta\sigma_{FAT}}{\gamma_{Mf}} \qquad (4)$$

$$\Delta\sigma_{hs} = \sum_{i=1}^{n} SCF_i \cdot \Delta\sigma_{i,nom} \qquad (5)$$

2.2 Determination of structural stress

It has to be emphasized that the structural stress σ_{hs} (and its stress range resp.) of a particular constructional detail is not the direct outcome of a Finite Element Analysis. In fact, it is determined by an extrapolation from stresses at more or less well-defined distances L from the weld toe outside the weld region, **Figure 4**.

The determination of the structural stress range $\Delta\sigma_{hs}$ can effectively be simplified by (5) if appropriate SCF-values (SCF = stress concentration factor) are available. In this case the structural stress range may be derived from the nominal stress range by multiplication with the SCF-values. In general, the actual stressing has to be resolved into several basic load cases i such as axial chord loading, chord bending etc. Subsequently, the structural stress and the structural stress range, respectively, are a superposition of n basic load cases, **Figure 5**.

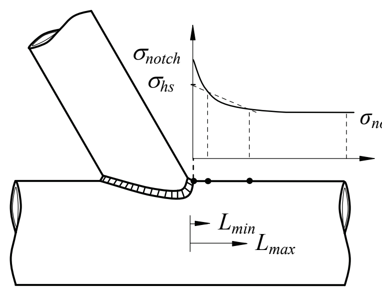


Figure 4. Determination of structural stress by extrapolation

2.3 Particular aspects of thickwalled K-joints

2.3.1 Appropriate fatigue strengths and SCF-values

In summary, the fatigue evaluation of thickwalled K-joints requires reliable fatigue strengths $\Delta\sigma_{FAT}$ in accordance with the structural stress concept and appropriate SCF-values to determine the structural stress range $\Delta\sigma_{hs}$. Unfortunately,

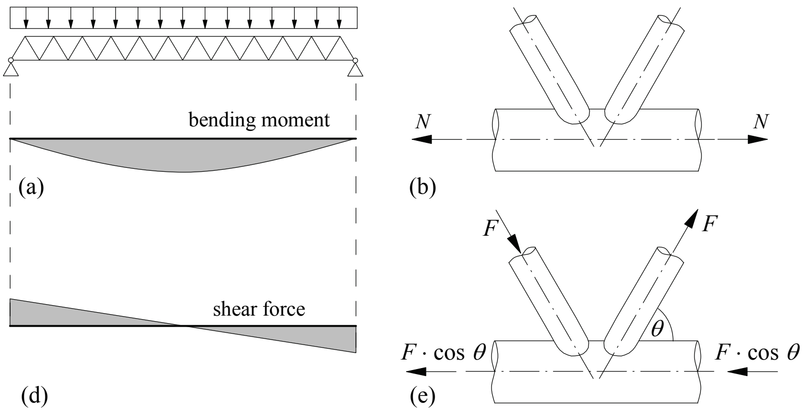


Figure 5. Real stressing of a truss girder: bending moment (a) and selected corresponding basic load cases: normal chord force (b), chord in-plane bending (c); shear force (d) and selected corresponding basic load cases: normal brace force (e), brace in-plane bending (f)

