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# STUDY ON THE MODELLING OF CRACK PROPAGATION IN THE JOINTS OF TUBULAR STEEL ELEMENTS

BY

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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. Steel hollow sections are often used due to the advantage of low weight to strength ratio. Beside the normal static behaviour many non-linearities due to the geometry or to the welding process have to be taken into account. Dynamic loads like wind, ocean or machine loads have got an influence on the fatigue life of the welding line of a joint. Different variants of cracks can occur in structures. The main focus is about the realistic numerical reproduction of the crack propagation. Much research was made on this issue so far. A review of the main aspects, methods and difficulties in modelling the crack propagation at welded nodes are given.

**Keywords:** welded joints; hollow sections; numerical simulation; fatigue; cracks.

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## 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 (*e.g.* 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. There are different geometries for hollow section joints. The most common ones for industrial purposes are T-, Y- and K-joints. Much research was made about these joints.

Next to the static loads, these structures are mostly induced by dynamic loads, generated by wind, ocean waves or machine vibration. The welded nodes are the weakest area at these structures. Due to the dynamic loads the fatigue life is reduced, which ends up to a crack and at the same time with collapsing of the resistance. To calculate the fatigue life of a structure and numerically simulate a crack propagation is a large research topic. In the following there is a review of research, methods, information of experimental and numerical tests regarding crack propagation given by the literature.

## 2. Crack Propagation

Yang (Yang *et al*., 2020) did experimental studies about reinforced overlapped K-joints. It was found, that in case of overlapped CHS K-joints the hidden weld has no significant influence on the bearing capacity. But the failure mode can be affected (Zhao *et al*., 2006). Yang (Yang *et al*., 2020) tested the hysteric behaviour of the joint types. With other words different K-joints are impacted by cycling loadings. It was found out, that in case of a rectangular to circular joint, the crack first arises at the intersection of the two braces and then moves along the weld to the saddle point (Fig. 1). In case of a circular to circular joint the crack first arises at the flange side of the welding toe and then moves along the welding to the heel, which can be seen in Fig. 1*d*. Like it is shown in this figure it is only valid for cycling loadings.

Islamovic (Islamovic *et al*., 2009) 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 (Mishra, 2020) collected many aspects in his presentation 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 jointed. In contrast there are disadvantages like the risk 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.

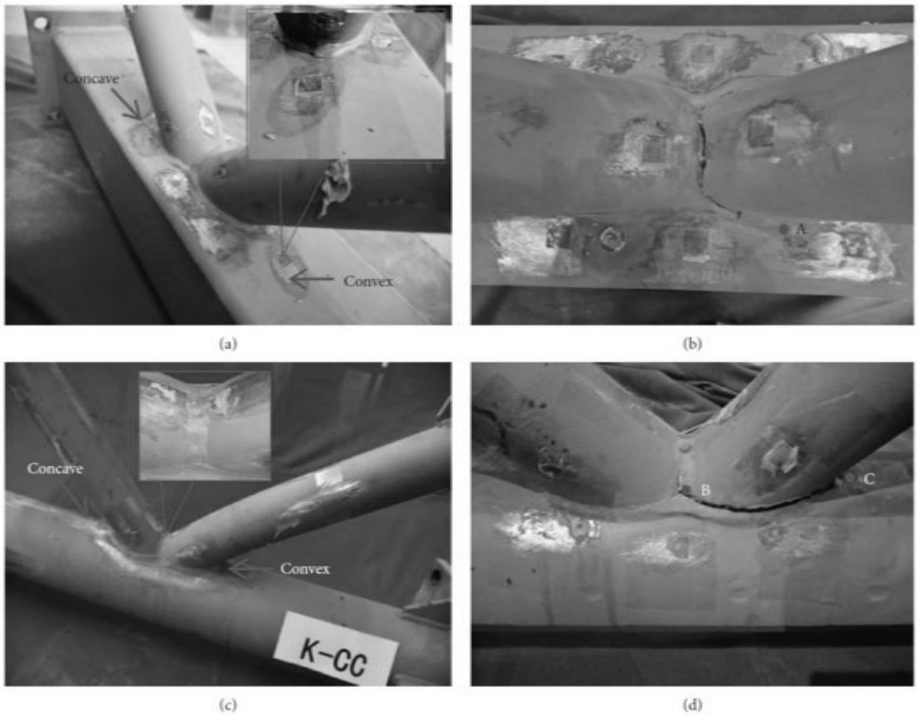



Fig. 1 – Crack propagation of an RHS to CHS and CHS to CHS joint (Yang *et al*., 2020).

