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Assessment of behaviour of tubular joints in offshore structures according to the standards Norsok N-004, ISO 19902 and Eurocode 3-Part 1-8

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RESUMO

Na presente tese estuda-se o comportamento mecânico de ligações entre perfis tubulares, as quais são as mais comuns nas estruturas offshore. Efetuou-se uma descrição geral das ligações tubulares (X-,Y- e K-) bem como um estudo ao comportamento que estas exibem. Estudou-se, ainda, ligações tubulares reforçadas (chord can) uma vez que se trata de uma solução útil que confere resistência ao conjunto sem alterar significativamente a geometria da mesma.

Realizou-se um estudo sobre os regulamentos utilizados no dimensionamento de ligações em estruturas offshore, como é o exemplo de Norsok N-004, ISO 19902 e EC3 -1-8, com vista à aplicação destas e posterior comparação. Através do mesmo, constatou-se que factores como o estado de tensão, o tipo de carga na diagonal e a configuração da geometria influenciam significativamente os resultados. Analisaram-se algumas ligações correntes, sujeitas a diferentes cargas, de forma a retirar conclusões.

De forma a obter informação detalhada acerca do comportamento mecânico das ligações entre perfis tubulares, efetuou-se uma análise plástica estática. Realizou-se, ainda, uma análise numérica com base no MEF no software Abaqus CAE , para além de uma pesquisa a investigações anteriores de forma a que os resultados numéricos pudessem ser validados. Uma vez efetuada e validada a análise numérica, realizou-se um estudo paramétrico de forma a compreender a influência do parâmetro "y" na ligação. Os resultados mostraram que, para pequenos valores de "y", as ligações apresentam uma boa resistência axial e de flexão para além de que os valores obtidos analiticamente encontram-se próximos da zona de cedência, para valores de "y" mais altos observa-se uma redução considerável da resistência enquanto os valores analíticos obtidos através das curvas Força/Momento-Deslocamento/Rotação se encontram mais abaixo da zona de cedência. O que acontece para evitar rotura local que usualmente ocorre antes da rotura global nas seções com baixa capacidade de carga axial e de momento fletor.

Palavras-chave: Ligações tubulares, Capacidade resistente, Analise de Elementos Finitos, Parametrização.

ABSTRACT

This thesis studies the mechanical behaviour of tubular joints which are the most common connections on offshore platforms. A general description of tubular joints (X-, Y- and K-) and its structural behaviour is done. Reinforcement (chord can) on tubular joints is also revised as it is a very useful resource that strengthens the joint without significant changes in the geometry.

A preliminary study about the current regulating standards (Norsok N-004, ISO 19902 and EC3-1-8) in tubular joints is performed. Therefore, deep comparison among standards results is done so as to understand the differences and similarities. It was found that factors that accounts for the chord stress state, type of loading on the brace and geometry configuration were very significant in the results. Useful cases studies are performed for each joint with different loads to have a better idea about those conclusions.

In order to enter in more detail about the mechanical behaviour of tubular joints, a static plastic analysis is carried out. Then, a finite element analysis was performed and to validate the results of our model, comparison with a previous research was done and satisfactory results were obtained to continue our research. Once validation is done, parametric study is considered to find out if the parametric factor "γ" has a high influence in joint strength. Several values of "γ" for each joint were calculated numerically with Abaqus CAE and Load/Moment-Displacement/Rotation curves obtained to be compared with design strengths from standards. Results demonstrated that for small values of "γ", joints had a very good axial and bending capacity and standard design strengths were located nearby the yielding zone. However, for large values of "γ", reduction of the strength was considerable and standard design strengths were located much more below the yielding zone. This is to avoid local failure which usually occurs before yielding in sections with low axial and moment capacity.

Keywords: Tubular joints, Strength capacity, Finite Element Analysis, Parametric study.

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1 INTRODUCTION

The analysis, design and construction of offshore structures are perhaps one of the most demanding sets of tasks faced by the engineering profession. Over and above the usual conditions and situations met by land-based structures, offshore structures have the added complication of being placed in an ocean environment where hydrodynamic interaction effects and dynamic response become major considerations in their design. The range of possible design solutions leads to their own peculiar demands in terms of, for example, hydrodynamic loading effects, foundation support conditions. Technically, offshore structures design and construction are a hybrid of steel structure design and harbour design and construction (El-Reedy, 2012).

Although the oil and gas business is one or the most lucrative in the world, only a limited number of faculties of engineering focus on offshore structural engineering, including the design of fixed offshore platforms, floating or other types of offshore structures. This fact is perhaps due to the limited number of offshore structural projects in comparison to the number of building steel structural projects, such as residential and factories. In addition, offshore steel structure construction depends on continuous research and study drawn from around the world. Furthermore, the continuous increase in the water depth for which these structures have to be designed require the use of demanding technologies and always new modelling approaches to understand how these structures behave under realistic loads.

Among the several types of offshore structures, steel structures with tubular elements will have more consideration in this thesis and specially one of its most important components will be here studied: The tubular joints. When designing tubular structures, it is important the designer considers the joint behaviour right from the beginning. Designing members based only on the member loads may result in undesirable stiffening of joints afterwards. This doesn’t mean that the joints have to be designed in detail at the conceptual design phase. It only means that the chord and brace members have to be chosen in such way that the main governing joint parameters provide an adequate joint strength and an economical fabrication (J. Wardenier *et al*, 2008).

1.1 Framework

Research in offshore structures is such a wide area that is impossible to treat their main characteristics in this thesis. The purpose of this thesis is to study a component of the jacket structures, the Tubular Joints.

Fixed jacket structures are defined by tubular members interconnected to each other forming a three dimensional stiff truss system, see Figure 1.1. These structures usually have four to eight legs with the outside legs brace with vertical, horizontal and diagonal tubular members to achieve better stability against collapse. Main piles, which are also tubular, are usually driven through the jacket legs into the seabed.

Figure 1.0.1- Jacket structure (J. Wardenier et al, 2010).

The term jacket structure has evolved from the concept of a structure hanging from and enclosing the top of the piles. These platforms generally support a superstructure having two or three decks with drilling and production equipment and work over rigs. The jacket also must provide support for boat landings, mooring bits, barge bumpers, the corrosion protection system and many other platform components (El-Reedy, 2012).

As already mentioned above, jacket structures are defined by bracing systems, tubular members interconnected to each other with joints, which are required to bear all the loads from the decks. About the bracing systems, there are variations of the bracing pattern, and every system has its advantages and disadvantages. The bracing systems are defined with joints, which simple joints configurations could be K, Y and X. About the advantages and disadvantages of these joints, for example, the K brace has fewer members intersecting at joints, so it has reduced welding and assembly costs. But its disadvantage is that has less redundancy than X joint (El-Reedy, 2012)

The joint strength is influenced by the geometric properties of the members; optimum design can be only obtained if the designer understands the joint behaviour and takes it into account in the design.

1.2 Objectives

The purpose of this thesis is to study the strength of the planar tubular joints. For that, a parametric study with different geometric properties will be performed and evaluated.

In order to achieve our goals, the analysis obtained from a numerical analysis is compared with the main standards on the oil and gas industry and CEN european standards, Norsok N-004 (Norsok N-004, 2013), ISO 19902 (ISO 19902, 2007) and Eurocode 3-Part1-8 (EC3-1-8, 2005), as they regulate the security and structural integrity of any component. Secondly, a guideline will be done to demonstrate the design strength of some tubular joints. In order to achieve the first goal, a numerical analysis will be put into practice to carry out a static plastic non-linear analysis with the software Abaqus CAE (Abaqus, 2011). Thirdly, a parametric study will be done to find out the most important parameters which have major influence in joint strength and finally, conclusions will be drawn and discussed from obtained results.

1.3 Organization

Several issues will be exposed in this report so the reader could comprehend the steps taken to achieve the final design of tubular joints and understand the parameters that lead to the strength of those elements. Therefore, Chapter 1, is an introduction to get into the offshore overview and manage to know what kind of problems will be faced. Chapter 2 consists briefly in all the research done about regulating standards in offshore structures and strength of tubular joints until now. Then, results of those reports will be exposed and consequently reasons about why this research is needed will be given.

From Chapter 3, analysis on tubular joints is considered, starting with the codes and standards that regulate their design as well as guidelines to estimate their design strength according to those. Chapter 4 deals with the numerical analysis with the software Abaqus CAE, a powerful tool in numerical methods and simulation. Validation of results from static plastic analysis will be performed as well as a general explanation about the numerical characteristics (type elements, mesh, etc) will be exposed. Chapter 5 deals with the parametric study which is about finding out the most important parameters that affect the most to the joint strength. That way, different results will be obtained and compared to each other. Finally, Chapter 6 and 7, results obtained from the previous chapters will be discussed and conclusions will be drawn to lead future research on tubular joints.

2 JOINT BEHAVIOUR - A REVIEW

Offshore structures have experienced a wide spread around the world, especially oil and gas platforms and lately wind farms as every time population needs more energy. However, finding new locations to pursue natural resources is becoming complicated and new technologies to reach them are needed. Thus, more research related to offshore structures is being developed. The offshore structures analysis is a huge area to be studied and presented in one master thesis. A general overview about offshore structures is exposed below in order to understand the most common existing types of structures on this area.

Currently many types of offshore structures have been created due to the complexity of its environment, see Figure 2.1. Each one of them is aimed to reach deeper places and bear considerable environmental loading.

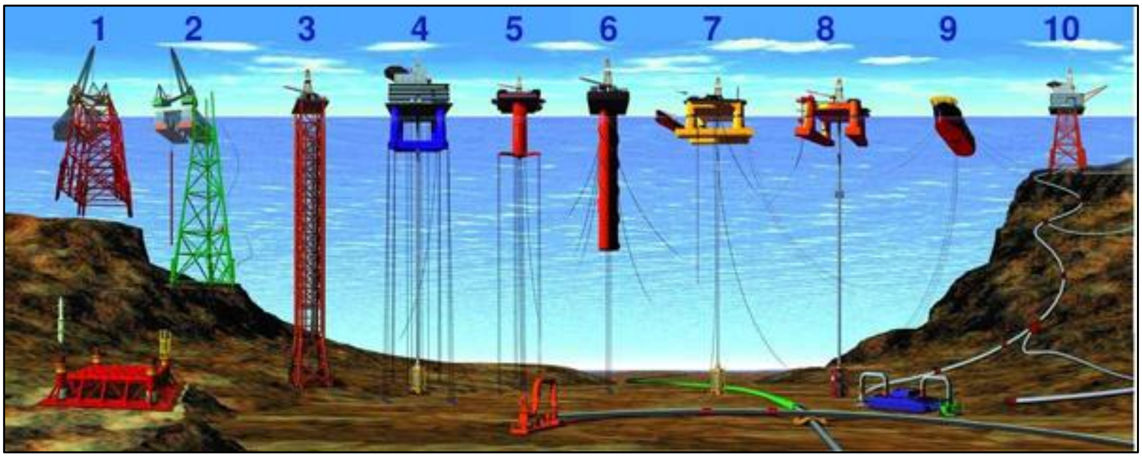
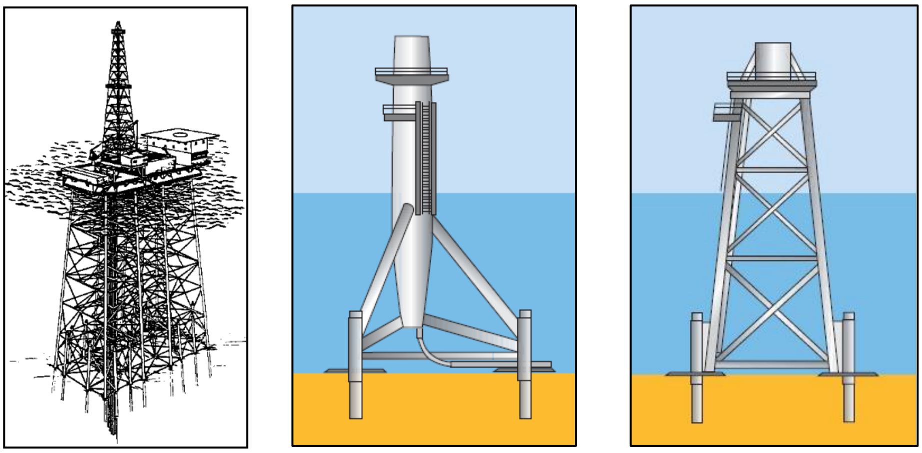


Figure 2.1- Types of offshore structures (NOAA, 2010)

Although several factors are considered for design of these structures, the most demanding is depth. As Figure 2.1 shows, depth is very important when it comes to decide the most optimum solution: (1), (2) Fixed structure; (3) Compliant tower; (4), (5) Tension Leg Platform; (6) Spar; (7),(8) Semi-Submersible; (9) Floating production, storage; (10) sub-sea completion and tie-back to host facility.

This thesis only deals with the study of steel tubular joints which belong to tubular structures used in Jacket platforms, an offshore fixed structure, see Figure 2.2. As mentioned before, these structures are usually considered for a depth up to 520m and suffer a lot of lateral loads due to oceanic currents and waves but are a good and feasible solution when it comes to the design of offshore wind farms which are not required to be deep (20-80m) (EESI, 2010).



(a) (b) (c)

Figure 2.2- (a) Jacket platform (Ben C. Gerwik Jr, 2007); (b) (c) common foundation for wind turbines, tripod and jacket respectively (EWEA, 2011)

2.1 Tubular joints

Tubular joints are defined by the intersection of tubular members and bear all type of loading. Then, tubular joints are usually subject to local stress concentrations that may lead to local yielding and plastic strains at the design load. During the service life, cyclic loading may initiate fatigue cracks making additional demands on the strength design.