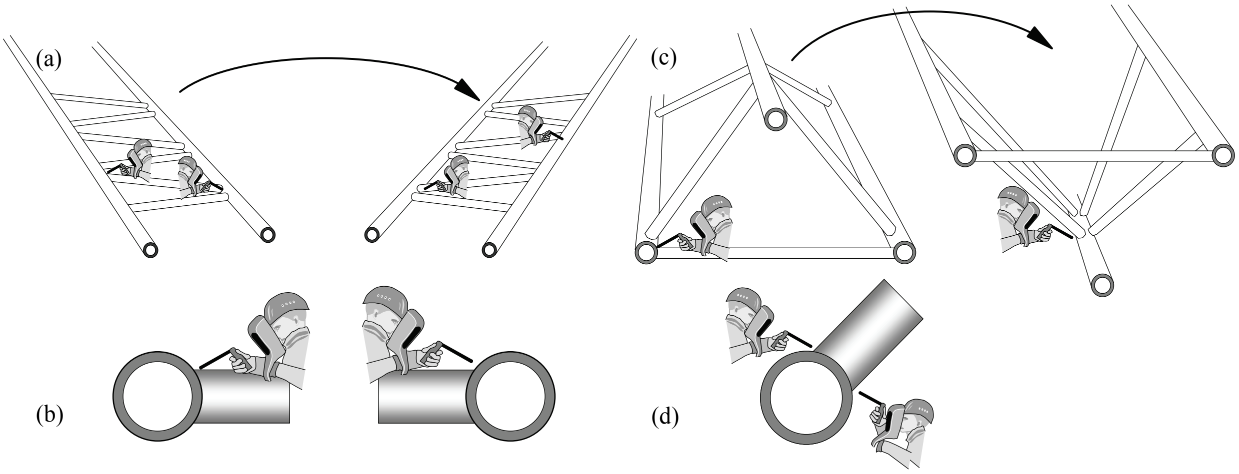


Figure 6. Usual fabrication of uniplanar tubular trusses (a), corresponding welding positions (b), usual fabrication of multiplanar tubular trusses (c), corresponding welding positions (d)

the existing design guides for fatigue [5] are not applicable to K-joints with low γ-values, since their fatigue strengths are mainly backed up by testing in the range of $12 \leq \gamma \leq 30$.
Moreover, the available SCF-values tend to overestimate the actual stressing of the K-joints [3]. To illustrate the particular importance of appropriate fatigue strengths and SCF-values, one should keep in mind that for instance the absolute wall thickness of the chord members for highway bridges normally ranges between 25 and 65 mm. An overestimation of the stressing penalizes such constructions twice since higher stresses do not only result in an increase in tonnage but also in an essential decrease in resistance due to the scale effect of greater wallthicknesses.

2.3.2 Fabrication

As thickwalled tubular trusses are usually of large size they cannot always welded in the most favourable welding position. Therefore, a non-representative inquiry among German steel construction companies was carried out in order to identify the usual welding positions. **Figure 6** a, c show the conventional way how an uniplanar tubular truss and a multiplanar truss of medium size are fabricated. It is understood that the single company might fabricate trusses in a different way.

2.3.3 Weld configuration

The weld shape determines the cost effectiveness and the reliability of welded K-joints. Up to now only thickwalled K-joints with a full penetration weld around the brace to chord intersection have been tested [3], **Figure 7** a. This kind of weld configuration is well known from offshore structures that are normally accessible (d_0 > 2000 mm) allowing for laying a root pass from the inside. On the contrary, the thickwalled tubular structures are not accessible and can only be welded from outside.
In case of a full penetration weld, brace angles $\theta < 60°$ have to be regarded as critical from the standpoint of weldability (lack of fusion), **Figure 7** b. Moreover, the induced weld volumes of full penetraction welds are tremendous in case of smaller brace angles. Therefore, a weld configuration should be considered as favourable that