### 3. Notch Effect

Remes (Remes *et al*., 2020) did numerical and experimental tests about the fatigue strength of welded joints. Especially the different weld geometry and the plate thickness are 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 Fig. 2. Beside this, different methods for calculating fatigue life were presented. Most of them were introduced in 5. 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.

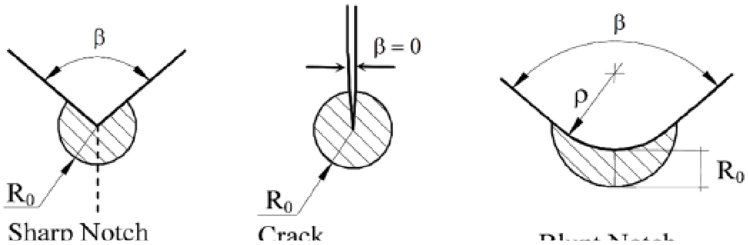



Fig. 2 – Notch geometries (Remes *et al.*, 2020).

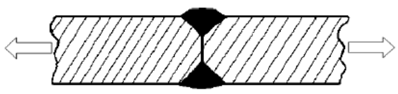
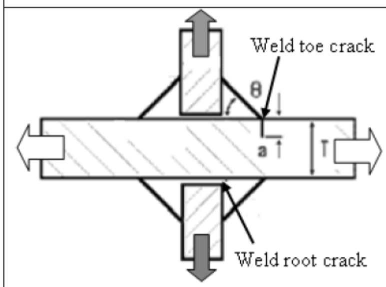
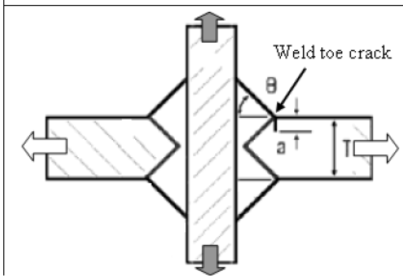
| | |
|---|---|
|  | Transverse loaded butt weld (X-groove or V-groove) with edges machined or ground flush to plate.<br>Double side complete weld penetration. Toe crack. |
|  | Transverse butt weld with weld reinforcement.<br>Double side complete penetration. Toe crack. |
|  | Transverse partial penetration butt welds, lack of penetration (LOP) considered to be as a root crack.<br>Double side incomplete weld penetration. |
|   | Cruciform joint or T-joint, fillet welds or partial penetration K-butt welds, toe and root crack.<br>Load can also be applied at the end of attached plate or main plate, in $y$-, or in $x$-direction, respectively, in case of weld root or weld toe crack consideration, respectively. $\theta$ is the weld toe angle, $a$ is the crack length, $T$ is the main plate thickness. |
|   | Cruciform joint or T-joint, K-butt welds, full penetration, toe crack.<br>Load can be applied at the end of attached plate in $y$-direction. Weld toe crack will be considered in this case. |

Fig. 3 – Fatigue cracking (Almukhtar, 2011).

Almukhtar (Almukhtar, 2011) showed a summary of the different cracks, which can occur. These are the most common crack types, shown in Fig. 3.

Chmelko (Chmelko *et al.*, 2018) did research on the notch effect of welded joints. He distinguishes between two kinds of fatigue strength reducing sources. On one hand the technological notch, which describes the inhomogeneity in the surface. Examples are cracks, bubbles, structural changes or residual stresses. On the other hand, there is the geometrical notch, which stands for geometrical discontinuities. Examples are welding errors. The total notch coefficient of a welding joint is defined by Eq. 1.

$$\beta_{\sigma(2Nf)} = \frac{\sigma^{H}_{a(2Nf)}}{\sigma^{Zv}_{a(2Nf)}} \tag{1}$$

where: $\sigma^{H}_{a(2Nf)}$ is the stress amplitude corresponding to chosen number of cycles to the fracture of the base material specimen, $\sigma^{Zv}_{a(2Nf)}$ is the stress amplitude corresponding to a certain number of cycles to the fracture of specimen with the weld joint (Chmelko *et al.*, 2018).