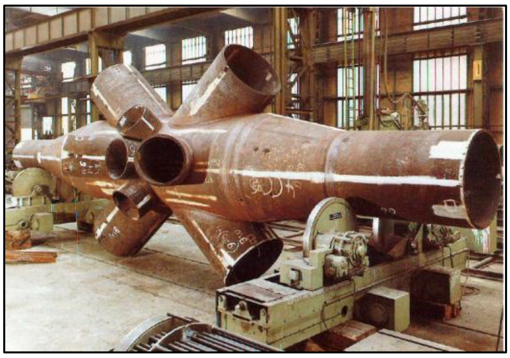


Figure 2.3- Complex multiplanar welded joint (J. Wardenier *et al*, 2008).

Firstly, geometric characteristics need to be defined to understand the coming process of analysis and formulations. A general simple planar joint is given as example in Figure 2.4:

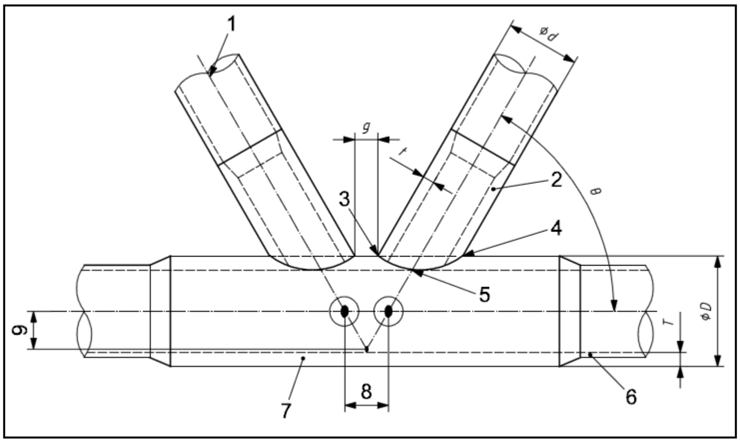


Figure 2.4- Simple tubular joint (ISO 19902, 2007)

Where: 1. Brace; 2. Stub (if present); 3. Crown toe; 4. Crown heel; 5. Saddle; 6. Chord; 7. Can; 8. Offset; 9. Eccentricity. θ, is the included angle between chord and brace axes and g, is the gap between braces, negative for overlapped stubs.

Moreover, additional parameters are calculated to consider the geometry of the tubular joint:

$$\beta = \frac{d}{D} \qquad \gamma = \frac{D}{2T} \qquad \tau = \frac{t}{T} \tag{1}$$

Where: t, is brace wall thickness at intersection; T, is chord wall thickness at intersection; d, is the brace outside diameter; and D, is the chord outside diameter.

2.1.1 Joint classification

Currently, there are three main types of simple and planar tubular joints, Figure 2.5. Each one has its own mechanical behaviour as described below (ISO 19902, 2007).

- A Y-joint consists of chord and one brace. Axial force in the brace is reacted by an axial force and beam shear in the chord.
- A K-joint consists of a chord and two braces on the same side of the chord. The components of the axial brace forces normal to the chord balance each other, while the components parallel to the chord add and are reacted by an axial force in the chord.
- An X-joint consists of a chord and two braces, one on each side of the chord, where the second brace is a continuation of the first brace. Axial force in one brace is

transferred through the chord to the other brace without an overall reaction in the chord.

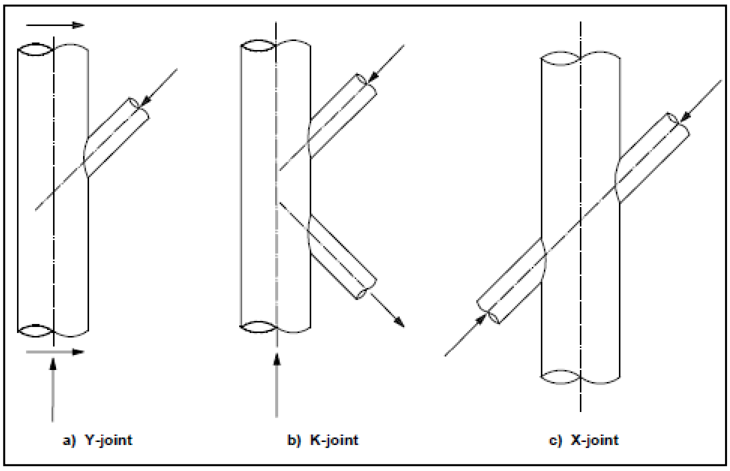


Figure 2.5- Simple planar tubular joints (ISO 1990, 2007)

From figure 2.5, new and complicated joints may be created. In all joint types, the chord is the through member.

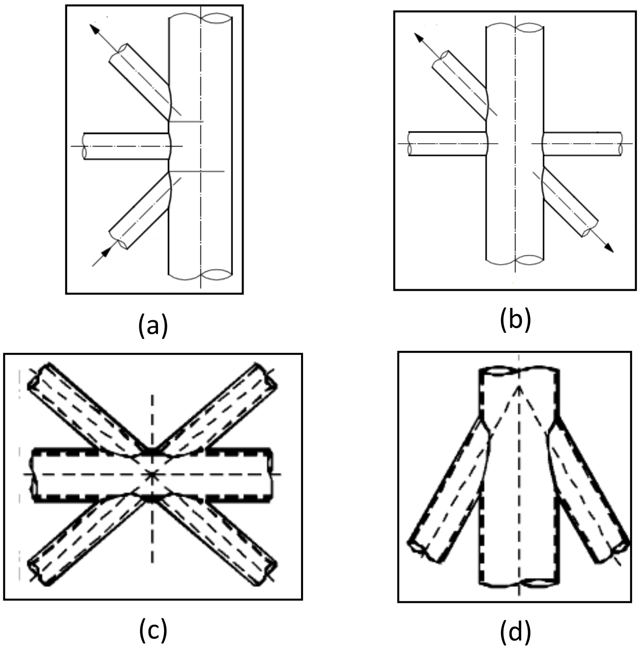


Figure 2.6- Examples of several joints (EC3-1-8, 2005 and ISO 19902, 2007)

According to the typologies presented in figure 2.5, new and more complicated joints can create (a) KT-joint, (b) NX-joint, (c) DK-joint, (d) DY-joint (Figure 2.6). Many joints are combinations of the above joint types, containing mixtures of behaviour either in one plane or in several planes (multi-planar joints). Joint classification among Y-, K- and X-joints is based solely on consideration of the axial forces in the braces.

Jacket structures are normally space frames, containing both multiplanar and planar Y-, K-, X-joints. The practical use of the basic joint formulation shall reflect, as closely as possible, the force pattern assumed in deriving the formulas by classifying each combination of brace(s) and chord according to the flow of the axial force in the brace(s). A joint should be classified as combinations of Y-, K- and X-joints when the behaviour of the braces contains elements of more than one type.

Classification as a Y-, K- or X-joint shall apply to the combination of an individual brace with the chord, rather than to the whole joint, on the basis of the axial force pattern for each load case. This classification is relevant to both fatigue and strength considerations.

The classification of each individual brace-chord combination for a given load case shall be as a Y-, K- or X-joint. If the brace-chord combination carries part of the axial brace force as a K-joint, and part as a Y-joint or X-joint, it shall be classified as a proportion of each relevant type, e.g. 50 % as a K-joint and 50 % as an X-joint. The subdivision in Y-, K- and X-joint axial force patterns normally considers all members in one plane at a joint; brace planes within ±15° of each other may be considered as being in the same plane (ISO 19902, 2007).

The classification should be based on the following:

- A brace should be classified as a K-joint only if the component of axial force in the brace perpendicular to the chord is balanced to within 10 % by force components (perpendicular to the chord) in other braces in the same plane and on the same side of the joint.
- A brace should be considered as a Y-joint if it does not meet the criteria for a K-joint and if the component of axial force in the brace perpendicular to the chord is reacted as beam shear in the chord.
- A brace should be considered as an X-joint if it does not meet the criteria for a K-joint or a Y-joint; in this classification the axial force in the brace is transferred through the chord to the opposite side.

2.1.2 Detailing practice

Joint detailing is essential element for joint design. Where an increased wall thickness or higher yield or toughness properties is required for the chord, this material should extend beyond the outside edge of incoming bracing, see Figure 2.7.

The strength of Y- and X-joints is a function of the can length and short can lengths can lead to a reduction of the joint strength. Increasing the can lengths beyond the minimum values given, should be considered to avoid the need for downgrading strength. Where an increased brace wall thickness or higher yield or toughness properties is required for the brace, this material should extend beyond both the connection with the chord and the connection with any overlapping braces.

As already stated above, limitations given by ISO 19902 (2007) and Norsok N-004 (2013) are a minimum extend of the chord can beyond the outermost intersection of D/4 or 300mm and brace stubs lengths of d or 600mm.

Norsok N-004 (2013) and ISO 19902 (2007) provide equations to quantify the partial effectiveness of a short chord can. For K joints, loads are generally transferred in the gap region whereas the influence of the can in resisting overall bending and preventing ovalisation is more significant for Y and X joints.

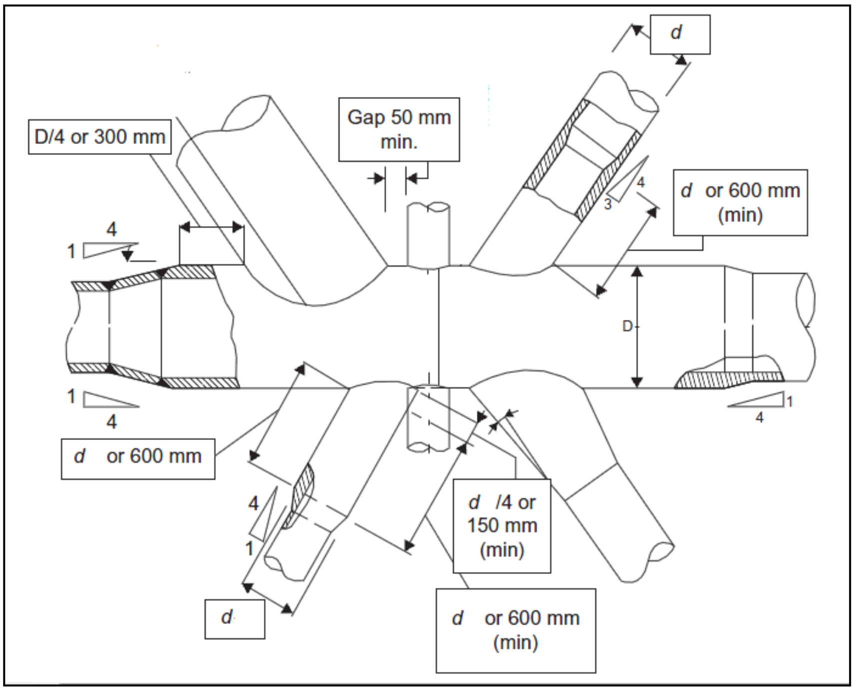


Figure 2.7- Joint detailing (El-Reedy, 2012)

2.2 Regulating standards related to tubular joints

Currently, design for offshore structures is conducted by standards that ensure the structural integrity of any jacket platform: Norsok N-004 (2013), ISO 19902 (2007), Eurocode 3-Part 1-8 (2005).

The Norsok standards (NORsk SOkkel Konkurranseposisjon) are developed by the Norwegian petroleum industry to ensure adequate safety, value adding and cost effectiveness for petroleum industry developments and operations. It specifies general principles and guidelines for the design and assessment of offshore facilities and verification of load bearing structures subjected to foreseeable actions and related maritime systems (Skaras E., 2012). Furthermore, Norsok standards are, as far as possible, intended to replace oil company specifications and serve as references in the authorities' regulations (Norsok N-004, 2007).

The International Organization for Standardization (ISO) is a worldwide federation of national standards bodies. The work of preparing International Standards is normally carried out through ISO technical committees.

The series of ISO applicable to Petroleum and natural gas industries are the ISO 19900 - Petroleum and natural gas industries — General requirements for offshore structures (ISO 19900, 2002) to ISO 19906 - Petroleum and natural gas industries — Arctic offshore structures (ISO 19906, 2010). These series of standards for offshore structures, constitutes a common basis covering those aspects that address design requirements and assessments of offshore structures used by the petroleum and natural gas industries worldwide. Through their application, the intention is to achieve reliability levels appropriate for manned and unmanned offshore structures, whatever the type of structure and the nature or combination of the materials used (ISO 19902, 2007).

This European Standard, Eurocode 3: Design of steel structures-Part 1-8: Design of joints (EC3-1-8, 2005), has been prepared by Technical Committee in order to eliminate technical obstacles to trade and harmonize technical specifications. Then, it applies to the design of buildings and civil engineering works in steel. It complies with the principles and requirements for the safety and serviceability of structures, the basis of their design and verification that are given in EN 1990 – Basis of structural design (EC0, 2002).

Eurocodes standards provide common structural design rules for everyday use for the design of whole structures and component products of both a traditional and an innovative nature. However, unusual forms of construction or design conditions are not specifically covered and additional expert consideration will be required by the designer in such cases, i.e: Offshore steel structures (EC3-1-8, 2005).

2.3 Existing research on tubular joints

In order to update research and technology, new things need to be carried out. Therefore, a previous knowledge and documentation about our research is performed in this thesis, so we can add or extend new information and conclusions about tubular joints.

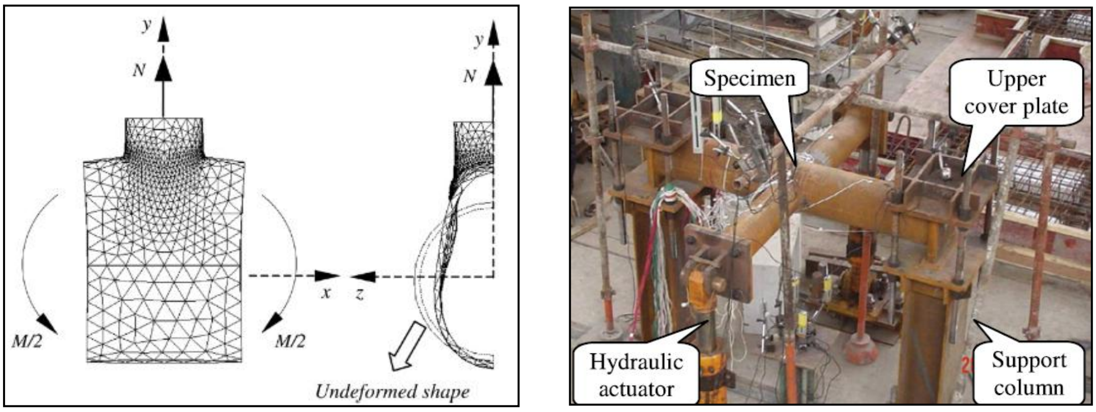
M.M.K. Lee (1999), reviews modelling techniques used in the finite element analysis of tubular joints for obtained information on strength, stress fields and stress intensity factors. Guidelines were given for discretisation, choice of elements, material modelling, welds, etc. The information given will prove to be useful to both practitioners and researchers alike.

