The influence of materials on the behaviour of joints with multiple bar connections

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Abstract. Joints made out of tubular steel members are often used in industrial constructions, like offshore, trusses or tree-shaped columns. The joint area is the weakest point in a truss structure. Beside the normal static behaviour many non-linearities due to the geometry or to the welding process have to be taken into account. Steel hollow sections are often used. Much research was made on welded nodes so far. To increase the resistance of a joint it is an option to vary the material choice. Many variations were tested in the past. It is possible to change the overall material of a joint or using composite structures, like a concrete filled column. Or the steel of the welding line can get an additional material component. Another aspect is to reinforce the joint for example by a stiffened ring. In this paper a state-of-the-art review of the influence of different materials to the resistance of welded nodes is given.

1. Introduction

For industrial buildings or extravagant structures, the main focus is on their stability and resistance. At the same time, it must be a very low weight to reach the requirements to the height or length, for example at widespan constructions. This is the reason why trusses, especially together with hollow profiles are often used. Rectangular (RHS) or square hollow sections (SHS) can be found in truss structures, bridges and high-rise buildings. Mostly for offshore platforms circular hollow sections (CHS) are used. To calculate the nodes of these structures is the more complex part. There are different types of joints. Figure 1 shows the types which are listed in the standards. The most common type in industry is the K-joint [1].

In tubular joints where two pipes have different diameters the lager pipe is called chord and the smaller one brace. The angle between brace and chord is called inclination angle. The joint area with a small inclination angle is called brace crown heel, with large brace crown toe.

A great part of welding research is about the microstructure of the welding lines, which is influenced by the welding heat/procedure. Younise et al. [3] did tests and determined the influence of material heterogeneity. He calculated the critical void volume fraction and used a mesh size of 0.2 - 0.5 mm. Baniari et al. [4] explained a non-destructive method of analysing the residual stress, called X-ray. There are three types of residual stresses: Macrostresses, Microstresses and stresses without specific name. By method of X-Ray stress can be determined by the measurement of the distance between crystallographic planes.
To increase the resistance of a above described joint it is an option to change the material choice. There are many variations to change the overall material, like stainless steel, timber, cold-formed steel or concrete filled hollow sections. Another option is to vary the welding line material, or to add additives to the welding material. Examples for the physical variation are reinforced structures, like stiffened rings or rib-plates. In the following paper a state-of-the-art review of the described variations is given.

2. Analysis of joints made of different materials

2.1. Stainless Steel
For industry purposes stainless steel is an underpart. But due to its resistance to corrosion much research is done to that material.

Buchanan et al. [5] did research about stainless steel CHS beam columns under axial loading and bending moments. Buchanan explained, that the advantages of stainless steel are the high ductility, stiffness, strength, corrosion resistance, recyclability and aesthetics. The most common types of stainless-steel constructions are austenitic, duplex and ferritic. The austenitic grades are most prevalent, duplex offers improved mechanical and corrosion resistance and ferritic have the lowest costs. The most

![Figure 1. Joint types [2].](image-url)
common profile types are the CHS profiles, including high torsional resistance. There is a limited data for stainless steel CHS columns or beams. It was concluded, that the current design code is conservative regarding the described material for members with a high ratio of bending moment to axial load, while it is slightly unconservative for members with a low ratio of axial loading to bending moment. Gardener [6] explained, that stainless steel has got a number of established benefits over carbon steel, but also higher costs.

Ashraf et al. [7] did research about stainless steel CHS columns. His approach does not require a classification of cross-sections, but it is based on a continuous relationship between the slenderness of a cross-section and its deformation capacity. The concept is extended further to determine flexural buckling resistance for long columns based on Perry type column curves. It was said, like in the first paragraph, that the Eurocode is highly conservative regarding the resistance of the CHS stub columns. In case of long columns, the Eurocode guidelines result in overprediction of the considered test results.