## 4. Stress Distribution

Stress is the main criteria in stability and resistance of structures. When there is a constant stress distribution in the cross section it is less complex to calculate. But due to different geometries or heat influence like in the welding process stress concentration in a very small area can happen. Stress concentration is a complex problem, because it depends on many factors like: weld-size effect, thickness of brace and chord, fixing the point of extrapolation, loading conditions in the brace and chord or the type of material.
There are three different types of stresses (Saini *et al.*, 2016):

1) Nominal stress

The nominal stress is the stress which is induced by axial loads or bending moments. The stress can be calculated by using the simple beam theory. The physical notation is $\sigma_{nom}$ (Eq. 2). The nominal stress does not include geometric discontinuity or welding effects.

$$\sigma_{nom} = \frac{P}{A} \pm \frac{M}{I} y \tag{2}$$

2) Geometric stress

The geometrical stress is the stress caused by geometrical differences between chord and brace. Effects are different diameters, inclination angle, shapes or welding radii. Some literature name it structural- or hot-spot-stress. The geometric stress is used to calculate the fatigue life of the structure. The physical notation is $\sigma_G$.

3) Local stress

The local stress can have some reasons. It depends on the quality of the welding. It can occur because of the notch of the welding toe. It is very difficult to calculate this effect. Experimental tests include the microstructure of the welding line. The physical notation is $\sigma_n$. Most of the calculation methods neglect this effect.

## 5. Methods

Many structures in the offshore purpose are under influence of static and cyclic loading. As a result, fatigue damage can occur. There are some more or less complex methods to calculate the fatigue resistance of a joint. Every method has got advantages and disadvantages. In the following a little summary of the common methods can be found.

The **Hot-spot stress method (HSS)** is calculated at the location where a crack is possible (Saini *et al.*, 2016; Espinosa *et al.*, 2017). The HSS is computed as linear extrapolation to the weld toe from stresses at positions near by the welding toe. In general, there are three components of notch stress, which can be seen in Fig. 4. First is the membrane stress, which is constant. The second is the shell bending stress, which varies through the thickness of the material. And thirdly the non-linear stress part which is neglected in this method. The fatigue life is defined in S-N curves. Where S is the stress range and N is the number of cycles to failure. The HSS depends on the material thickness. Because of that it is necessary to multiply the stress range with a thickness correction factor. In this method the ratio between hot-spot stress and nominal stress is called **Stress concentration factor (SCF)**.

$$SCF = \frac{\sigma_{HSS}}{\sigma_{nom}} \tag{3}$$

Eq. (3) is valid for a one-load case. With other words when the brace or the chord is induced by a force. In a multi-load case, Eq. (4) has to be used in where k is the loading type.

$$HSS' = \sum_k (SCF)_k \, \Delta\sigma_{nom}^k \tag{4}$$

In the evaluation of an experimental test by the HSS, Eqs. (5), (6) is needed, with ν Poisson's ratio, $\xi_n$ the nominal strain, $\xi_\perp \xi_\perp$ the hot-spot strain perpendicular and $\xi_{||}$ the hot-spot strain parallel to weld toe.

$$SCF = \frac{1+\nu\frac{\xi_{||}}{\xi_\perp}}{1-\nu^2} SNCF \tag{5}$$

$$SNCF = \frac{\xi_{||}}{\xi_{nom}} \tag{6}$$

In the experiments the hot-spot strains can be measured in both directions by strain gauges. The fatigue damage of steel tubular joints is proportional to $\Delta S^3$, given by the recommended Wöhler exponent m = 3 tabulated in guidelines (Espinosa *et al*., 2017). Espinosa *et al*. also explain, that an uncertainty of 20% on the SCF yields deduces approximately a 70% uncertainty in fatigue life (Espinosa *et al*., 2017).