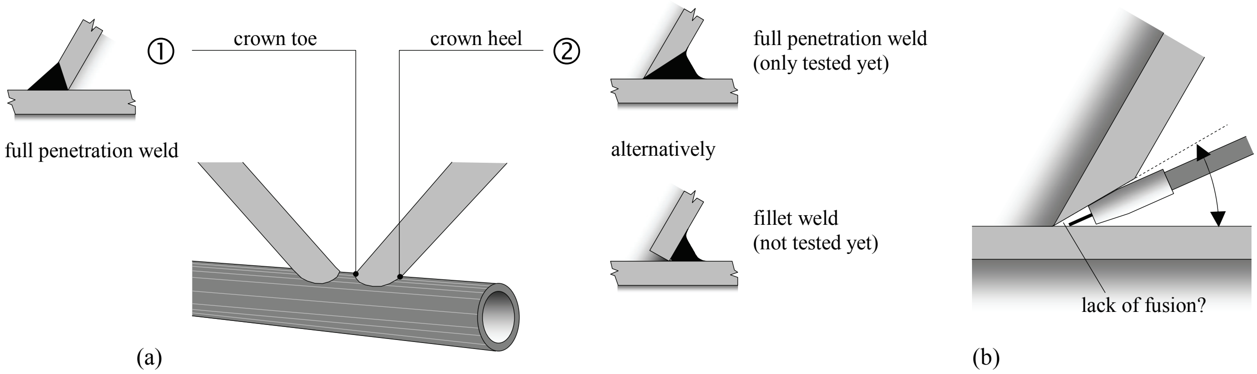


Figure 7. Weld configuration of thickwalled K-joints (a), welding problems in case of a full penetration weld at the crown heel (b)

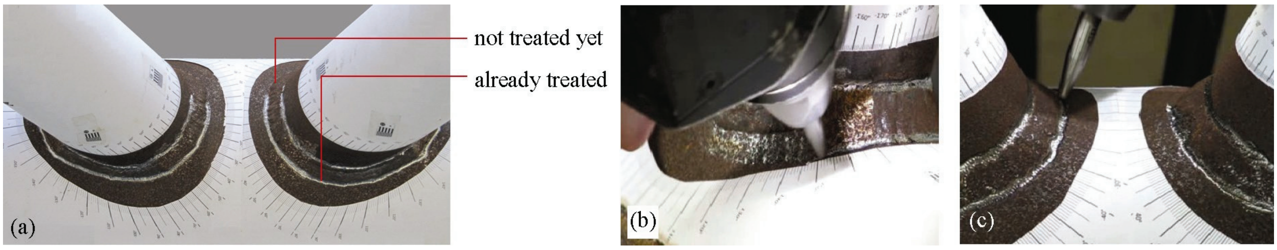


Figure 8. Post-weld treatment by high-frequency hammering (a), different phases of treatment (b,c)

starts with a full penetration weld at the crown toe and turns into a fillet weld at the crown heel with a smooth transition. Up to now such a weld configuration has not been tested under fatigue loading.

2.3.4 Post-weld treatment

Due to the particular design of welded K-joints lacking any reinforcement such as stiffeners at the joint region, the capacity of the tubular joints can be significantly lower than that of the truss members connected with each other. Therefore, each enhancement of the joint's fatigue strength improves the cost effectiveness of the whole structure. As it is shown later the fatigue cracks are predominately initiated at the weld toe of either the chord or the brace, the application of any weld profile or residual stress modification technique is favourable.

For the last ten years the technology of the high-frequency hammering has become pratically applicable, **Figure 8**. The high-frequency hammering is fast, focuses the input of energy on the locations of interest (weld toe) and exhibits a more pronouced increase in fatigue strength compared with conventional hammering methods. Up to now there has not been any systematic research on the benefit in case of tubular structures.

3 INVESTIGATIONS

3.1 Research project

The goal of a still on-going research project No. P815/ IGF 325 ZBG of the Forschungsvereinigung für die Stahlanwendung (FOSTA) financed by the German Federal Ministry of Economics and Technology (BMWi) is to study the fatigue behaviour of thickwalled K-joint in uni- and multiplanar configurations more detailled. The research project is carried through by four partners (1) Stuttgart University, (2) Munich University of Applied Sciences, (3) Munich University of Armed Forces and (4) SLV Halle and comprises experimental and numerical investigations.

The testing programme includes 87 component tests and 1 large-scale girder test in addition to several material tests and four series of small scale tests in order to study the fatigue behaviour of a fillet weld and full penetration weld laid in different welding positions.

3.2 Fabrication of specimens

The geometry of the test specimens – especially the diameters of the chord and braces and the size of the gap between the braces – has been chosen according to a former research project [2]. **Figure 9** gives an overview about the specimens to be tested. The material of the test specimens is S355J2H and was friendly delivered by VALLOUREC & MANNESMANN TUBES for free.

All specimens exhibit a wallthickness that is larger than the reference wallthickness of 16 mm according to CIDECT [5]. The chords of all specimens are thickwalled showing γ-values ranging from 3.4 to 6.4. The maximum wall thickness amounts 60 mm. In summary, all test specimens are absolutely and relatively thickwalled.