HSE (2001), carried out a comparison between different standards related to tubular joint strength namely with (API-RP2A, 1993; HSE, 1990, ISO 13819-2; Norsok N-004,1998). Explanation about the most important factors that have a significantly influence is done. They concluded that use the same formulation to compute axial and moment strength design (N_{Rd}, M_{Rd}) but Q_u (geometric) and Q_f (chord effects) factors differ slightly from each other and lead to different calculated strengths. The interaction criteria takes the same format in ISO, Norsok and HSE but different from API.

W. Wang and Y.-Y Chen (2007), studied the cyclic performance of circular hollow sections (CHS) joints. Quasi-static experimental study into the response of eight T-joint specimens is done. Four of them are subjected to cyclic axial load and the other four are subjected to cyclic in-plane bending. Test results showed that failure modes of axially loaded joints mainly contain weld cracking in tension and chord plastification in compression. But for joints under cyclic in-plane bending, both punching shear and chord plastification become regular failure modes accompanied by ductile fracture of the welds. Joints have good energy dissipating capacity. However, there’s a significant distinction in the energy dissipation mechanism. The axially loaded joints dissipate energy mainly by plastic deformation of the chord wall and in-plane bending loaded joints dissipate energy mainly by plastic deflection of the brace (see Figure 2.8).

W. Wang *et al.* (2010), dealt with the seismic behaviour of three thick-walled CHS X-joints subjected to out-of-plane bending (OPB). It was found that failure modes and connection efficiency were significantly dependent on τ and β ratios. Small values of τ demonstrated higher connection efficiency and large values of τ, strengthened the brace, leading to final fracture along the chord wall, thus showing lower connection efficiency. For the joint with large β ratio, the fracture occurred mainly due to tension field near saddle position, whereas for the smaller β ratios, the fracture was caused by chord punching shear (see Figure 2.8).

The CHS X-joints with larger β become the best choice for seismic applications due to the high connection stiffness and satisfactory energy dissipating capacity.



(a) (b)

Figure 2.8- (a) FEA for cyclic axially loaded joints (W. Wang, Y.-Y Chen, 2007), (b) X-joint subjected to OPB loading (W. Wang *et al*, 2010)

DNV Technical Report (2011), performed an extensive and detailed comparison among different standards related to offshore structures (API-RP2A, ISO 19900 to19904, Norsok N-001 to N006). Overview about general characteristics is done, such as environmental criteria and loading conditions, structural steel and connections design, fatigue, foundation design, maintenance, assessment, installation and seismic design guidelines. Regarding to tubular joints, they concluded that API LRFD lacks of validity ranges. Formulae for joint basic capacity are identical in the four codes, but the API LRFD moment capacity equation includes the numerical factor of 0.8. For load interaction, the formula is the same in all standards, but an additional formula is provided in ISO for critical joints in order to ensure that the joint strength exceeds the brace member strength. In ISO and Norsok, the strength factor Q_u is identical (no longer in new Norsok rev.2013) and different values are suggested in API WSD and API LRFD. Formulations for chord load factor Q_f are identical in API LRFD, Norsok and ISO except in API WSD and the coefficients "C" are different among the three codes.

Y.-B. Shao *et al.* (2011), performed a research on the reinforced tubular joints by increasing the chord wall thickness at the intersection. The stiffness of the joint is usually weak in the chord radial direction, thus failure occurs at the weld toe in the form of brittle fracture caused by crack propagation due to cyclic loading. Considering this reinforcement (chord can), the failure position can be transferred to the chord intersection, and hence the cracking along the weld toe is prevented. Both experimental test and FEA were carried out on reinforced and un-reinforced RHS T-joints subjected to quasi-static cyclic loads in order to verify its efficiency. They reached to the conclusion that hysteretic curves were generally plump and have a good capacity of energy dissipation, which is especially useful in resisting seismic loading. Mode failures are different; the un-reinforced specimen is fractured in a brittle manner at the intersection unlike the reinforced specimen whose failure is caused by yielding. Finally, local buckling does not occur easily when chord thickness is bigger as energy dissipation capacity is increased.

J. Yang *et al* (2012), performed experimental tests on two full-scale un-reinforced circular tubular Y-joints and two corresponding chord reinforced ones subjected to brace axial compressive loading. It was found that the static strength of a tubular Y-joint can be greatly improved by increasing the chord thickness locally near the weld toe. In addition, finite element models (FEM) was built to analyze the static strength of the four specimens.

Shubin *et al* (2013), made also a similar research but considered another type of reinforcement: Inner Doubler Plate which was welded onto the inner surface of the chord by using fillet weld then, an axial compression on the brace was applied. The research was only numerical (FEM) and they analyzed the ultimate load and failure mode of the reinforcement. It was found that radial stiffness of the chord was improved, and hence the strength was increased

Finally, several technical reports are used for guidance in this thesis such as M.M.K. Lee (1999) that explains how to perform an accurate FEA in tubular joints and those advises will be useful for our validation. Previous theoretical comparison among standards is shown but need to be updated (DNV, 2011) because considers and old version of Norsok N-004 (2004) and there is no EC3-1-8 (2005) included and finally, consideration of the chord can in Y-joints (J. Yang *et al* , 2012) and our reinforced model will be an X-joint. Therefore, this thesis intends to fill up a little some holes about what it is also significant in terms of strength of joints.

3 JOINT DESIGN ACCORDING TO STANDARDS

Here in Chapter 3, an overview on the calculation of tubular joints strength will be done and taken into account the standards that regulate the design and integrity of these elements. Then, in order to carry out the estimation of the joint strength, the methodologies applied by the different standards will be explained and some examples will be given as well.

Generally, standards provide for the calculation of the static strength of tubular joints in steel structures in the following areas (HSE, 2001).

1. Joint capacity.
   a. Axial force and moment capacity.
   b. Geometric effects.
   c. Chord stress effects.
   d. Brace load interaction.
2. Joint detailing.
3. Validity ranges.

3.1 Norsok N-004. Design of steel structures

3.1.1 Axial force and moment capacity

Formulation in Norsok N-004 (2013) regarding to structural capacity is as follows:

$$N_{Rd} = \frac{f_y T^2}{\gamma_M \sin\theta} Q_u Q_f \tag{2}$$

$$M_{Rd} = \frac{f_y T^2}{\gamma_M \sin\theta} Q_u Q_f \tag{3}$$

Where: Q_u: Strength factor; Q_f: Chord action factor; T: Chord wall thickness; γ_M: Partial safety factor, which value is equal to 1.15; f_y: Yield stress; θ: Angle between the chord and brace.

3.1.2 Geometric effects. Strength factor, Qu.

This factor varies with the joint and action type. In order to find the value of Qu, the following table is provided:

Table 3.1- Values for Qu,(Norsok N-004, 2013)

<table>
<tr><td></td><td colspan="4">Brace Action</td></tr>
<tr><td>Joint Classification</td><td>Axial Tension</td><td>Axial Compression</td><td>In-plane Bending</td><td>Out-of-plane Bending</td></tr>
<tr><td>K</td><td colspan="2">$\min\begin{cases}(16+1.2\gamma)\beta^{1.2}Q_g\\ 40\beta^{1.2}Q_g\end{cases}$</td><td rowspan="3">$(5+0.7\gamma)\beta^{1.2}$</td><td rowspan="3">$2.5 + (4.5+0.2\gamma)\beta^{2.6}$</td></tr>
<tr><td>Y</td><td>30β</td><td>$\min\begin{cases}2.8+(20+0.8\gamma)\beta^{1.6}\\ 2.8+36\beta^{1.6}\end{cases}$</td></tr>
<tr><td>X</td><td>$6.4\,\gamma^{(0.6\beta^2)}$</td><td>$(2.8+(12+0.1\gamma)\beta)Q_\beta$</td></tr>
</table>

Q_β and Q_g are the geometric and gap factor respectively and their formulation is as follows,

$$Q_\beta = \begin{cases}\dfrac{0.3}{\beta(1-0.833\beta)} & for\ \beta > 0.6\\ 1.0 & for\ \beta \le 0.6\end{cases} \tag{4}$$

$$Q_g = \begin{cases}1+0.2\left(1-\dfrac{2.8g}{D}\right)^3 & for\ \dfrac{g}{D} \ge 0.05,\quad but\ Q_g \ge 1.0\\ 0.13+0.65\phi\gamma^{0.5} & for\ \dfrac{g}{D} \le -0.05\end{cases} \tag{5}$$

Where,

$$\phi = \frac{t \cdot f_{y,brace}}{T \cdot f_{y,chord}} \tag{6}$$

3.1.3 Chord stress effects. Chord action factor, Q_f

This factor accounts for the presence of factored actions in the chord. In order to find the value of Q_f, the following formulation is provided:

$$Q_f = 1.0 + C_1\frac{\sigma_{a,Sd}}{f_y} - C_2\frac{\sigma_{my,Sd}}{1.62f_y} - C_3A^2 \tag{7}$$

The parameter A is defined as follows,

$$A^2 = \left(\frac{\sigma_{a,Sd}}{f_y}\right)^2 + \left(\frac{\sigma_{my,Sd}^2 + \sigma_{mz,Sd}^2}{1.62\ f_y^2}\right) \tag{8}$$

Where: $\sigma_{a,Sd}$, corresponds to the design axial stress in chord, positive in tension; $\sigma_{my,Sd}$, the design in-plane bending stress in chord, positive for compression in the joint footprint. $\sigma_{mz,Sd}$, the design out-of-plane bending stress in chord; f_y, yield strength.

Factors C_1, C_2 and C_3 are coefficients depending on joint and load type and obtained from the following table:

Table 3.2- Factors C_1, C_2 and C_3 (Norsok N-004, 2013)

Joint Type	C_1	C_2	C_3
K joints under balanced axial loading	0.2	0.2	0.3
T/Y joints under brace axial loading	0.3	0	0.8
X joints under brace axial tension loading			
β ≤0.9	0	0	0.4
β =1.0	0.2	0	0.2
X joints under brace axial compression loading			
β ≤0.9	0.2	0	0.5
β =1.0	-0.2	0	0.2
All joints under brace moment loading	0.2	0	0.4

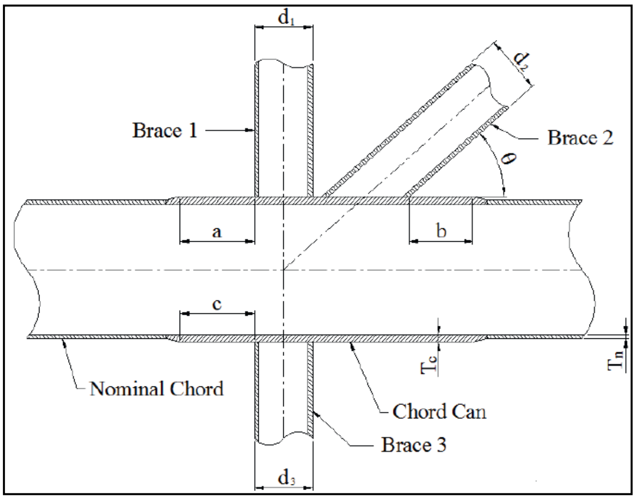
3.1.4 Joint Detailing. Chord Can

Norsok N-004 (2013) considers an increased chord wall thickness, well known as chord can, as reinforcement. Then, new joint strength should be calculated as is follows.

$$r = \begin{cases} \dfrac{L_c}{2.5D} & \text{for } \beta \leq 0.9 \\ (4\beta - 3)\dfrac{L_c}{1.5D} & \text{for } \beta > 0.9 \end{cases} \tag{9}$$

$$N_{Rd} = \left[r + (1-r)\left(\frac{T_n}{T_c}\right)^2\right] N_{can,Rd} \tag{10}$$

Where, $N_{can,Rd} = N_{Rd}$ from equation (2) based on chord can geometric and material properties; T_n = Nominal chord member thickness; T_c = Chord can thickness and L_c = Effective total length.



Brace	Length Lc
1	$2a + d_1$
2	$2b + d_2/\sin\theta$
3	$2c + d_3$

Figure 3.1- Effective length for joint reinforcement,(Norsok N-004, 2013)

3.1.5 Brace load interaction

Each brace in a joint that is subjected either to an axial force or a bending moment alone, or to an axial force combined with bending moments, shall be designed to satisfy the following conditions:

$$\frac{N_{Sd}}{N_{Rd}} + \left(\frac{M_{Sd}}{M_{Rd}}\right)^2_{ipb} + \left(\frac{M_{Sd}}{M_{Rd}}\right)_{opb} \leq 1.0 \tag{11}$$

Where *ipb* and *opb* refers to in-plane bending and out-of-plane bending

3.1.6 Validity ranges.

Norsok N-004 (2013), considers a range for its application.

$$0.2 \leq \beta \leq 1.0 \tag{12}$$
$$10 \leq \gamma \leq 50 \tag{13}$$
$$30^\circ \leq \theta \leq 90^\circ \tag{14}$$

For K-joints also applies:

$$\frac{g}{D} \geq -0.6 \tag{15}$$

3.2 ISO 19902. Fixed steel offshore structures

3.2.1 Axial force and moment capacity

Formulation in ISO 19902 (2007) regarding to structural capacity of tubular joints is as follows:

$$N_{Rd} = \frac{f_y T^2}{\gamma_{R,j} \sin\theta} Q_u Q_f \tag{16}$$

$$M_{Rd} = \frac{f_y T^2 d}{\gamma_{R,j} \sin\theta} Q_u Q_f \tag{17}$$

Where f_y, T, θ, Q_u and Q_f are already defined (clause 3.1.1) and $\gamma_{R,j}$ is the partial safety factor with value 1.05.