Feng et al. [8] did research about hybrid CHS to SHS tubular joints under axial compression. Experimental tests were done to 4 T-joint, 5 Y-joints and 9 X-joints made of stainless steel. It was found out, that the current design rules are not appropriate for these types of joints. The FEM model was built out of 4-noded 10 x 10 mm shell elements. This is also valid for the welding line, which is not as exact as solid elements. But in this case, it is comprehensible, because mainly the study is about the difference of the material in the braces and chord. It is not about the welding line. In opposite to the author’s numerical studies, Feng calculated the load capacity by the deformation limit criteria, invented by Lu et al. [9]. Next to the introduction to the four failure modes, Gao and Gho [10] also did studies about the geometric parameters. Most results are depending to the hybrid material, they are not described to that point, but the results are about the decreasing load capacities for T/Y- and X-joints with an increasing inclination angle. Feng concludes that four failure modes can be occur. The strength of the joints is affected by geometric parameters, especially by the β value. The methods to calculate the load-carrying capacity by the design codes and guides are close to the FEA results, but on the conservative side.

Zamzami et al. [11] explained that by comparing the strength of the welded and non-welded components, made of the same material, that there is a significant reduction in the fatigue strength of the welded components. Azari-Dodaran et al. [12] stated it more precisely and concluded a difference of nearly 10% in the ultimate strength.

Sometimes because of weight reduction the industry uses different materials. Zamzami did some research on hybrid joints, where the chord is made of steel and the braces are made of aluminium.

A very big issue is the resistance of the welding line itself. There are three zones in a welding area with different resistance, including the welding line. Mostly the welding steel is combined with some chemical additions.

2.2. High and low strength steel

The less expensive alternative to stainless steel or aluminium is to vary the hardness grade of the steel. In the following paragraph the main research results to the high and low strength steels are presented.

Xin et al. [13] did research about welded rectangular hollow section joints made out of high strength steel. It has got many advantages, but it is also expensive and only relevant for special constructions. It is used especially for truss girders of long spans used in sport arenas and bridges [14, 15]. Xin explains, that the steel grade is included in the books of the Committee for International Development and Education on Construction of Tubular structures (CIDECT) up to S460 and in the EC3 up to 700 MPa. The secondary bending moment is strongly dependent on the geometry and material properties [16]. Especially for high strength steel the secondary bending stress should be analysed in detail. Xin concludes that K-joints made out of HSS have got a higher ultimate load resistance of 20 - 142% (depending on the steel grade) compared to S355. The ultimate load resistance increases with increasing of the yield strength. Systems with a larger β-value result in larger secondary bending stresses. Joints with a lower gap size create a larger secondary bending stress.
Swoo-Heon Lee et al. [17] did numerical and experimental research on CHS to plate joints. For his FEA simulation he used shell and solid mesh elements. The element size was in the range of 30, 20 or 10 mm for the coarser mesh. For the refined area a size with a factor of 0.5 was implemented. Also, a comparison between the different methods is expressed, which are quite similar. First there is the NJS (Normalized Joint Strength) \( \frac{R_{\gamma_d} F_{yt}}{F_{yt}} \), secondly the AISC (American Institute of Steel Construction) \( \frac{R_n}{R_{\gamma_d}} \) of 2016, thirdly the Eurocode \( \frac{N_{1,\text{Ed}}}{R_{\gamma_d}} \) of 2005 and the last is the ISO (International Organisation of Standardization) \( \frac{F_1}{R_{\gamma_d}} \) of 2013. It was concluded that the axial tension chord stress acting on ISO 14346 is similar at the yield strength of 460 MPa, but AISC and Eurocode 3, which do not consider the strength reduction effect are similar with increasing yield strength. Lee explained that by using high-strength steel under axial tension chord stress, the strength reduction effect can be neglected. Islamovic et al. [18] did experimental tests about welded joints induced by bending moments. Steel plates with different conditions were analysed. The plates had butt welding lines. It was concluded, that for a bending angle of 120° no cracks appear in case of the steel S.0361.