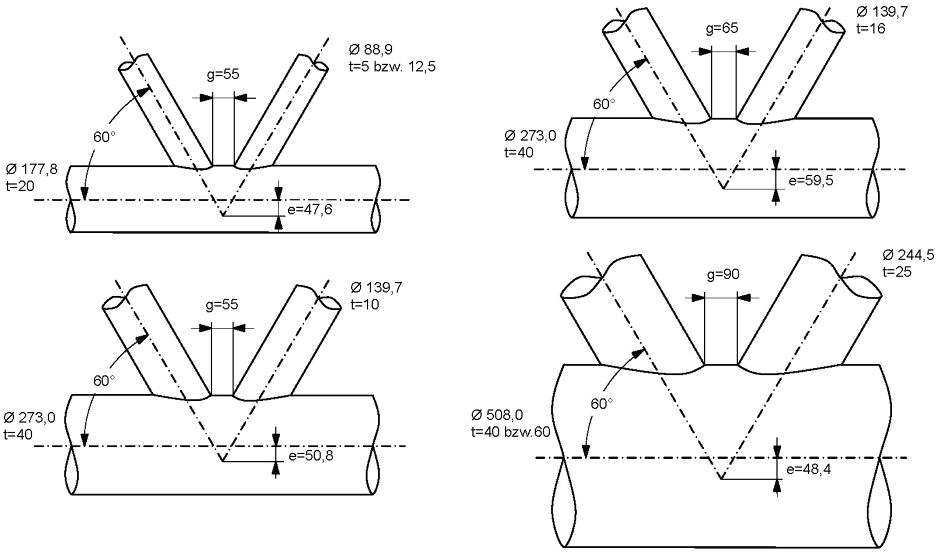
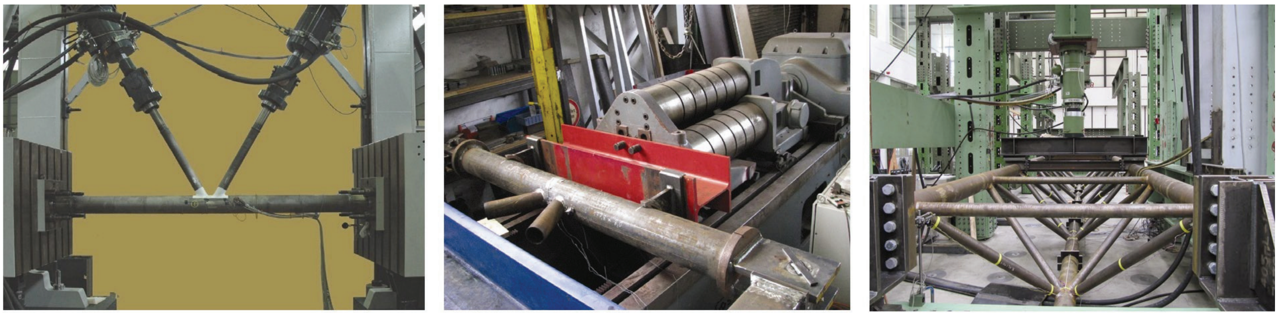


Figure 9. Geometry of test specimens



(a) (b) (c)

Figure 10. Component test set up at Stuttgart University (a), at Munich University of Applied Science (b), girder test at Munich University of Armed Forces (c)