3.2.2 Geometric effects. Strength factor, Qu

This factor varies with the joint and action type. In order to find the value of Qu, the following table is provided:

Table 3.3- Values for Qu , (ISO 19902, 2007)

<table>
<tr><th rowspan="2">Joint Classification</th><th colspan="4">Brace Force</th></tr>
<tr><th>Axial Tension</th><th>Axial Compression</th><th>In-plane Bending</th><th>Out-of-plane Bending</th></tr>
<tr><td>K</td><td colspan="2">$(1.9 + 19\beta)Q_\beta^{0.5}Q_g$</td><td rowspan="3">$4.5\ \beta\ \gamma^{0.5}$</td><td rowspan="3">$3.2\ \gamma^{(0.5\beta^2)}$</td></tr>
<tr><td>Y</td><td>30β</td><td>$(1.9 + 19\beta)Q_\beta^{0.5}$</td></tr>
<tr><td>X</td><td>$23\beta \quad \text{for } \beta \leq 0.9$
$20.7 + (\beta - 0.9)(17\gamma - 220)$
$\text{for } \beta > 0.9$</td><td>$[2.8 + (12 + 0.1\gamma)\beta]Q_\beta$</td></tr>
</table>

Q_β and Q_g are the geometric and gap factor respectively and their formulation is as follows,

$$Q_\beta = \begin{cases} \dfrac{0.3}{\beta(1-0.833\beta)} & \text{for } \beta > 0.6 \\ 1.0 & \text{for } \beta \leq 0.6 \end{cases} \tag{18}$$

$$Q_g = \begin{cases} 1.9 - 0.7\gamma^{-0.5}\left(\dfrac{g}{T}\right)^{0.5} & \text{for } \dfrac{g}{T} \geq 2.0, \text{but } Q_g \geq 1.0 \\ 0.13 + 0.65\phi\gamma^{0.5} & \text{for } \dfrac{g}{T} \leq -2.0 \end{cases} \tag{19}$$

Where,

$$\phi = \frac{t \cdot f_{y,brace}}{T \cdot f_{y,chord}} \tag{20}$$

3.2.3 Chord stress effects. Chord force factor, Qf

This factor accounts for the presence of factored actions in the chord. In order to find the value of Q_f, the following formulation is provided:

$$Q_f = 1.0 - \lambda\, q_A^2 \tag{21}$$

Where λ is a factor dependent on force pattern,

Table 3.4- Values for λ, (ISO 19902, 2007)

Force Pattern	λ
Brace axial force	0.030
Brace in-plane bending moment	0.045
Brace out-of-plane bending moment	0.021

The parameter q_A is defined as follows:

$$q_A = \left[C_1\left(\frac{P_C}{P_y}\right)^2 + C_2\left(\frac{M_C}{M_p}\right)^2_{ipb} + C_2\left(\frac{M_C}{M_p}\right)^2_{opb}\right]^{0.5} \gamma_{R,q} \tag{22}$$

Where *ipb* and *opb* refers to in-plane bending and out-of-plane bending and,

P_C = Axial force in the chord member from factored actions.
M_C = Bending moment in the chord from factored actions.
P_y = Representative axial strength, ($P_y = A \cdot f_y$)

A = Cross sectional area of the chord or chord can at the brace intersection.
M_p = Representative plastic moment strength of the chord member.
$\gamma R,q$ = Partial safety factor for yield strength, with value 1.05.

C_1, C_2 are coefficients given by the following table,

Table 3.5- Values for C_1 and C_2 , (ISO 19902, 2007)

Joint Type	C_1	C_2
Y-joints for calculating strength against brace axial forces	25	11
X-joints for calculating strength against brace axial forces	20	22
K-joints for calculating strength against balanced brace axial forces	14	43
All joints for calculating strength against brace moments	25	43

3.2.4 Joint Detailing. Chord can

ISO 19902 (2007) considers an increased chord wall thickness, well known as chord can, as reinforcement. Moreover, it uses the same formulation as Norsok N-004 (2013). Then, new joint strength should be calculated as it is referred in clause 3.1.4

3.2.5 Brace load interaction

Each brace in a joint that is subjected either to an axial force or a bending moment alone, or to an axial force combined with bending moments, shall be designed to satisfy the following condition:

$$\left|\frac{N_{Sd}}{N_{Rd}}\right| + \left(\frac{M_{Sd}}{M_{Rd}}\right)^2_{ipd} + \left|\frac{M_{Sd}}{M_{Rd}}\right|_{opd} \leq 1.0 \tag{23}$$

And for critical joints;

$$\left|\frac{N_{Sd}}{N_{Rd}}\right| + \left(\frac{M_{Sd}}{M_{Rd}}\right)^2_{ipd} + \left|\frac{M_{Sd}}{M_{Rd}}\right|_{opd} \leq \frac{U_b}{\gamma_{zj}} \tag{24}$$

Where U_b is the utilization of the brace and $\gamma_{z,j}$ is an extra partial resistance factor to ensure that members fail before the joint yields (ISO 19902, 2007).

3.2.6 Validity ranges

ISO 19902 (2007) considers a range for its application.

$$0.2 \leq \beta \leq 1.0 \tag{25}$$

$$10 \leq \gamma \leq 50 \tag{26}$$

$$30^{\circ} \leq \theta \leq 90^{\circ} \tag{27}$$

$$\tau \leq 1 \tag{28}$$

For K-joints also applies:

$$g \cdot T > -1.2\gamma \tag{29}$$

3.3 Eurocode 3. Part 1-8. Design of joints

3.3.1 Axial force and moment capacity

Unlike ISO 19902 (2007) and Norsok N-004 (2013), Eurocode 3 (EC3-1-8) considers a formulation for each type of joint with different configuration such as CHS braces members with CHS, RHS chords; I,H,or RHS with CHS chords; etc.

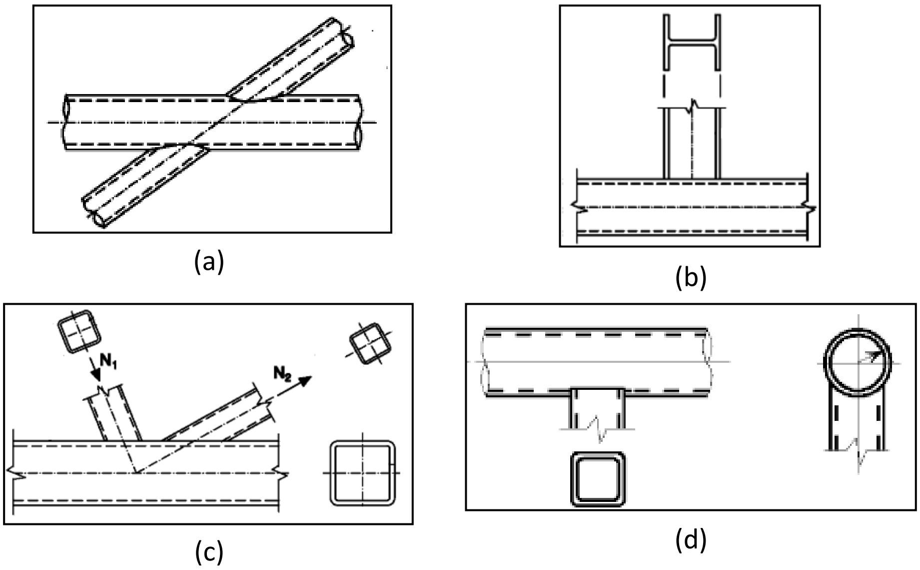
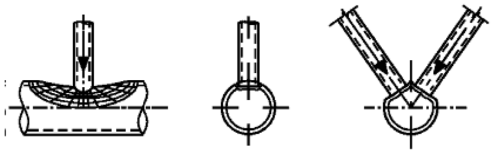
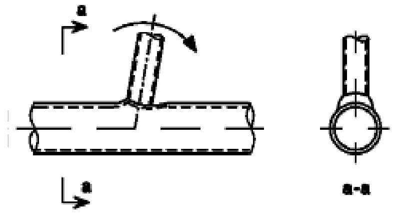
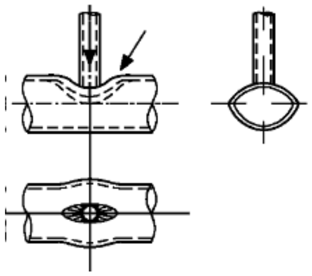
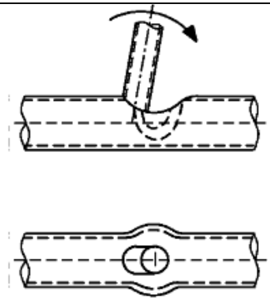
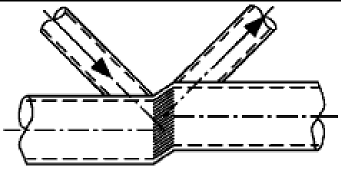
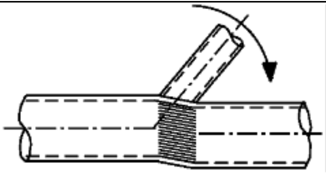
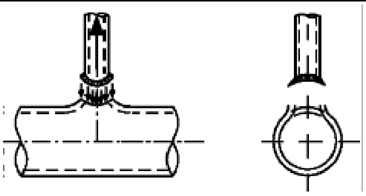
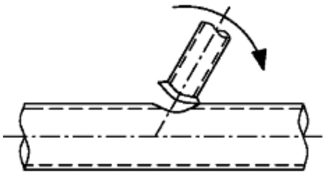
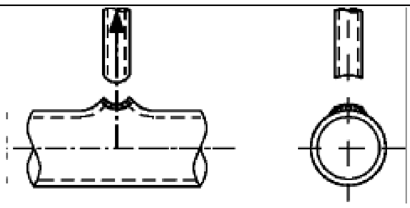
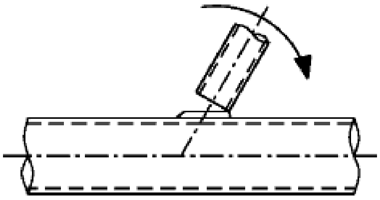


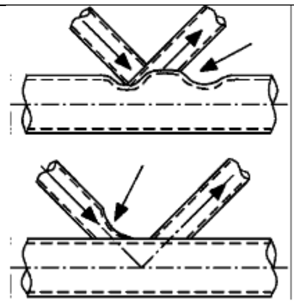
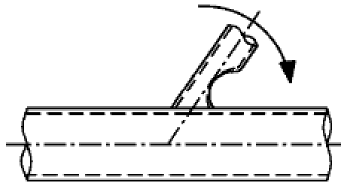
Figure 3.2- Different configurations of joints (EC3-1-8)

As we can see in Figure 3.2, several types of joints are considered. (a) CHS brace -CHS chord, (b) I section brace-RHS chord, (c) RHS brace-RHS chord and (d) RHS brace-CHS chord. However, only CHS brace-CHS chord joints are explained as this thesis is aimed to study the mechanical behaviour of tubular joints.

Eurocode 3 Part 1-8 (EC3-1-8) mentions several failure modes (Table 3.6) to take into account in joint strength design: (a)Chord face failure, (b)Chord side failure. (c)Chord shear failure, (d)Punching shear failure, (e)Brace failure, (f)Local buckling failure.

Table 3.6 - Failure modes,(EC3-1-8, 2005)

	Axial loading	Bending moment
a		
b		
c		
d		
e		

f		

Moreover, as long as considered joints to be designed are inside of the defined validity ranges, only both failure modes need to be considered: Chord face failure (chord plastification) and Punching shear failure (crack initiation leading to rupture). The design resistance of a connection should be taken as the minimum value for these two criteria.

Table 3.7- Design Axial Strength (EC3-1-8, 2005)

Mode Failure	Joint Type	Axial Strength, N_{Rd}
Chord face	X	$N_{Rd} = \frac{k_p f_y T^2}{\sin(\theta)} \frac{5.2}{1-0.81\beta} \frac{1}{\gamma_{M5}}$
	Y/T	$N_{Rd} = \frac{k_p f_y T^2}{\sin(\theta)} \frac{5.2}{1-0.81\beta} \frac{1}{\gamma_{M5}}$
	K	$N_{Rd,Brace1} = \frac{k_g k_p f_y T^2}{\sin(\theta)} \left(1.8 + 10.2 \frac{d}{D}\right) \frac{1}{\gamma_{M5}}$ $N_{Rd,Brace2} = \frac{\sin(\theta_{Brace1})}{\sin(\theta_{Brace2})} N_{Rd,Brace1}$
Punching Shear	X	When $d \leq D - 2T$: $N_{Rd} = \frac{f_y}{\sqrt{3}} T \pi d \frac{1+\sin(\theta)}{2\sin^2(\theta)} \frac{1}{\gamma_{M5}}$
	Y/T	
	K	

Where $\gamma_{M5} = 1.0$ and k_g and k_p are defined as follows,

$$k_g = \gamma^{0.2}\left(\frac{1 + 0.024\gamma^{1.2}}{1 + \exp\left(\frac{0.5g}{T} - 1.33\right)}\right) \tag{30}$$

For $n_p > 0$ (compression) $\quad k_p = 1 + 0.3n_p(1 + n_p)$ $\quad$ but $k_p \leq 1.0$

For $n_p \leq 0$ (tension) $\quad k_p = 1.0$ $\quad$ (31)

It is important to know that values of the factor k_g can be obtained graphically (Fig 3.3) as it is used to cover both gap type and overlap type joints by adopting "*g*" for the gap and the overlap and using negative values of *"g"* to represent the overlap *"q"*.