The **Mesh insensitive structural stress method (SSM)** is a robust method based on the mesh size (Saini *et al*., 2016). In this method structural stress is calculated by nodal forces of Finite Element Method (FEM). A master S-N curve is established for a wide variety of joints including typical tubular joints. The structural stress is the sum of membrane stress (Eq. 7) and bending stress (Eq. 8). Eq. 9 shows the nonlinear stress. Fig. 4 shows graphical version of the equations.

$$\sigma_{mem} = \frac{1}{t}\int_{x=0}^{x=t} \sigma(x)dx \tag{7}$$

$$\sigma_{ben} = \frac{6}{t^2}\int_{x=0}^{x=t} (\sigma(x) - \sigma_{mem})\left(\frac{t}{2} - x\right)dx \tag{8}$$

$$\sigma_{nlp} = \sigma(x) - \sigma_{mem} - \left(1 - \frac{2x}{t}\right)\sigma_{ben} \tag{9}$$

Saini found out, that the structural stress method is far more effective than conventional hot-spot stress method.

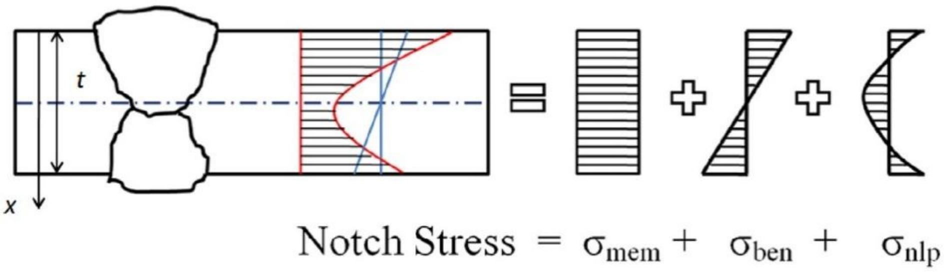



Fig. 4 – Components of the stress distribution through the thickness of the weld plate (Saini *et al*., 2016).

The **Extrapolation methods** is an addition for the HSS method (Saini *et al*., 2016). The HSS does not include stresses caused by the welding. For experimental tests it is not easy to measure the stress in the welding toe, because there is no possibility to fix the strain gauge at the welding toe and get realistic results. The strain gauge has to be fixed close to the welding joint in a definitely distance and combines the results with a mathematical extrapolation method. In the literature there are different recommendations for the maximum extension. Most of them are in the range of 6 mm to $0.1 \cdot \sqrt{r \cdot t}$. In General, there are two extrapolation methods, the linear and the quadratic. The linear can be used for square and rectangle hollow profiles, the quadratic for circular hollow profiles which will be the interesting part for this thesis. Like Fig. 5 shows, the linear method just needs two measurement points. These points should have a distance of 0.4t and 0.6t from the welding toe. In this ‘t’ is the thickness of the tubular member.

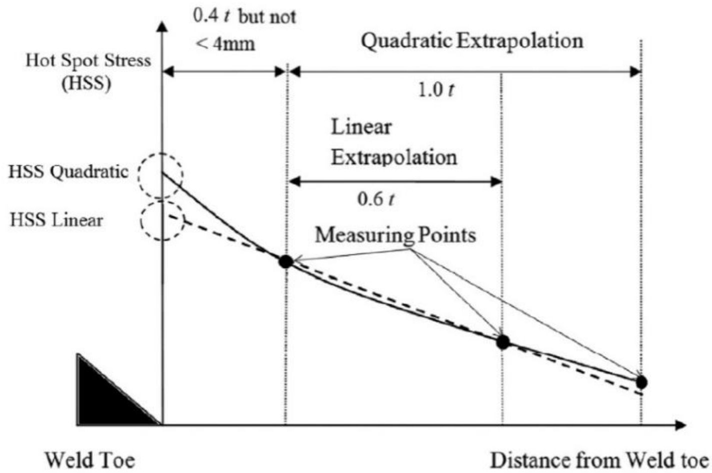



Fig. 5 – Extrapolation methods (Saini *et al.*, 2016).

To simulate a joint with the extrapolation method a couple auf FEA parameters are needed. Besides this parametric equation are needed to determine the SCFs. There are different equations, the most common ones are the: Kuang, Wordsqorth/Smedley, UEG, Efthymiou/Durkin, Hellier, Connolly and Dover, Lloyd’s register, Morgan and Lee equations.