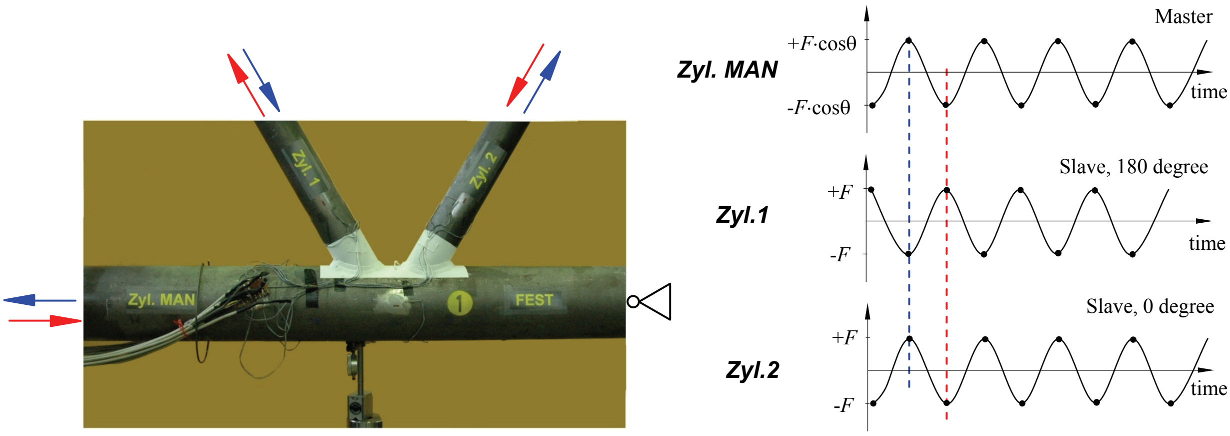


Figure 11. Stressing under brace normal force loading

The chosen weld configuration of the test specimens comprises a fillet weld at the crown heel, **Figure 7**. Undoubtably, the fatigue strength of the fillet weld is less in comparison with a full penetration weld. Through the tests it should be shown whether the smaller fatigue strength of the fillet weld becomes decisive in case of the K-joints. The weld preparation was automatically cut with friendly support by ZIS Meerane, Germany. As this research project does not solely focus on the determination of fatigue strength values, an important outcome will be a series of recommendations concerning the design and the fabrication of welded K-joints such as the weld configuration, the weld preparation and the welding itself.
Owing to the fact that this research project investigates thickwalled tubular trusses in various parameter studies and that the number of specimens is limited it was decided to have the specimens fabricated by only one steel construction company (Zwickauer Sonderstahlbau, Germany) specialized in fabricating bridges and mining structures to minimize

the scatter. This decision is appropriate since the goal of the research project is to identify the underlying damage mechanism in a systematic way for the first time rather than to appraise the fabrication scatter of different companies. Undoubtedly, for a final design recommendation the fabrication scatter among different steel construction companies has to be determined in order to guarantee an uniform level of safety.
In order to investigate the gain of fatigue life due to high-frequency hammering several test specimens were post-weld treated, too.

3.3 Component tests under brace loading

The component tests under brace loading have been carried through at MPA Stuttgart, **Figure 10** a. The tests have been performed in a test rig with three simultaneously operating actuators, **Figure 11**. Thus, the stressing of the specimens is identical to that of a real truss. The resultant of the horizontal components of the brace forces F is balanced with the chord force.
Due to the test set up the chords have to measure always ∅ 177.8 x 20. The braces have a diameter of 88.9 mm. Their wall thickness varies from 5 to 12.5 mm. The brace angle θ amouts to 60°. The tests have been performed under constant amplitude loading with a stress ratio of R = -1 and a frequency of around 1 Hz.

3.4 Component tests under chord loading

The component tests under chord loading with constant amplitude have been carried out at Munich both, at University of Applied Science (**Figure 10**b) and at University of Armed Forces. The specimens have been subjected to chord bending and chord normal force. The normal forces have been applied by servohydraulic actuators. The bending tests have been driven in a resonance testing machine.

3.5 Girder test

The girder test being still running is performed at Munich University of Armed Forces, **Figure 10** c. The girder is about 11.5 m long and 1.0 m high. It is tested under four-point bending (constant amplitude loading) with a stress ratio of $R \approx 0.1$ and a frequency of around 1 Hz. The chord of the girder measures ∅ 193.7 x 25 and the braces are of ∅ 88.9 x 12.5. The brace angles are $\phi \approx 90°$ and $\theta \approx 45°$.