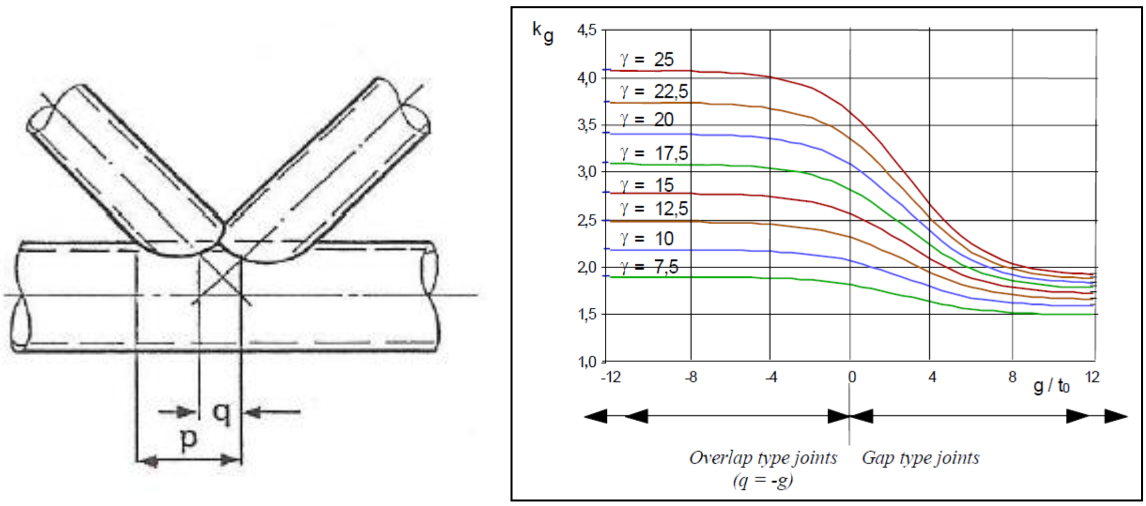


Figure 3.3- Values for k_g (EC3-1-8, 2005)

Table 3.8- Design bending moment strength (EC3-1-8, 2005)

Mode Failure	Joint Type	Bending Moment Strength, M_{Rd}	
		In-plane Bending	Out-of-plane bending
Chord face	X	$M_{Rd} = 4.85\frac{f_y T^2 d}{\sin(\theta)}\frac{\sqrt{\gamma}\beta k_p}{\gamma_{M5}}$	$M_{Rd} = \frac{f_y T^2 d}{\sin(\theta)}\frac{2.7}{1 - 0.81\beta}\frac{k_p}{\gamma_{M5}}$
	Y		
	K		
Punching Shear	X	When $d \leq D - 2T$: $M_{Rd} = \frac{f_y T d^2}{\sqrt{3}}\frac{1 + 3\sin(\theta)}{4\sin^2(\theta)\,\gamma_{M5}}$	When $d \leq D - 2T$: $M_{Rd} = \frac{f_y T d^2}{\sqrt{3}}\frac{3 + \sin(\theta)}{4\sin^2(\theta)\,\gamma_{M5}}$
	Y		
	K		

Where γ_{M5} = 1.0 and k_p is defined in equation (31).

3.3.2 Geometric effects

Geometric features are considered in each joint formulation which makes difficult to determine an only one factor to account for the geometry and load action.

3.3.3 Chord stress effects, k_p factor

In this case formulation from EC3 (EC3-1-8, 2005) relies on the factor k_p (equation 31) to account for the loads applied on the chord. Moreover, we can see in this equation that has a factor n_p which is defined as follows:

$$n_p = \frac{\sigma_{chord,Sd}}{f_y} \cdot \frac{1}{\gamma_{M5}} \tag{32}$$

3.3.4 Joint detailing

Despite of being a very common reinforcement in offshore jackets, Eurocode 3 Part-1-8(EC3-1-8, 2005) does not consider the chord can as reinforcement for tubular joints. Then, there is no formulation to analyse the joint strength.

3.3.5 Brace load interaction

Each brace in a joint that is subjected either to an axial force or a bending moment alone, or to an axial force combined with bending moments, shall be designed to satisfy the following conditions:

$$\frac{N_{Sd}}{N_{Rd}} + \left(\frac{M_{Sd}}{M_{Rd}}\right)_{ipb}^2 + \left(\frac{M_{Sd}}{M_{Rd}}\right)_{opb} \le 1.0 \tag{33}$$

3.3.6 Validity ranges

Eurocode 3 considers a range for its application. Cross sections shall be class 1 or 2 for all joints (EC3-1-8, 2005).

$$0.2 \le \beta \le 1.0 \tag{34}$$

$$10 \le 2\gamma \le 50 \tag{35}$$

But for X-joints:

$$10 \le 2\gamma \le 40 \tag{36}$$

For K-joints also applies:

$$g \geq t_1 + t_2 \tag{37}$$

3.4 Main similarities and differences

The standards were presented in the previous clauses in order to calculate the design strength of tubular joints, same conclusions can be set.

Norsok N-004 (2013) and ISO 19902 (2007) have similar expressions to calculate the design strength of the joint, N_{Rd} and M_{Rd}. They have the same consideration for joint detailing (chord can), validity ranges and expressions for the brace load interaction.

Regarding the factors Q_f and Q_u, their formulations are different and depend mainly on the parameters γ and β (see Table 3.1 and Table 3.3). Actually, those factors are responsible for the possible different values for design strength as they are considered as linearly proportional factors (see eq. 2, eq.3, eq.16, eq. 17).

Furthermore, partial safety factors are slightly different in all three standards: $\gamma_M = 1.15$ (Norsok N-004, 2013), $\gamma_{Rj} = 1.05$ (ISO 19902, 2007) and $\gamma_{M5} = 1.0$ (EC3-1-8, 2005). This makes Norsok N-004 (2013) to be more conservative than others as it is reducing the strength up to 87%.

Eurocode 3 (EC3-1-8, 2005) has different methodology but maintains the general factors such as γ and β in its formulation. Moreover, the factor k_p, which would be the equivalent to Q_f, considers a loaded chord to estimate the joint strength design and it has the same formulation for brace load interaction.

Unlike Norsok N-004 (2013) and ISO 19902 (2007), EC3-1-8 (2005) does not consider the influence of the chord can which is a very common reinforcement in joints for offshore jackets. It gives a general idea about its limited applicability in offshore structures. Moreover, it strictly applies to members with class section 1 or 2 in order to make sure about avoiding any failure due to plastification.

3.5 Guidelines for tubular joints strength design

In this clause the standards are applied on planar joints. For each type of tubular joint (X-, Y-, K-), design strength will be estimated according to the ISO 19902 (2007), Norsok N-004 (2013) and EC3-1-8 (2005). In order to proceed, each geometry is adopted from Usfos (2011).

3.5.1 Design strength for a K-joint

As stated before, we will proceed to calculate the design strength for a planar tubular joint. This case is a K-joint with same thickness for both chord and braces but different angle is considered in each brace.

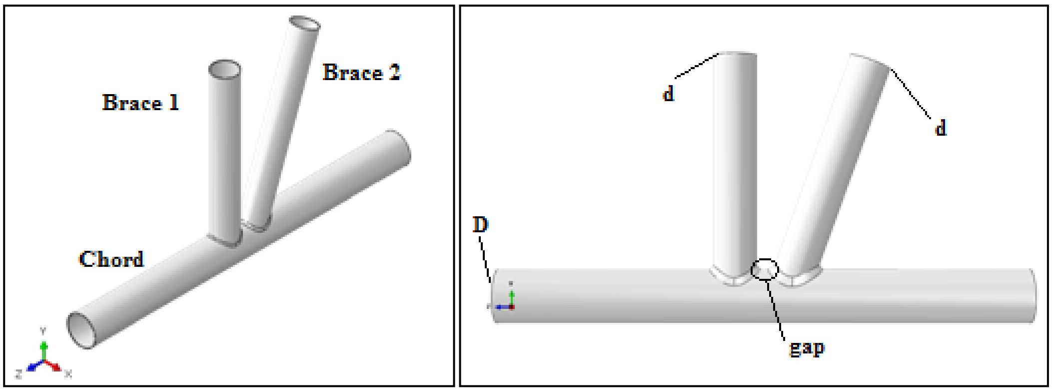


Figure 3.4- Geometry of K-joint

Figure 3.4 graphically describes the geometry of the K-joint and some parameters as gap which is the space between the crown toes of both braces. In addition, Table 3.9 and Table 3.10 describe the dimensions and material properties of the K-joint.

Table 3.9 – Characterization of the K-joint (Usfos, 2011)

Brace diameter	d	320	mm
Chord diameter	D	400	mm
brace wall thickness	t	20	mm
chord wall thickness	T	20	mm
gap	g	50	mm
Angle brace 1	θ1	90	º
Angle brace 2	θ2	70	º
Nominal Chord Area	A_{chord}	23876.10	mm^2
Diameter ratio	β	0.8	
Diameter-Thickness ratio	γ	10	
Thickness ratio	τ	1.0	

Table 3.10- Material Properties [MPa], (Usfos, 2011)

fy chord	355
fy brace	355

This K-joint is subjected only to axial load, compression in the perpendicular brace (Brace 1) and tension in the other brace (Brace 2). Then, the formulation explained above will be applied for each brace to estimate the design strength. The minimum design strength value from both braces will be the design strength for this joint.

Table 3.11- Loads [N] (Usfos, 2011)

N_{brace1}	$-2.00\cdot10^6$
N_{brace2}	$2.00\cdot10^6$
N_{chord}	$-1.30\cdot10^6$

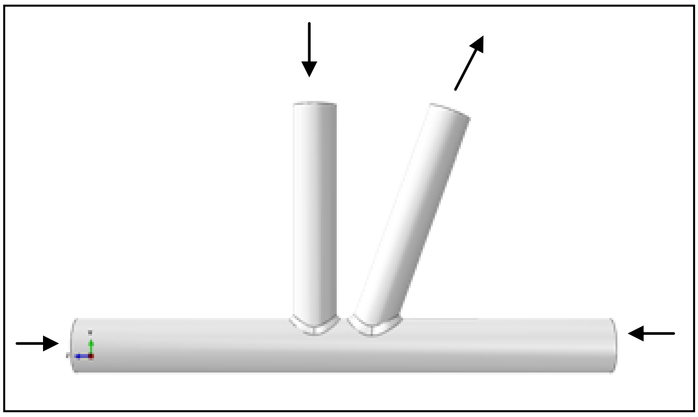


Figure 3.5- Load configuration

It is observed in Figure 3.5 and Table 3.11 that chord is already compressed. Therefore, stresses in that point will have to be evaluated and taken into account in the factor Qf (eq.7 or eq. 21) or in the factor k_p (eq. 31).

The strength of the joints is calculated according to Norsok N-004 (2013), ISO 19902 (2007) and EC3-1-8 (2005) standards and the values are shown in the tables below:

Table 3.12. Strength design and load interaction, Norsok N-004 (2013)

Axial Strength Design		
	Brace 1	Brace 2
g/D	0.125	
γ_M	1.15	
Q_g	1.055	1.055
Q_u	**22.60**	**22.60**
C_1	0.2	0.2
C_3	0.3	0.3
A^2	0.024	0.024
Q_f	**0.96**	**0.96**
N_{Rd} [N]	2685185.01	2857514.20
N_{Rd} [KN]	**2685.19**	

Load interaction		
$N_{sd,1}$ [KN]	2000.00	
$N_{sd,2}$ [KN]	2000.00	
N_{Rd} [KN]	2685.185	
$U_{j,brace\ 1}$	0.74	**OK**
$U_{j,brace\ 2}$	0.74	**OK**

Table 3.13- Strength Design and load interaction, ISO 19902 (2007)

Axial Strength Design		
	Brace 1	Brace 2
gT	1000	
$\gamma_{R,q}$	1.05	
Q_g	1.55	1.55
Q_β	1.12	1.12
Q_u	**28.10**	**28.10**
λ	0.03	0.03
C_1	14	14
q_A	0.60	0.60
Q_f	**0.99**	**0.99**
N_{rd} [N]	3946955.44	4200262.25
N_{Rd} [N]	3759005.18	4000249.76
N_{Rd} [KN]	**3759.01**	

Load interaction		
$N_{sd,1}$	2000.00	KN
$N_{sd,2}$	2000.00	KN
N_{Rd}	3759.005	KN
$U_{j,brace1}$	0.53	**OK**
$U_{j,brace2}$	0.53	**OK**

Table 3.14- Strength Design and load interaction, EC3-1-8 (2005)

Axial Strength Design					
Parameters				Chord Face Failure	Punching Shear Failure
D/T	20.0	n_p		0.153	
ε	0.81	**K_p**		**0.947**	
class section	1	**K_g**		**1.898**	
		$N_{rd,brace1}$ [N]		2542417.15	4120952.16
γ_{M5}	1.00	$N_{rd,brace2}$ [N]		2705583.82	4526149.11
		N_{Rd} [KN]		**2542.42**	

Load interaction		
$N_{sd,1}$ [KN]	2000.00	
$N_{sd,2}$ [KN]	2000.00	
N_{Rd} [KN]	2542.42	
$U_{j,brace\ 1}$	0.79	**OK**
$U_{j,brace\ 2}$	0.78	**OK**

As stated before, standards have already been applied. Steps explained in clause 3.1, 3.2 and 3.3 have been applied. Factors Q_f and Q_u are calculated, then N_{Rd} is obtained and finally strength check is performed. Regarding to EC3 (EC3-1-8, 2005), factor k_p and k_g are calculated as we are considering a K-joint and joint strength for both mode failure is calculated. Then, we obtain as the joint strength design the smaller value from both and perform the strength check.

Table 3.15- Design strengths for K-joint

Standard	Design strength [KN]
ISO 19902	3759.01
Norsok N-004	2685.19
Eurocode 3. Part 1-8	2542.42

Although Norsok N-004 (2013) and ISO 19902 (2007) have similar methodology, results for this K-joint are different. It is likely to be due to the partial safety factor which is different from each other: γ_M = 1.15 (Norsok N-004, 2013) and γ_{Rj} = 1.05 (ISO 19902, 2007). In addition, we can see that results from EC3 are closer to Norsok N-004 (2023).