Mishra [19] collected in his presentation many aspects about welded joints, including calculation methods. According to filled welds, advantages and disadvantages were listed. In summary the main advantages are: Filled welds are easy to prepare, they can be formed between two dissimilar metals, accommodation of different thicknesses and thin material such as diaphragms and foils can also be used. In contrast there are disadvantages like the chance of lower tensile strength, it is less rigid than the base material, overlaps may be undesirable for mechanical or aesthetic reasons, Micro-cracks and cavity deflects may occur or corrosion and fatigue cracking may occur. The butt-welds have different characteristics. It is the simplest form of welding, it does not require cutting the material, two metals are joined by simple placing their ends together and if the thickness is smaller than 5 mm bevelling is not necessary.

Al Rashed [20] did a presentation about the tensile strength of welded joints. Information about the hardness in different zones in the microstructure were already given. Especially a focus was given to the heat-affected zone. Different experimental bending test were made to see the difference of the absolute strength.

Shakhmatov and Usmanova [21] did research about the strength of welded joints under quasi brittle fracture. It was explained, that the strength of welds with structural faulty welds depends on the mechanical characteristics of the material, the length of the faulty weld, as well as on the radius at its top. The critical opening of the concentrator depends on the radius at its top.

\[ \text{Figure 2. Notch geometries [22].} \]

Remes et al. [22] did numerical and experimental tests about the fatigue strength of welded joints. Especially the different weld geometry and the plate thickness were focused. It was distinguished between normal and high-performing welds, which are characterised by a benefit of fatigue strength, e.g. due to weld notch geometry. The three kinds of notches are presented in figure 2. Beside this, different methods for calculating fatigue life were presented. Examples are Linear Elastic Fracture Mechanics (LEFM), Effective Notch Stress approach (ENS), Strain-based Crack Growth (SCG) or the averaged Strain Energy Density approach (SED). It was concluded, that a simplified modelling of the weld notch effect can cause significant uncertainties in the fatigue strength of high-performing welds.
2.3. Cold formed steel

The influence of the process of cold forming steel is explained in the following paragraph. A focus is given to the imperfection of the hollow section members, which is automatically generated by the process.

Mitsui et al. [23] did research about the effect of initial imperfection on elasto-plastic behaviour of SHS columns under axial force with bending moment. It was explained, that due to the cold forming process and geometrical initial imperfections, residual stresses can occur. In the numerical model, on one hand global imperfection, in form of initial bow imperfection was set, on the other hand there are local imperfections, which set as lack of flatness in the plate. Beside this, there is a distribution of the residual stresses in the thickness direction as material initial imperfection. The imperfections are given with equation (1) to equation (3). A four-node shell model was used (figure 3).

\[ u_{y,c} = D_L L \sin \frac{\pi}{L} z \]  
\[ u_{x,L} = \pm \frac{D_B B}{L} \left( \cos \frac{2\pi}{B} y - 1 \right) \sin \frac{\pi}{B} z \]  
\[ u_{y,L} = \pm \frac{D_B B}{L} \left( \cos \frac{2\pi}{B} x - 1 \right) \sin \frac{\pi}{B} z \]  

Figure 3. Analysis model [23].

It was explained, that in this case, the analysis model with individual initial local imperfection, regardless of the collapse mode, the maximum bending moment and the plastic deformation capacity decrease with the increment of the amplitude of the initial local imperfection. Beside this, it was concluded, that the magnitude of the residual stress which changes in the thickness direction has hardly an effect on performance. The amplitude of the residual stress which does not change in the thickness direction has an impact on performance. The amplitude of the local imperfections is the most influential imperfection on the deformation capacity.

2.4. Timber

Timber is a lightweight and ecological material. Especially for building constructions, which should be integrated in nature setting, timber structures are often chosen. Because of the heterogeneity of the microstructure and the difficultness of connection, often a hybrid technique is used. The wooden chords and braces are axial compression or tensional members, while the joint is made out of steel, which can
be seen in figures 4 and 5. However due to the normal forces these constructions are comparable to truss structures.