4 FIRST PRELIMINARY RESULTS

As this research project is still running only first preliminary results can be presented. This paper focuses on the component tests under brace normal force loading. In the following the test results of the thickwalled K-joints are compared with existing results of tests on thinwalled K-joints that had been performed in the 1970s in the same test setup at MPA Stuttgart [6].
For fatigue testing of tubular structures there are a couple of failure criteria, **Table 1**. Usually, only the failure criterion N3 is recorded in fatigue tests because of its objectivity. In this research project, the criteria N1, N2 and N3 are recorded for each component test. For N1 strain gauges are placed in the gap region in order to record any shift in strain. For N2 the specimens are checked under stressing by means of magnifiers permanently in order to detect the crack initiation. Finally for N3, the airproof chord tube is set under a small air pressure. If the crack propagates through the chord wall, the recorded air pressure will drop.
Up to now the most important findings have been:
(i) Independent of the load case the component tests on thinwalled K-joints [6] show a slope of m = 5 when plotting the nominal stress of the braces against the number of load cycles. The S-N curve of the thickwalled K-joints seems to be steeper. That might be an onset for a scale effect, **Figure 12**.
(ii) In the low cycle fatigue range the tested thickwalled K-joints appear to be stronger than the thinwalled ones. A reason might be the progress of welding technology and material properties. Nevertheless, in the high cycle fatigue range the thickwalled K-joints show smaller fatigue strengthes.
(iii) For a ratio of τ = 0.63 (ratio of wallthicknesses of brace and chord) the critical hotspot is the weld toe on the chord surface in the gap region. This is in good agreement with Finite-Element Analyses, **Figure 13** a, b.
(iv) The fillet weld at the crown heel of the welded K-joints has not been decisive in the tests, yet. The weld quality exhibits typical weld defects such as incomplete fusion of the fillet weld, **Figure 13** c.

Table 1. Common failure criteria for tubular joints [4]

Criterion	Description	Objectivity
N1	Number of cycles until a 15% change in strain occurs, measured "near" the crack initiation point	subjective, since what is "near"
N2	Number of cycles until a "visible" crack occurs	subjective, depending on the sensitivity of the visual inspection
N3	Number of cycles until a through thickness crack occurs	objective
N4	Number of cycles until end of test (complete loss of strength)	objective

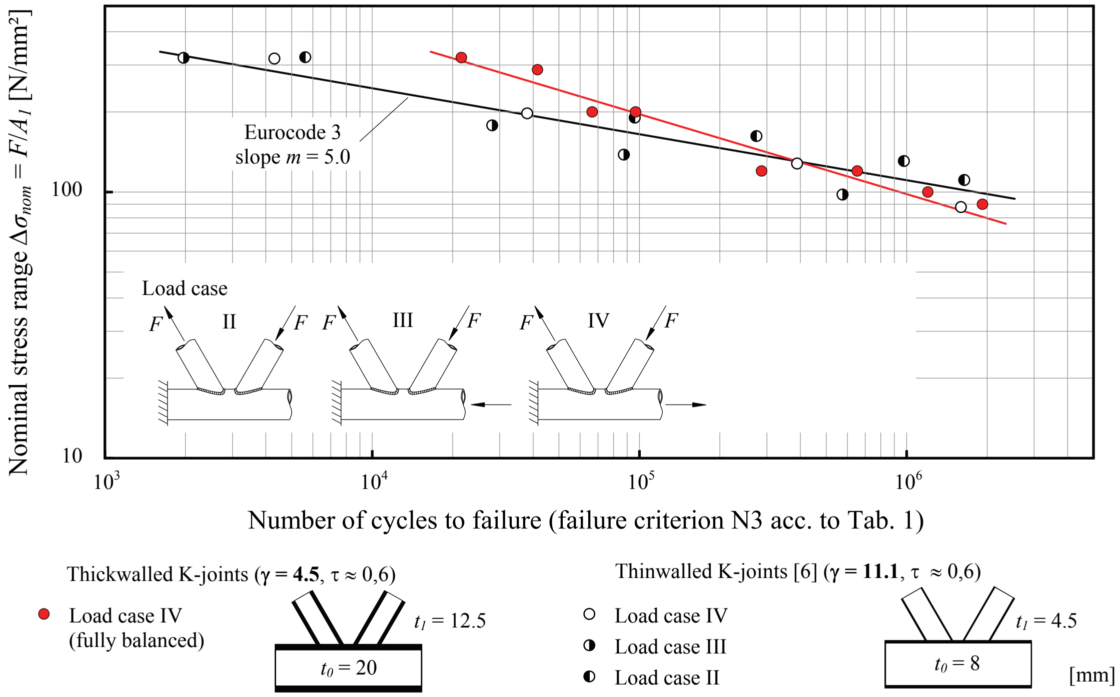
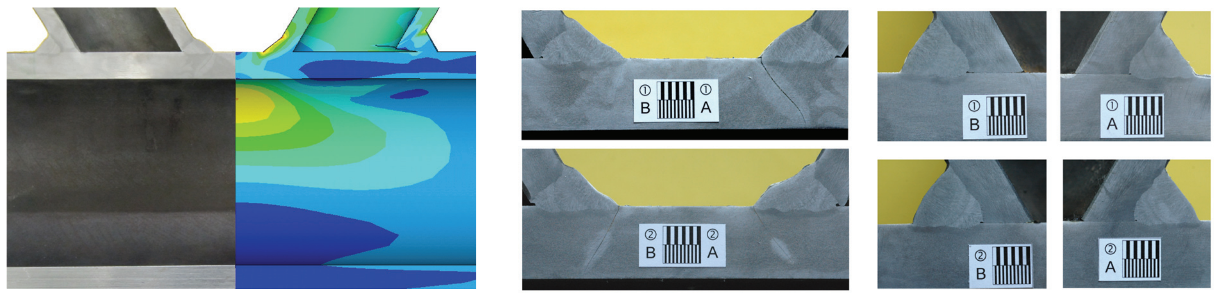