3.5.2 Design strength for a Y-Joint

As stated before, we will proceed to calculate the design strength for a tubular joint. In this case, a Y-joint with same thickness for both chord and brace and considering an angle of 90°

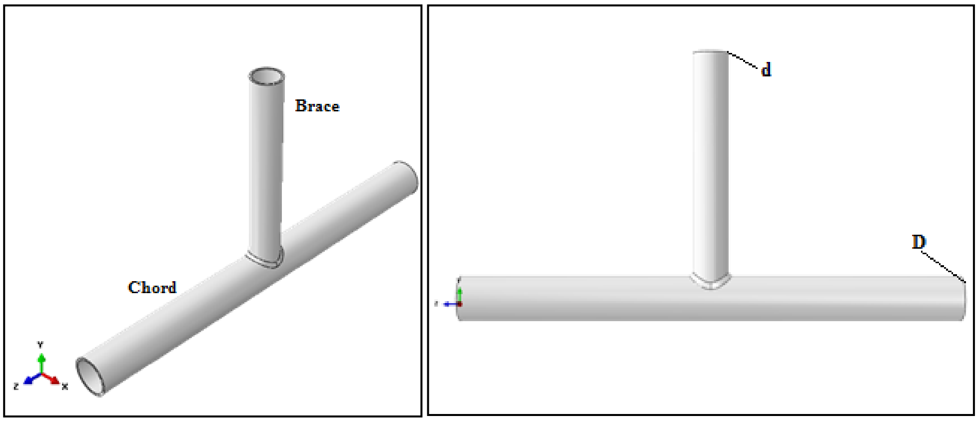


Figure 3.6 - Geometry of Y-joint

Figure 3.6 graphically describes the geometry of the Y-joint and Table 3.16 and Table 3.17 describe the dimensions and material properties of the Y-joint.

Table 3.16 - Characterization of the Y-joint (Usfos, 2011)

Brace diameter	d	320	mm
Chord diameter	D	400	mm
brace wall thickness	t	20	mm
chord wall thickness	T	20	mm
Angle1	θ	90	º
Nominal Chord Area	A_{chord}	23876.10	mm^2
Diameter ratio	β	0.8	
Diameter-Thickness ratio	γ	10	
Thickness ratio	τ	1.0	

Table 3.17 – Materials [Mpa], (Usfos, 2011)

fy chord	355
fy brace	355

In order to analyse any type of loads, this Y-joint is under an axial and bending moment load (Figure 3.7). Then, formulation will be applied to calculate both axial and bending moment strength design.

Table 3.18 – Loads [N], [mm] (Usfos, 2011)

N_{brace}	$-1.00 \cdot 10^6$
M_{brace}	$2.00 \cdot 10^8$
N_{chord}	$-2.51 \cdot 10^6$

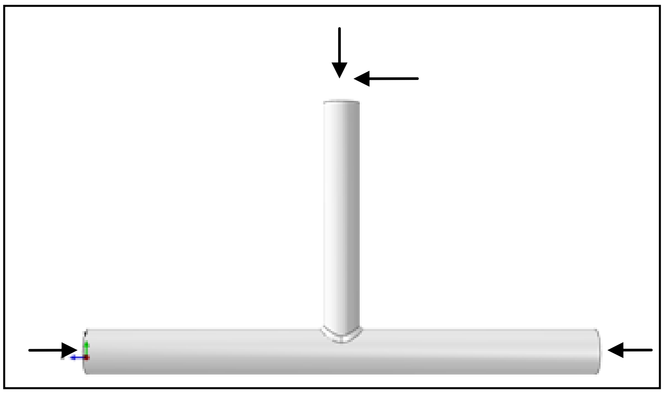


Figure 3.7- Loading configuration

In order to obtain the value of M_{brace} (Table 3.18) a horizontal load of 100 KN is applied. It is observed that chord is already compressed. Therefore, stresses in that point will have to be evaluated and taken into account on the factor Qf (eq.7 or eq. 21) or in the factor k_p (eq. 31).

As already mentioned above, the design strength of joints according to norms ISO 19902 (2007), Norsok N-004 (2013) and EC3-1-8 (2005) is shown in the next tables below:

Table 3.19- Strength Design and load interaction, Norsok N-004 (2013)

Axial and Bending Strength		
Parameters	Axial	Bending moment
γ_M	1.15	
Q_u	**22.39**	**9.18**
A^2	0.08	0.08
C_1	0.30	0.20
C_3	0.8	0.4
Qf	**0.84**	**0.90**
N_{Rd} [KN]	**2325.43**	-
M_{Rd} [KNm]	-	**328.56**

Load interaction		
N_{sd} [KN]	1000	
M_{sd} [KNm]	200	
N_{Rd} [KN	2325.43	
M_{Rd} [KNm]	328.56	
U_j	0.80	**OK**

Table 3.20 - Strength design and load interaction, ISO 19902 (2007)

Axial and Bending Strength		
	Axial	Bending moment
$\gamma_{R,q}$	1.05	
Q_β	1.12	-
Q_u	**18.13**	**11.38**
λ	0.03	0.045
C_1	25	25
q_A	1.55	1.55
Q_f	**0.93**	**0.89**
N_{Rd} [KN]	**2274.08**	**-**
M_{Rd} [KNm]	-	**439.08**

Load interaction		
N_{sd} [KN]	1000	
M_{sd} [KNm]	200	
N_{Rd} [KN]	2274.08	
M_{Rd} [KNm]	439.08	
U_j	0.64	**OK**

Table 3.21 - Strength Design and load interaction, EC3-1-8 (2005)

Axial Strength Design				
Parameters			Chord Face Failure	Punching Shear Failure
D/T	20.0	n_p	0.29	
ε	0.81	**K_p**	**0.88**	
Class section	1	N_{Rd} [N]	2367382.32	4120952.16
		M_{Rd} [KNm]	493334296.84	419756739.71
γM5	1.00	**N_{Rd} [KN]**	**2367.38**	
		M_{Rd} [KNm]	**419.76**	

Load interaction		
N_{sd} [KN]	1000	
M_{sd} [KNm]	200	
N_{Rd} [KN]	2367.3	
M_{Rd} [KNm]	419.76	
U_j	0.64	**OK**

In order to find out the strength of this joint, the previous steps have been followed. In addition, we consider the bending moment resistance that adds another Q_u factor.

Finally, comparison results are made for the Y-joint with the axial strength and the bending moment strength:

Table 3.22- Design strengths for Y-joint

	Axial Strength, N_{Rd} [KN]	Bending Moment Strength, M_{Rd} [KNm]
ISO 19902	2274.08	439.08
Norsok N-004	2325.43	328.56
EC3- 1-8	2367.38	419.76

Regarding to this example of Y-joint, axial force results(Table 3.22) obtained from standards are quite similar. However, bending moment strength results are not. This is due to differences on the in-plane bending formulation between Norsok N-004 (2013) and ISO 19902 (2007).

3.5.3 Design strength for a X-Joint

As stated before, we will proceed to calculate the strength design for a tubular joint. This case is about an X-joint.

In order to extend the variety of our examples, we will consider chord can reinforcement. It consists in a thicker chord wall at the intersection. The purpose is to increase the strength against loads without changing grade steel, diameter, nominal thickness and other parameters.

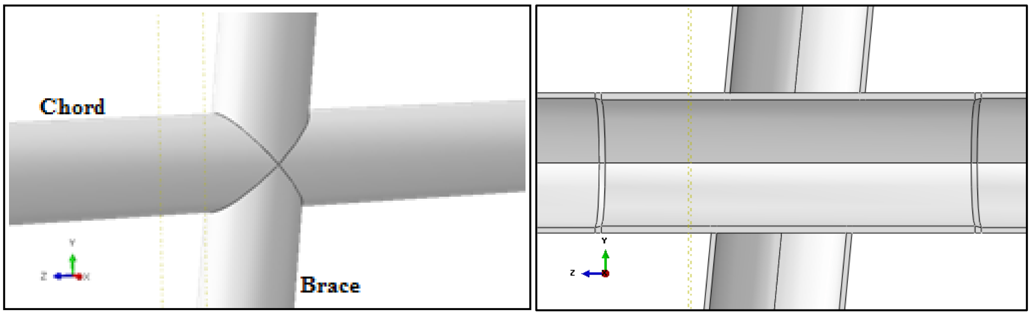


Figure 3.8 - X-joint and chord can detailing

Figure 3.8 graphically describes the geometry of the X-joint and Table 3.23 and Table 3.24 describe the dimensions and material properties of the X-joint.

Table 3.23- Characterization of the Y-joint

Brace diameter	d	900	mm
Chord diameter	D	900	mm
Brace wall thickness	t	35	mm
Chord wall thickness	T_n	32	mm
Can wall thickness	T_c	45	mm
Angle	θ	84.6	º
Can Cross Area	Acan	120872.78	mm^2
Nominal Chord Area	Achord	87260.88	mm^2
Effective Length	L_c	2400.00	mm
Diameter ratio	β	1	
Diameter-Thickness ratio	γ	10	
Thickness ratio	τ	0.78	

Table 3.24 - Material [MPa]

f_y chord	325
f_y brace	340

This X-joint is under an axial load, tension in both braces. Then, formulation to estimate the strength will be applied for one brace as both are symmetrical. In addition, the intersection has an angle close to 90º which is usual in common jacket offshore structures.

Table 3.25 - Loads [N]

N_{brace}	$9.00 \cdot 10^6$
N_{chord}	$-5.25 \cdot 10^6$

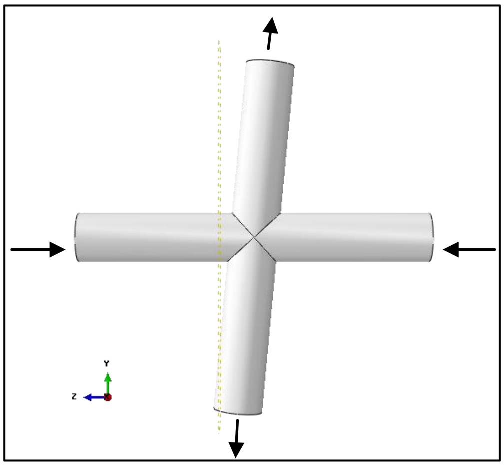


Figure 3.9- Loading configuration

It is observed that chord is already compressed. Therefore, stresses in that point will have to evaluated and taken into account on the factor Qf (eq.7 or eq. 21) or in the factor k_p (eq. 31).

As already mentioned above, the strength of joints according to norms ISO, Norsok and EC3 is shown below:

Table 3.26 - Strength design and load interaction, Norsok N-004 (2013)

Axial strength design			
γ_M	1.15	C_3	0.2
Q_u	**25.48**	**Q_f**	**0.97**
A^2	0.02	$N_{can,Rd}$ [N]	14202319.22
C_1	0.20	r	1
N_{Rd} [KN]	**14202.32**		

Strength Check		
N_{sd} [KN]	10000	
N_{Rd} [KN]	14202.32	
U_j	0.70	**OK**

Table 3.27 - Strength design and load interaction, ISO 19902 (2007)

Axial strength design			
$\gamma_{R,q}$	1.05	q_A	0.62755
Q_u	**15.7**	**Q_f**	**0.99**
λ	0.03	$P_{uj,c}$ [N]	10256002.3
C_1	20	$P_{u,j}$ [N]	10256002.3
N_{Rd} [KN]	**9767.62**		

Load interaction		
N_{sd}	9000	KN
N_{Rd}	9767.62	KN
U_j	0.921	**OK**

Table 3.28 - Strength Design and Load interaction, EC3-1-8 (2005)

Axial Strength Design					
Parameters				Chord Face Failure	Punching Shear Failure
D/T	20.0	n_p		0.13	
ε	0.85	**k_p**		**0.95**	
class section	1	N_{Rd} [N]		17269826.75	-
γ_{M5}	1.00	**N_{Rd} [KN]**		**17269.83**	

Strentgh Check		
N_{sd}	9000	KN
N_{Rd}	17269.82	KN
U_j	0.52	**OK**

Same steps have been applied, but there is only different and additional step. Chord can influence has been considered and added to the formulation to estimate the joint strength.

Table 3.29 - Design strength for X-joint

Standards	Axial Strength, N_{Rd} [KN]
ISO 19902	9767.62
Norsok N-004	14202.32
Eurocode 3. Part 1-8	17269.82

Regarding to this table, there are some details to be mentioned. Firstly, ISO 19902 (2007) owns a formulation that is conservative for X-joints in comparison to Norsok N-004 (2013) as the values of factor Qu which accounts for the type of joint and loading are different from each other (tables 3.26 and 3.27) with a result of different strengths.

Secondly, EC3-1-8 (2005) does not consider the chord can reinforcement in tubular joints. Then, according to this standard, the nominal chord wall thickness is 45mm with the result of a significant higher axial strength.

3.6 Conclusions

This chapter has treated deeply how tubular joints are designed to bear axial forces and bending moments according to current standards. It is clear that design resistance depends mainly on three factors Q_u, Q_f and k_p and their partial safety factor.

Table 3.30 - Design strength values; [KN], [m]

Joint Type	Norsok N-004		ISO 19902		EC3-1-8	
	N_{Rd}	M_{Rd}	N_{Rd}	M_{Rd}	N_{Rd}	M_{Rd}
K	2685.19	-	3759.01	-	2542.42	-
Y	2325.43	328.56	2274.08	439.08	2367.38	419.76
X	14202.32	-	9767.62	-	17269.82	-

As we can see in Table 3.30, the design strength results are mostly similar, because all standards are expected to have same criteria in considering strength materials. However, there are several formulations for each joint type, loading in brace and stresses in chord. Then, that makes visible that some results could differ from each other as it is the case of those case studies.

Firstly, in the K-joint, we observe a significant difference between Norsok N-004 (2013) and ISO 19902 (2007) in their axial strength. Besides the difference of the partial safety factor, factor Q_u accounts for being the main responsible, because the values are: $Q_{u,Norsok}$= 22.60 and

$Q_{u,ISO}$=28.10 and finally giving a difference in final result around 30% (see Table 3.12 and Table 3.13).