A. Lokaj and Klajmonova [24] did tests on timber joints. The influence of the angle of the joint is analysed. Test with an inclination angle of 0, 60 and 90 degrees were done. Figure 6 shows a comparison between test records of these three different angles.

Goncalves et al. [26] did research to tree-shaped timber structures. Especially the six faces “diamond” hexagonal columns (DC) were analysed. The columns are constructed out of 15 cm diameter steel connections compared with 16 cm diameter C30/C40 timber dowels. It is designed in the way, the wood parts acted like compression members, without having bending moments. The resultant model can be seen in figure 7. There is only one support point in the soil, which defines the Tree-shaped timber stayed structural system (SETAM), which builds the opposite to the SETA – Tree-shaped timber structural system, having three support points in the soil. An advantage is the light structural weight,
which can be a benefit to the application area of centres, malls hangars and so on. Beside this there is only a minimal environmental impact due to the natural architectonical shape.

![Comparison of test records of round timber samples in tension at a different angles](image1)

![Comparison of test records of squared timber samples in tension at a different angles](image2)

**Figure 6.** Comparison of the influence of the joint angle [24].

![Hexagonal column](image3)

**Figure 7.** Hexagonal column [25].
2.5. Carbon Fiber Reinforced Polymer (CFRP) and Concrete Filled Steel Tubular (CFST)

Carbon Fiber reinforced polymer is a composite material made out of a matrix and a reinforcement. For industrial purposes, this material is too expensive for an area-wide use, but a lot of research is done to that topic. It is a very low-weight and simultaneously a high strength base material. The method of concrete filled tubular steel is mainly used for large diameter hollow section geometries. Inside of the steel tubular profile, reinforcement together with concrete is set. This is done to reach a higher stability and resistance to the column.

Ammari and Narmashiri [27] did research about SHS steel columns, strengthened by CFRP. The method of Fiber Reinforced Polymer (FRP) or the Carbon Fiber Reinforced Polymer (CFRP) method is a very seldom, but effective method to reinforce columns to get a higher strength, corrosion resistance and easy application. Jiao and Zhao [28] concluded a 25% - 76% higher tensile strength by using this method.

Dong et al. [29] concluded that CFRP warping on hollow and filled circular columns had better results than square sections. Ammari and Narmashiri simulated the model by the use of shell elements. He concluded that the horizontal deficiency in steel columns indicated significant local buckling, which causes stress concentration at damaged areas. The horizontal deficiency in the middle of columns caused the most critical of middle and corner elements. Carbon fiber had a significant effect on lateral deformation and local buckling.

Shahraki [30] did experimental and numerical investigation of strengthened SHS steel columns under axial compressive loads. The advantages of FRP reinforced columns were focused, which are the high strength-to-weight ratio and the optimal corrosion resistance.

S. Saleh et al. [31] did research about K-joints. Two design types were compared. On one hand there are CHS and on the other hand CFST (concrete filled steel tubular) joints. Because of the material choice for the thesis, only the first type is relevant. A main focus in their study should be the effect of corrosion, which was implemented by thickness reduction. This method is an approach, because there is no numerical model, which is able to replicate the corrosion effect [31].

Saleh occurs different failure modes for the CHS K-joint in the compression load case. On one hand there is the failure by punching into the chord and on the other hand there is the failure by punching in the chord combined with local buckling. For the tension load case, there is the punching out of the chord mode. Saleh concludes, that corrosion has only a moderate influence on the behaviour of the joint.

In his experimental research Garifullin [32] did tests with brace-to-chord width ratios of 0.6 to 0.8. Beside this the material S420, S500 and S700 together with the welding types a6, a10 filled welds and 1/2 v butt welds were analysed. It was concluded, that the filled welds increase the brace to chord diameter ratio $\beta$ to a value of 0.85 and even greater. The ultimate resistance exceeded the plastic resistance of a steel joint by 16% average for all the joints. For joints with a higher $\beta$ the difference was smaller. So, designing joints by plastic resistance is the more conservative way.