The **Peak-stress method (PSM)** (Meneghetti and Campagnolo, 2018) is next to the HSS and SSM a method to calculate the fatigue design in welded joints. It is based on the **Notch Stress Intensity Factor (NSIF)**. With the PSM it is possible to estimate the mode 1 SIF (explained late this page) of a crack emanating from an ellipsoidal cavity. The NSIF can be defined by Eq. (10).

$$K_i = \sqrt{2\pi} \cdot \lim_{r \to 0} \left[ \left(\sigma_{jk}\right)_{\theta=0} \cdot r^{1-\lambda_i} \right] \tag{10}$$

where: $i = 1,2,3$ and $\sigma_{jk} = \sigma_{\theta\theta}, \tau_{r\theta}, \tau_{\theta z}$

The stress components along the notch bisector line $\theta = 0$ can be calculated by FEA. $\lambda_i$ is the stress singularity for mode 1, 2 or 3. Cracks appear mainly in a semi-elliptical shape (Djokovic *et al.*, 2018). This approach should have better accuracy than the other methods. In some literature a more 'exact' definition of the K1-K3 NSIFs values are given with Eqs. (11)-(13), which is derived from Eq. (10):

$$K_{FE}^{1} = \frac{K_1}{\sigma_{\theta\theta,\theta=0,peak} \cdot d^{1-\lambda_1}} \quad (11)$$

$$K_{FE}^{2} = \frac{K_2}{\tau_{r\theta,\theta=0,peak} \cdot d^{1-\lambda_2}} \quad (12)$$

$$K_{FE}^{3} = \frac{K_3}{\tau_{\theta z,\theta=0,peak} \cdot d^{1-\lambda_3}} \quad (13)$$

where: *d* is a global element size to input *e.g.* in Ansys software. The PSM estimates the NSIF from the singular, linear elastic, opening, sliding and anti-plane FE peak stresses, referred to the V-notch bisector line. This approach seems to be the most complex one in comparison to HS and SSM.

The sensitive to fatigue can be estimated in two ways: Firstly, there isthe empirical S-N method, secondly the **Linear-Elastic-Fracture-Mechanics** principles **(LEFM)** (Djokovic *et al.*, 2018) can be used. The LEFM considers the growth rate of existing defects in each phase of their expansion and is most convenient for estimating the remaining working life of welded structures (Djokovic *et al.*, 2018). There are three phases of fatigue fracture. It starts with the crack initiation, then the crack growth and after that the fracture. The fracture occurs abruptly. The results can be drawn in a diagram in K/$\sigma_n$ over a/t or da/dN over a/T where a is the crack length, T the thickness, $\sigma_{ij}$ the stress at the crack tip (Eq. (14)), $\sigma_n$ is the normal stress (Eqs. (16)-(18)), $M_k$ correction factor and K the **stress intensity factor(SIF)** (Eq. (15)).

$$\sigma_{ij} = \left(K/\sqrt{2\pi r}\right) f_{ij}(\theta) \quad (14)$$

$$K = Y \cdot M_k \cdot \sigma_n \sqrt{\pi a} \quad \textbf{(SIF)} \quad (15)$$

The stress intensity factor controls the crack propagation and the size of the plastic zone around the crack tip (Djokovic *et al.*, 2018).

$$\sigma_n = \frac{P}{\{\pi[r^2-(r-t)^2]\}} \quad \text{for axial loading} \quad (16)$$

$$\sigma_n = \frac{4rM_f}{\{\pi[r^4-(r-t)^4]\}} \quad \text{for in-plane bending} \quad (17)$$

$$\sigma_n = \frac{4rM_t}{\{\pi[r^4-(r-t)^4]\}} \quad \text{for out-of-plane bending} \quad (18)$$

To get the fatigue crack growth rate the Paris-Erdogan equitation Eq. (19) can be used.

$$(da/dN) = C(\Delta K)^m \tag{19}$$

Beside the described method there is another indirect method to get the SIF. It is called **Virtual Crack Closure Technique (VCCT)** (Jacob *et al*., 2019; Wang *et al*., 2013). Like in Eq. (15) the notation of SIF is K. But it can also be defined by the strain energy release rate Eq. (20).

$$G = \frac{K^2}{E(1-\nu^2)} \tag{20}$$

The amount of energy dissipated per unit crack growth and per unit thickness. All the parameters which are needed for the VCCT can be extracted by *e.g.* Abaqus. For the crack propagation Eq. (21) can be used to get the range of the stress intensity factor Eq. (22).

$$G = -(0.5t \cdot \Delta \cdot a)\left(F_{yd} \cdot U_{yb} + F_{yd} \cdot U_{yc}\right) \tag{21}$$

$$\Delta K_{eff} = K_{max\,,RS} - K_{min\,,RS} \tag{22}$$

The relation between the stress and the strain can be described by Eq. (23) and Eq. (24) (Jacob *et al*., 2019).

$$\varepsilon_T = ln(1 + \varepsilon) \tag{23}$$

$$\sigma_T = \sigma(1 + \varepsilon) \tag{24}$$

where: $\varepsilon_T$ is the true- and $\varepsilon$ is the engineering-strain. $\sigma$ is the notation for the stress.