Secondly, differences are observed in the moment design strength of the Y-joint, where factor Q_u is also responsible but this time the main difference lies on the partial safety factor of ISO 19902 (2007) and Norsok N-004 (2013) whose values are $\gamma_{R,j}$= 1.05 and γ_M=1.15 respectively.

Thirdly, regarding the X-joint, we can appreciate big different results among three standards, one because is quite conservative and the other one because of its lack of the application in this area. Once again values of Qu from Norsok N-004 (2013) and ISO 19902 (2007) are different $Q_{u,Norsok}$= 25.48 and $Q_{u,ISO}$=15.70 then, it turns out to give big differences so we can conclude that ISO 19902 (2007) considers a very conservative way to obtain design strength.

Finally, another different result comes from EC3-1-8 (2005). According to clause 3.3.4, there is no consideration of any chord can so formulation cannot take into account the strength of the reinforced joint. Therefore, in this case study, EC3-1-8 (2005) only considers the thickness of the chord can as the nominal thickness along the entire chord and giving higher design strengths as final results

4 FINITE ELEMENT MODELLING OF TUBULAR JOINT

There is need to achieve a more accurate result in the analysis of tubular joints so a static plastic analysis is performed. In order to carry out the analysis, we will make use of the Finite Element Analysis (FEA) which is a powerful, tool to describe the mechanical behaviour of solids and structures. The FEA is conducted with Abaqus CAE software by making use of the several numerical techniques to carry out the method i.e.: Numerical integration, Direct Vectorial Iteration, Inverse Vectorial Iteration, Newton-Raphson method, etc). The three-dimensional FE model is built with hexahedral elements, based on the geometry of tubular joints.

A good practice in research is to proceed the validation of results from numerical model. In order to do so, a previous research will be used to compare the numerical model and its results. The validation model is obtained from a master thesis developed in the University of Stavanger in the field of offshore technology (Ghanemnia N., 2012). The geometry of the joint analysed consists in a simple planar X-joint which is axially brace loaded, described in the chapter 3.5.3.

4.1 Description of the FE model

The FE model is defined by an X-joint whose geometrical parameters are described on the following table. Afterwards, both geometries (from previous research and the actual studied here) are compared to make out slightly differences.

Table 4.1- Geometrical Parameters, (Ghanemnia N., 2012).

Brace diameter	d	900	mm
Chord diameter	D	900	mm
Brace wall thickness	t	35	mm
Chord wall thickness	T_n	32	mm
Can wall thickness	T_c	45	mm
Angle	θ	84.6	^{o}
Can Cross Area	A_{can}	120872.78	mm^2
Nominal Chord Area	A_{chord}	87260.88	mm^2
Effective Length	L_c	2400.00	mm

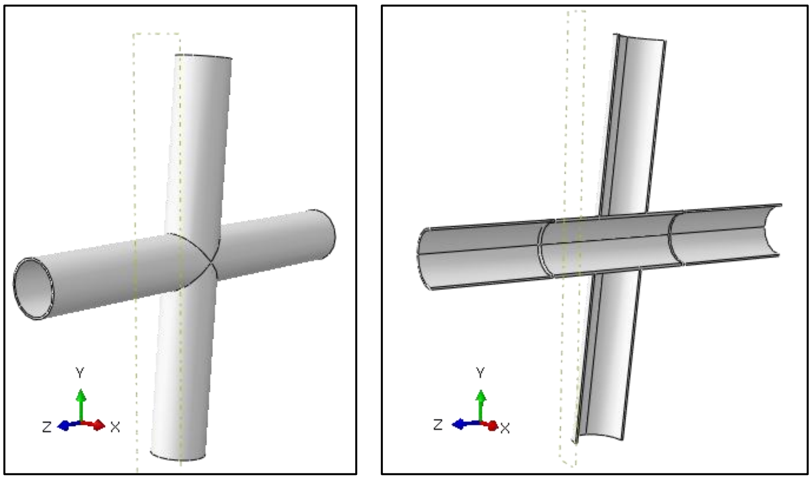


Figure 4.1 - Geometry of present work

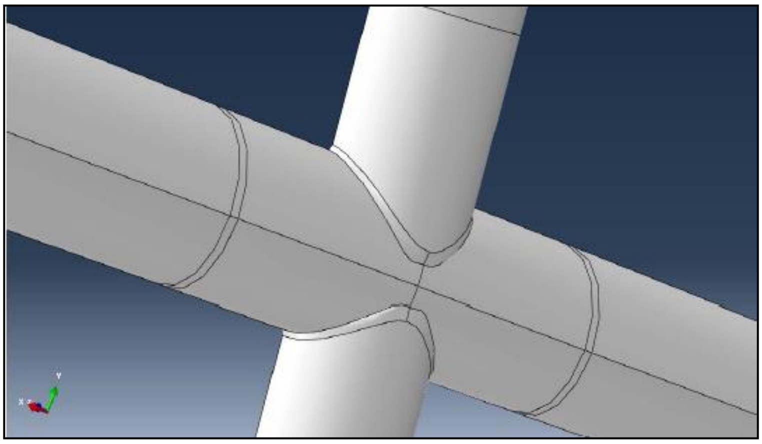


Figure 4.2 - Geometry from previous research (Ghanemnia N., 2012).

In the geometry of previous research (Figure 4.2), weld is simulated. However, it is not considered in our research as it was very complicated to define that geometry on Abaqus CAE. Therefore, a modification of the joint strength might take place giving finally different results. Even though, final results will be compared between both models so as to find out whether our simulation is accurate enough to continue the analysis and then becoming validated.

4.2 Material properties

In this clause, material used is exposed. Steel is one of the most used materials in civil engineering structures, and when dealing with offshore structures it becomes a very important material to take into account. Note that steel has a ductile behaviour which is able to undergo a substantial amount of plastic deformation, generally much larger than the elastic deformation, before rupture (Silva V, 2006).

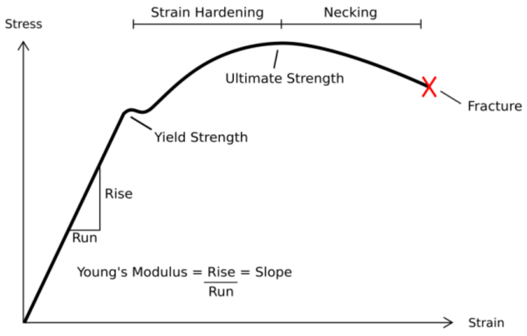


Figure 4.3 - Real stress-strain curve

Describing the real behaviour of any material implies several complex mathematical formulations, especially in theory of plasticity, as none of them follows a uniform distribution of stress-strains curves from yielding zone. Then, material non-linearity is usually defined by simplifying the stress-strain curve with several models which tend to simulate as accurate as possible the mechanical behaviour of the material (Ghanemnia N., 2012).

The proposed model in this research is the Ramberg-Osgood equation which gives a good approximation regarding to plastic zone of metallic materials (eq. 38).

$$\varepsilon = \frac{\sigma}{E} + \alpha \frac{f_y}{E}\left(\frac{\sigma}{f_y}\right)^n \tag{38}$$

Where α and n are coefficients depending on the type of material and its mechanical properties and f_y and E are the yield stress and Young modulus respectively.

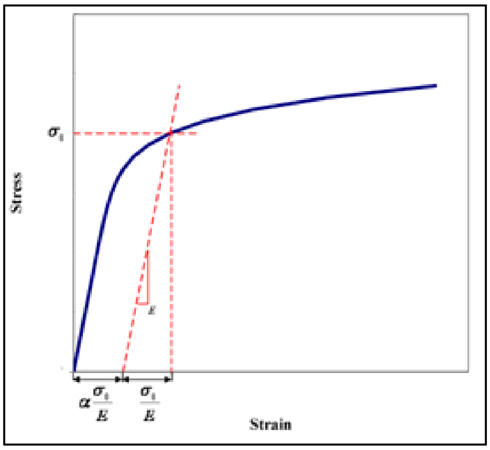


Figure 4.4 - Ramberg-Osgood curve (Ghanemnia N., 2012).

In order to apply this equation to our considered material, mechanical parameters are provided in Table 4.2:

Table 4.2 - Mechanical Properties (Ghanemnia N., 2012).

		Chord	Brace
Yield Stress	fy(MPa)	325	340
	σy(Pa)	3.25E+08	3.40E+08
Ultimate tensile stress	σt(Pa)	4.60E+08	4.60E+08
Strain at yield	εy	0.005	0.005
Strain at ultimate tensile	εt	0.2	0.2
Young Modulus	E(Pa)	2.10E+11	2.10E+11
Coefficients	α	2.23	2.088
	n	11.65	13.46

Once these parameters are applied on the Ramberg-Osgood equation, the idealized stress-strain curve for our model is shown in Figure 4.4.

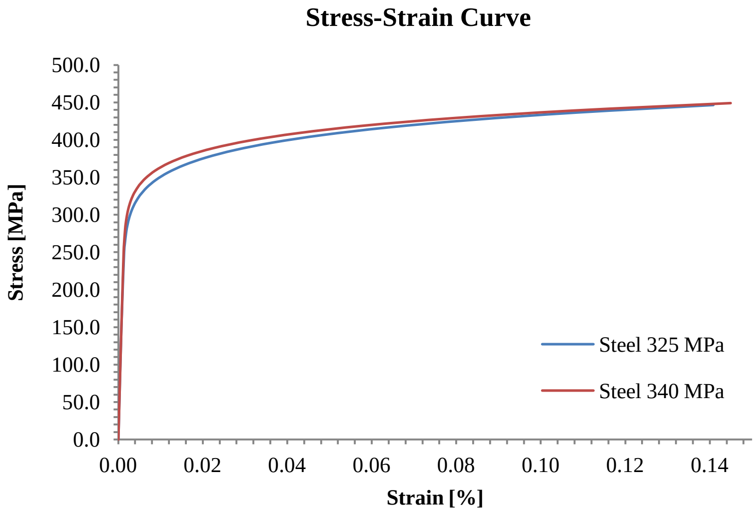


Figure 4.5- Ramberg-Osgood curve considered in the model

The Figure 4.5 will be applied on the software Abaqus CAE in order to simulate the non-linear behaviour of our plastic analysis.

4.3 Boundary and loading conditions and specimen discretization

The X-joint model has been simplified by the use of symmetry conditions in axes "x", then displacement in that direction are restrained at the symmetry surface as well as rotations on their perpendicular axes (Figure 4.6). The load is applied on both braces and both extremes of the chord on "y" (local axe) and "z" directions respectively (Fig. 4.7 and 4.8)

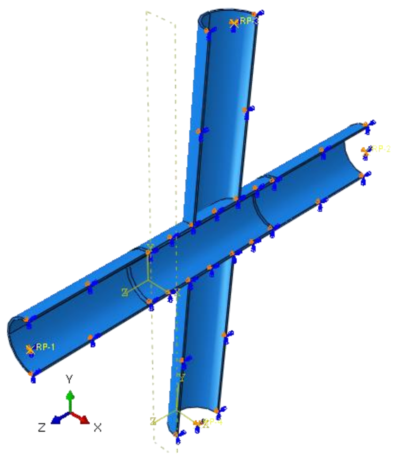
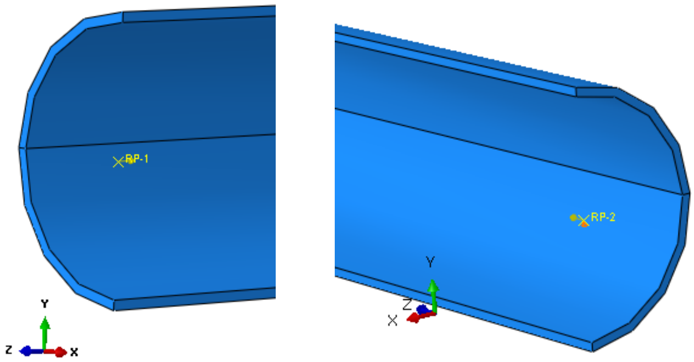


Figure 4.6 - Boundary conditions

As it is observed in Figure 4.6, symmetry conditions are created in order to respect the other half of the joint. Reference points (RP) are created and given a kinematic coupling constraint so that all conditions given to those points are also applied to the outer surfaces (Fig 4.7 and 4.8). Then, vertical and horizontal displacements on the extremes of the chord and braces respectively are also restrained through the RP to make sure about obtaining the expected behaviour.

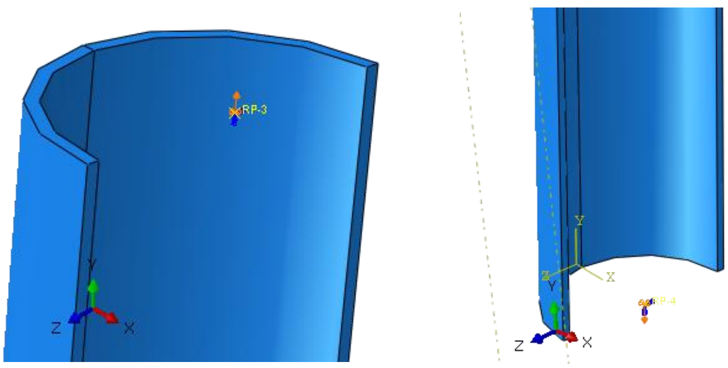
- Joint: Symmetry boundary conditions are applied in symmetry surface. Thus, U1=UR2=UR3=0.
- Chord: Vertical displacement is restrained. Thus, U2=0.
- Brace: Horizontal displacement is restrained, Thus U3=0.

Loads are applied on the RP as we can see in Fig. 4.6(a) RP-1, left chord end; Fig.4.6(b) RP-2, right chord end; Fig.4.7(a) RP-3, top brace end and Fig. 4.7(b) RP-4, bottom brace end. Then, compression loads go to chord ends and tension loads go to brace ends.