Figure 12. Preliminary test results under brace loading (d_0 = 177.8 mm, d_1 = 88.9 mm)



(a) (b) (c)

Figure 13. FE model with *Von Mises* stresses (a), fatigue cracks at the weld toes in the gap region of test specimen No. 1 and No. 2 (b), fillet weld at the crown heel (c)

5 CONCLUSION

This paper introduced a still running research project on welded K-joints made of thickwalled circular hollow sections. The goal of this project is to study the fatigue behaviour of such joints with particular focus on an efficient, reliable and partical weld configuration. The joints are tested in component tests under different basic load cases such as normal force and bending. Additionally, a girder test is performed that is supposed to show how the results of the component tests can be transferred on real structures. First test results are presented.

6 REFERENCES

[1] Eurocode 3. "Design of steel structures, Part 1-9: Fatigue." European Committee for Standardization.

[2] Kuhlmann U., Euler M. 2010. „Empfehlungen für geschweißte KK-Knoten im Straßenbrückenbau", Schriftenreihe Berichte der Bundesanstalt für Straßenwesen, Brücken- und Ingenieurbau Heft B71, Germany, 2010.

[3] Schumacher A. 2003. "Fatigue Behaviour of Welded Circular Hollow Section Joints in Bridges". Dissertation Thèse 2727, EPFL, Lausanne, Switzerland.

[4] van Wingerde A. M., van Delft D. R. V., Wardenier J., Packer J. A. 1997. "Scale Effects on the Fatigue Behaviour of Tubular Structures". IIW Conference "Performance of dynamically loaded welded structures", San Francisco.

[5] Zhao X.-L., Herion S., Packer J. A., Puthli, R. S. Sedlacek G., Wardenier J., Weynand K., van Wingerde A. M., Yeomans N. F. 2001. "Design guide 8 for CHS and RHS welded joints under fatigue loading." CIDECT (International Committee for Research and Technical Support for Hollow Section Structures), TÜV-Verlag GmbH, Germany, 2001.

[6] Zirn R. 1975. „Schwingfestigkeitsverhalten geschweißter Rohrknotenpunkte und Rohrlaschenverbindungen". Dissertation, Universität Stuttgart, Germany.