Liu (Liu and Liu, 2019) gave a summary of research on fatigue life assessment of welded joints. Four widely used fatigue life prediction methods were compared. All four methods, the nominal stress method, the hot-spot stress method, the notched stress method and the fracture mechanics method were explained above. The nominal stress method is the most widely used method. Fig. 6 shows a diagram of the nominal stress, hot spot stress and notched stress. It was concluded, that the nominal stress method is the most widely used method, but it is too conservative. The hot spot stress method is highly precise, but the scope is limited. The notch stress method considers the source of all stress concentrations, but it is not suitable for welded butt joints. The fracture mechanics method has a good effect in the crack propagation stage.

Recho (Recho and Remy, 1989) did a summary of the probabilistic to fatigue life of tubular joints. These are based on the use of fracture mechanics method to determine either the crack length as a function of several parameters which can be random, or the number of cycles to failure as a function of these parameters. It was concluded, that the accuracy of the results depends on two aspects. Firstly, the fitness of the deterministic fracture mechanic model is considered and the available statistics of each random variable taken into account in the model.

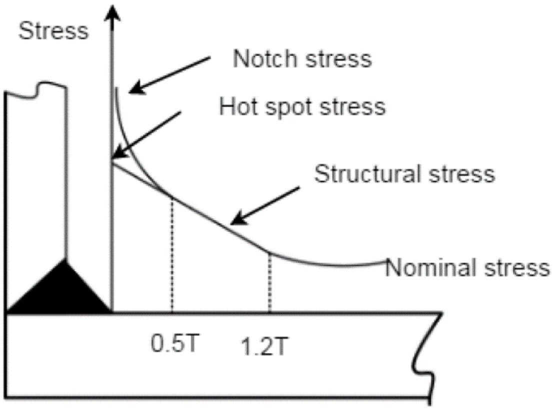



Fig. 6 – Diagram of nominal, hot-spot and notched stress (Liu and Liu, 2019).

### 5.1. J-Integral and CTOD

Doncheva (Doncheva *et al.*, 2018) did research on crack propagation. In her paper she explained the methods to get the elastic-plastic fractures parameters for characterization of the material state around crack tip: J-integral and CTOD. The J-integral method is implemented as standard option to Abaqus. Isoperimetric square finite elements with 4-node (2D) were used with a size of 0.2 x 0.2 mm. Crack growth has been simulated by tracing the path of completely or with other words by multiplying the original length of an element with the number of completely damaged elements. In general, there are six possible methods to simulate crack propagation: element splitting, node releasing, element deleting, stiffness decreasing, remeshing and extended finite element method. Doncheva concludes with reducing the size of the elements and increasing the void volume fraction, there is a loss of load bearing capacity, which also affects the lower crack resistance. The shape and size of the finite elements near the crack affects the results. At low load levels, before plastic zone, there is no effect due to the inhomogeneity of the yield properties.

### 5.2. Weibull

Swaddiwudhipong (Swaddiwudhipong *et al.*, 2011) did research on offshore structures and analysed numerical simulations by the Weibull stress method. It represents a cleavage fracture driving force with the notation $\sigma_W$. The

Weibull stress model considering strain gradient plasticity. Conventional treatment of cleavage fracture normally combines the classical theory of plasticity with the widely recognized Weibull statistical approach. Swaddiwudhipong showed that the crack tip stress is significantly higher than HRR solutions using $C^0$ element based on **Conventional Mechanism-Based Strain Gradient (CMSG)** theory (Eq. (25)):

$$\sigma_f = \sigma_Y \sqrt{f^2(\varepsilon^p) + l\eta^p},\ l = 18b\left(\frac{\alpha\mu}{\sigma_Y}\right)^2,\ \eta^p = \sqrt{\eta^p_{ijk}\,\eta^p_{ijk}}/2 \qquad (25)$$

where: $f$ material yield function, $\sigma_Y$ yield stress in uni-axial tension, $b$ magnitude of Burgers vector, $\eta^p_{ijk}$ plastic strain gradient vector, $\sigma_f$ the flow stress, $l$ the material length scale , $\eta^p$ effective plastic strain gradient tensor.