3. The influence of the material on the behaviour of a joint

In paragraph 2 several options are presented according material change for joints. In a numerical study the influence on von-Mises stress, strain and deformation distributions of the different materials are analysed. Overall, six different materials, representing each presented material group, is studied. The exception is timber (2.4), because of the different joint type and it is not comparable to the other materials. The materials are: Aluminium, stainless steel, steel with a high ratio of Carbon, steel with a low ratio of Carbon, Carbon and S 235 as common steel grade. Even it is not realistic, the composite material Carbon with its non-linear material parameters is set in the same way, like the others. The material parameters of the different categories are shown in table 1.

To see the differences in geometric purposes, a circular hollow-section Y- and a K-joint with inclination angles of $60^\circ$ is simulated. The chord’s profile is a CHS DN 50 with a length of the chord of 350 mm. The braces are CHS DN 40 profiles with a length of 175 mm. Figure 8 shows the geometry of
the K-joint. It is meshed by quadratic tetrahedral elements with a 10 mm coarser and a 1.3 mm refined mesh. For the simulation the numerical software Ansys [33] is used.

### Table 1. Material parameters.

| Material         | S 235 | Aluminium | Stainless Steel | High Carbon Steel | Low Carbon Steel | Carbon |
|------------------|-------|-----------|-----------------|-------------------|------------------|--------|
| Density [kg/m³]  | 7850  | 2770      | 7750            | 7850              | 7850             | 1490   |
| Tensile strength [N/mm²] | 360   | 310       | 586             | 1070              | 365              | 2231   |
| E-Modulus [N/mm²] | 210.000 | 71.000   | 193.000         | 212.000           | 210.000          | 121.000 |
| ν                | 0.3   | 0.33      | 0.31            | 0.29              | 0.29             | 0.27   |
| Bulk-Modulus [N/mm²] | 175.000 | 69.608 | 169.300         | 168.250           | 166.666          | --     |
| Shear-Modulus [N/mm²] | 80.769 | 26.692  | 73.664          | 82.171.           | 81.395           | 60.000 |

![Figure 8. Geometry and mesh of the K-joint.](image)

An axial force of 20.0 kN is affected to the braces’ ends. The chord is set as pinned. The 3 mm fillet weld is made out of the same material, like the members, even it is unrealistic in case of the composite material Carbon.

The figures 9 to 11 visualise the results for the stress, deformation and strain for both joint types. The distributions of the Y- and K-joint have got a similar trend. There is only a larger difference in case of Aluminium. In general, there is a gap of around 40 N/mm² in stress and a difference of smaller than 1% in stain and deformation for the steel types. The deformation of the Aluminium is significantly higher than for the other steel types. A large peak arises in all three categories for the non-linear material carbon. The stresses are larger by a factor of around 3.
Figure 9. Stress results.

Figure 10. Deformation results.
4. Conclusions
This paper summarises the different options regarding the material choice for structural joints. Connections made out of high-, low-strength steel, timber, CFRP, CFST, aluminium, cold formed and stainless steel were introduced. Each material has got advantages and disadvantages, but in common it has increased the resistance and stability of the normal used industrial steel. The timber structures are presented as an alternative to the steel structures. Much research is done to the high-performance materials to realise a slenderer construction. Some of the described materials, especially the Carbon Fiber Reinforced Polymer is just too expensive for the area-wide use.

A numerical study to a Y- and K-joint made out of different materials, which were presented in this paper was done. The results of the von-Mises stresses, deformation and strain are nearly superimposable for the S 235, stainless, high and low carbon steel. The Aluminium has not got the high resistance like the steel grades.

The Carbon has got much more higher stresses, strain and deformations. A reason is, that the theoretical model according the connection of one or two members by using a fillet weld is not applicable for a material like Carbon, which is produced out of a high number of fibres.

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