There are two types of crack models. The first one is a mathematically sharp crack tip and the second is a practical notched crack tip with an initial root radius. Swaddiwudhipong chose an element size of 2 nm. Because of this small size, the dimension of the whole model was also relatively small. Otherwise the computational time would increase dramatically. Abaqus is one of the most common numerical software. The Abaqus simulation was extended by the users-subroutine UMAT. The element type is a 20-node solid finite element with reduced integration. The boundary conditions correspond to a simple beam for X-joint. The material properties were chosen as: Young's modulus 205 GPa, Poisson's ratio = 0.3, strain hardening exponent N = 0.2 and $\sigma_Y$ = 410 MPa. The cumulative probability of cleavage fracture is defined by Eq. (26), before finally the Weibull stress can be calculated by Eq. (27):

$$P_f(\sigma_w) = 1 - exp\left[-\frac{1}{V_0}\int_V \left(\frac{\sigma_1}{\sigma_u}\right)^m dV\right] = 1 - exp\left[-\left(\frac{\sigma_w}{\sigma_u}\right)^m\right] \qquad (26)$$

$$\sigma_w = \left[\frac{1}{V_0}\int_V \sigma_1^m dV\right]^{1/m} \qquad (27)$$

where: $\sigma_1$ is the principal stress, $\sigma_u$ Weibull stress at failure probability $P_f = 0.632$, Weibull modulus $m$ = 10-20 and $V_0$= 1 unit ($mm^3$)

Swaddiwudhipong describes that about 5% deviations of the numerical results from the test data are observed. The strength enhancements of the grouted joints are observed to be about 2 - 3 times compared to those of the un-grouted specimens for larger (closer to one) values of $\beta = 1$.

## 6. Modelling

Atteya (Atteya *et al.*, 2019) did studies about crack propagation modelling in tubular joints. Especially the focus was on fatigue cracks due to cycling loadings in the field of offshore. These environmental loadings generated multi-planar stresses. The calculation methods can be seen in chapter 4. The following can be seen as an addition. The fatigue resistance can be calculated by S-N curves. Mainly the crack initiation and the crack propagation are split in four aspects. The first is the temporal point where the crack firstly is noted. The second is the notice of the visual crack. Thirdly, there is the through-thickness crack before fourthly there is the complete failure of the node. Fig. 7 visualises the Finite Element approach for the crack propagation. Zhang (Zhang and Stacey, 2008) did experimental tests with a total number of 281 about the ratio between the third and fourth aspect. It is given by 1.38. The numerical methods are FEM, extended finite element method (XFEM) and boundary element method (BEM). FEM is the most popular one, while the literature gives only two examples for the other two methods. To model a surface crack is much more complex than a through-thickness crack.

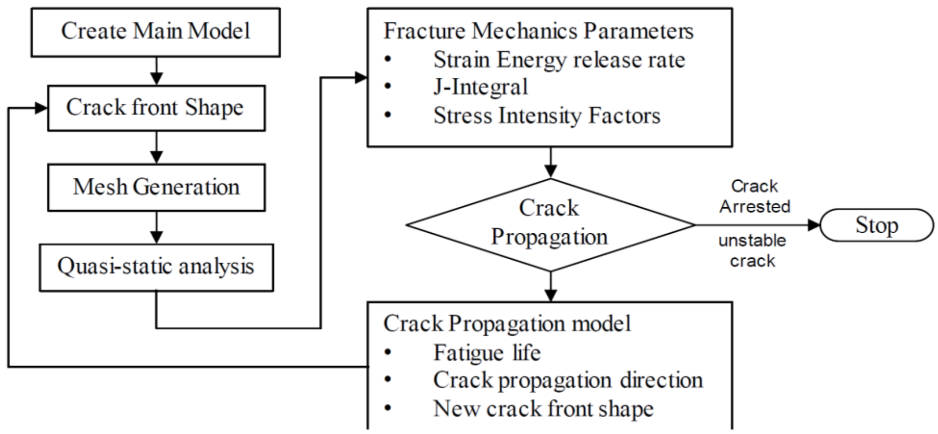



Fig. 7 – FE approach for crack propagation (Atteya *et al.*, 2019).

Reason for that is, that there are two stress field singularities. On one hand the near field singularity, which is over most of the crack front and on the other hand the Vertex stress singularity, which arises at the corner points. The Vertex stress is dependent on the Poisson' s ratio, the angle between the crack front and the free surface. Atteya explains, that there are two types of mesh generators. It is the structural and unstructured mesh generator. The structured mesh approach was described as building block algorism. It started with a discretization of a plain plate containing a semi-elliptical crack. The unstructured mesh approach is used by inserting an initial semi-elliptical surface crack at the weld toe. A solid element is applied for the cracking surface. This procedure is repeated for every increment of the crack.

Qian (Qian *et al*., 2002) did a comparison about FE mesh generators for unreinforced CHS T-, X- and K-Joints.

## 7. Repaired Welds

Farrahi (Farrahi *et al*., 2013) did research about the fatigue life of repaired welded tubular joints. In industrial unit, repaired welds are a large issue. It was found out, that the successfulness of fatigue life extension is about two factors. Firstly, the crack must be removed, before the size is larger than 30% of the plate thickness. Secondly, the crack initiation must take place at the repair ends. Farrahi explained, that the residual stress significantly influences the crack growth rate. A X-joint with repaired welding lines was tested under a fatigue loading of 600 kN and frequency of 5 Hz together with a stress frequency of 0.1. It was concluded that repaired welds raise the fatigue resistance by 150%. So, repairing welding can improve the fatigue behaviour of tubular joints significantly.

## 8. Conclusions

The paper summarises the state of art of crack propagation modelling. Next to the physical aspects, like stress distributions or notch effect, different calculation methods are shown. They are split in experimental and numerical analysation.

Much research was done so far to crack propagation, but most of the methods have got limitations. With other words, more research is necessary to this topic. The purpose of these researches will be to monitor welded joints with two or more bars in the structural node, so that transformation factors can be identified and used for to calibrate the FEM models. We assume that the calibration factors will depend on the number of bars in the node, the angle of incidence in relation to a characteristic axis for the joint, as well as on bars geometric characteristics and physical-mechanical characteristics of bars materials.

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STUDIU PRIVIND PROPAGAREA
FISURILOR ÎN CADRUL ÎMBINĂRILOR DINTRE ȚEVILE
CIRCULARE DIN OȚEL

(Rezumat)

Îmbinările elementelor liniare de tip țevi circulare din oțel sunt adesea utilizate pentru realizarea elementelor structurale ale construcțiilor industriale, precum grinzile cu zăbrele sau stâlpii reticulari. Este cunoscut faptul că zona de îmbinare dintre elementele liniare reprezintă zona cea mai sensibilă a unei grinzi cu zăbrele. Datorită raportului avantajos dintre greutate și rezistență, țevile din oțel sunt utilizate pentru a rezolva diferite probleme structurale. În analiza elementelor structurale realizate din țevi din oțel, pe lângă probleme statice clasice, trebuie luate în considerare diferite aspecte ce influențează comportamentul non-liniar al elementelor, ca geometria sau tipul și modul de realizare a sudurii. Rezistența la oboseală a sudurilor realizate în îmbinare este influențată negativ de încărcările dinamice rezultate din acțiunea vântului, a oceanelor sau a utilizării de utilaje în interiorul construcțiilor. Astfel, în perioada de utilizare a unei clădiri, în cadrul îmbinărilor realizate pot să apară mai multe tipuri de fisuri, iar reproducerea numerică cât mai fidelă a modului de apariție și propagare a acestor fisuri reprezintă unul dintre cele mai importante aspecte care trebuie rezolvate în etapa de proiectare. Pe această temă a fost realizată o serie largă de cercetări, iar în cadrul prezentului articol sunt prezentate aspectele principale ce țin de metodele de modelare a îmbinărilor sudate dintre elementele liniare de tip țeavă din oțel și a modului de apariție și propagare a fisurilor.