(a) (b)

Figure 4.7 - Compression loads on chord ends



(a) (b)

Figure 4.8 – Tension loads on braces ends

The model is generated with linear hexahedral elements of type C3D8R (Fig. 4.8) which is a valuable choice due to its reduced integration that avoids the shear locking problem and has a quicker convergence because of having fewer nodes (Abaqus, 2011). Generally a structured mesh technique with regular elements is used, except for those zones where geometry is not uniform and changes rapidly along the chord such as the intersection with the brace.

The X-joint analysed is under axial tensile stresses on the braces and with compression stresses on the chord. Load values in each brace and chord are ±5250 KN, according to the model adopted (Ghanemna N, 2012).

Regarding to mesh size is approximately around 10cm which gives us a very refined and accurate model. Weld has not been considered in this model due to the big complexity and lack of CAD software to import the geometry to Abaqus CAE. Therefore, mesh has been especially refined around the intersection (see Fig. 4.10) to balance the lack of weld geometry and then having a better distribution of the stresses as the centre is where maximum stresses will take place. Finally, number of elements is 22611 hexahedral elements which are similar to the previous research with 21377 elements, so that our model has the same accuracy as the previous research.

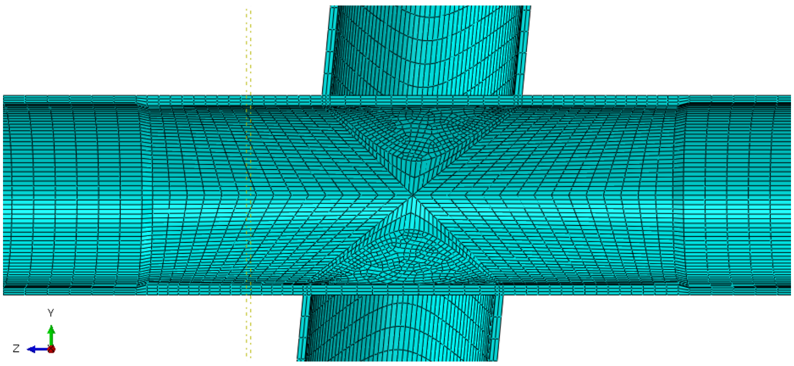


Figure 4.9- Representation of the mesh in the model

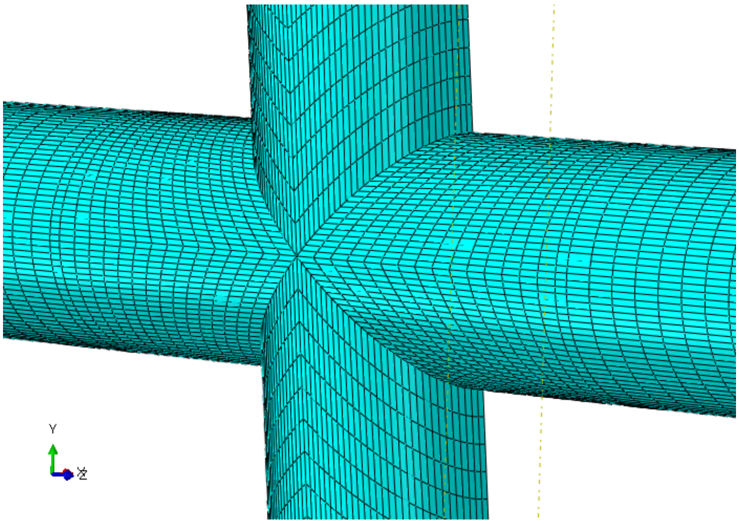


Figure 4.10- Finer mesh around intersection

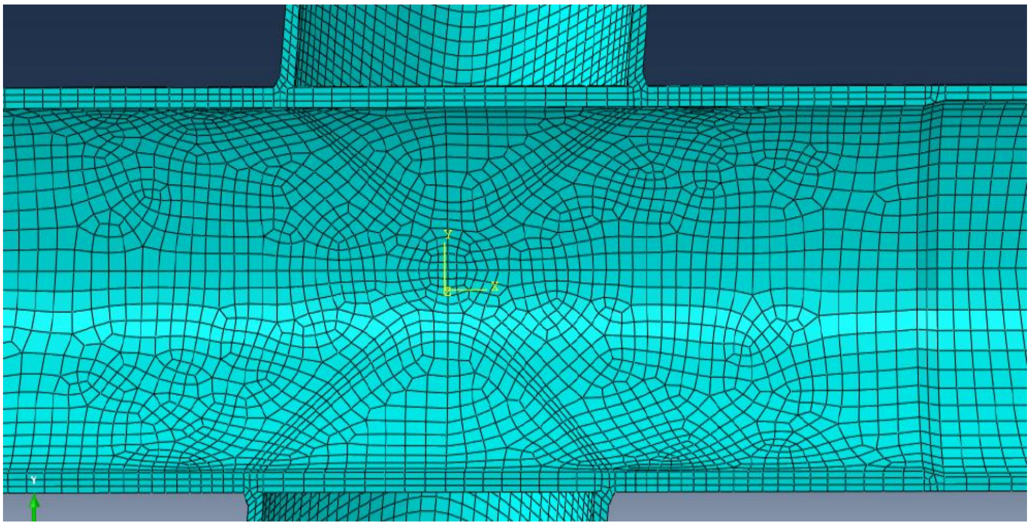


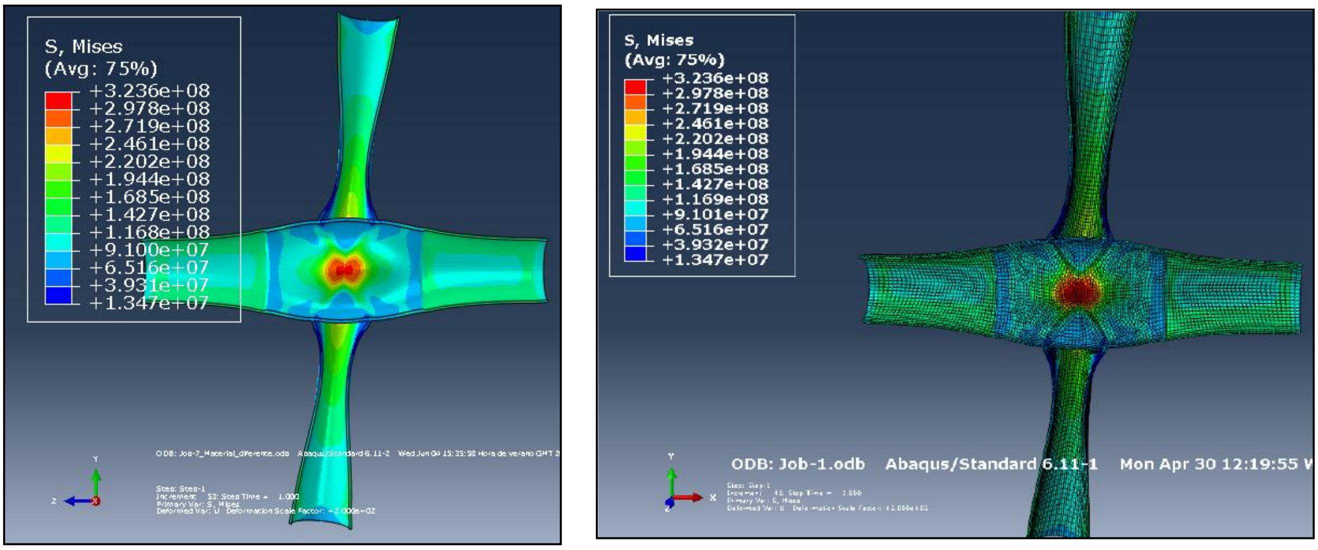
Figure 4.11 – Configuration of the mesh for the model developed (Ghanemnia N., 2012)

Same considerations have been taken into account while meshing. For example, three layers of elements are applied along the chord thickness as well as two layers along the brace thickness. In this manner, an accurate solution is obtained for the stresses along the brace-chord intersection.

4.4 Validation of numerical model

Once the numerical model is computed, the results are compared with the research done by Ghanemnia N. (2012). Results with significant importance on the model, to achieve our validation, are stress distribution, displacement and plastic strain.

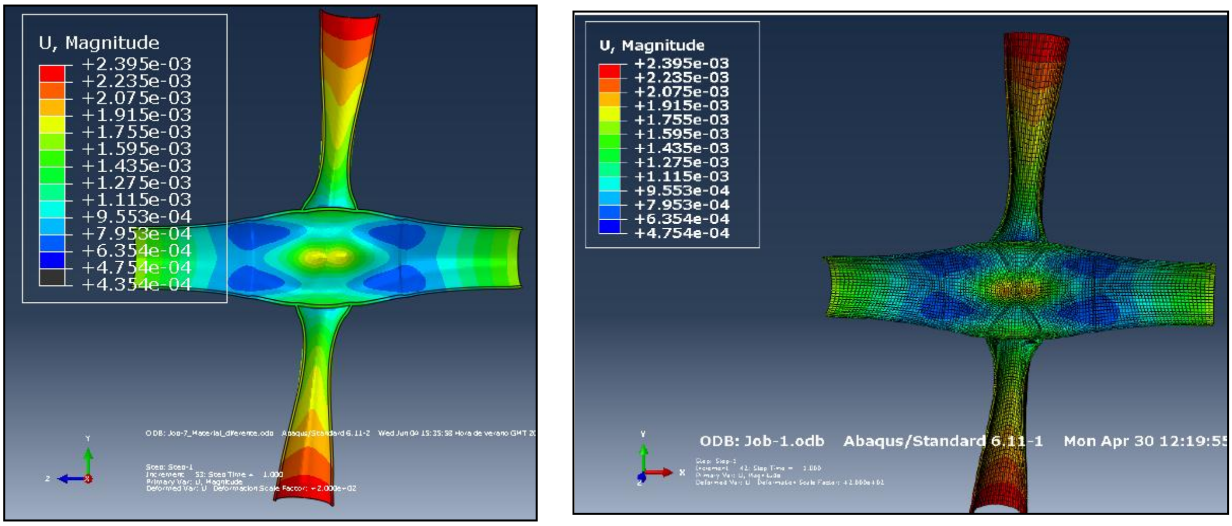
- Stresses



(a) (b)

Figure 4.12 - Stresses[Pa] (a) Model developed, (b) Previous research (Ghanemnia N.,2012)

- Displacements



(a) (b)

Figure 4.13- Displacements[m] (a) Model developed, (b) Previous research (Ghanemnia N., 2012)

Figure 4.12 compares with our model the numerical prediction for stresses obtained by Ghanemnia N. (2012). The model developed gives us a 312.73 MPa as maximum stress which takes place in the centre of the geometry. On the other hand, previous research gives a 323.6 MPa as a maximum stress which is very similar to our result.

Figure 4.13 compares with our model the numerical prediction for displacements obtained by Ghanemnia N. (2012). On one hand, our model gives 2.37 mm as maximum displacement which takes place in the extreme braces as expected. On the other hand, previous research gives 2.39 mm as maximum displacement which is very similar to our result.

- Plastic Strain

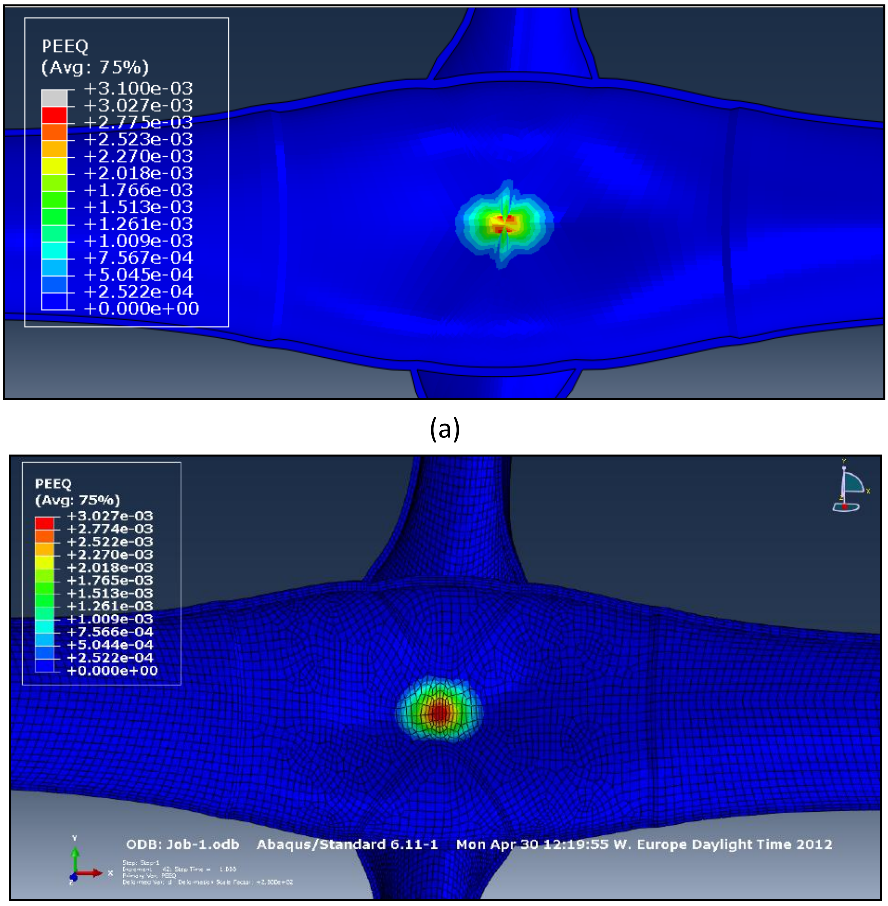


Figure 4.14- Plastic strain (a) Model developed, (b) Previous research (Ghanemnia N., 2012)

Figure 4.14 compares the numerical prediction for plastic strain obtained by Ghanemnia N. (2012) with our model. On one hand, our model gives $3.1 \cdot 10^{-3}$ as maximum plastic strain which takes place in the centre of the geometry as there is a concentration of stresses. On the other hand, previous research gives $3.02 \cdot 10^{-3}$ as maximum plastic strain which is very similar to our result.

- Force- Displacement Curve

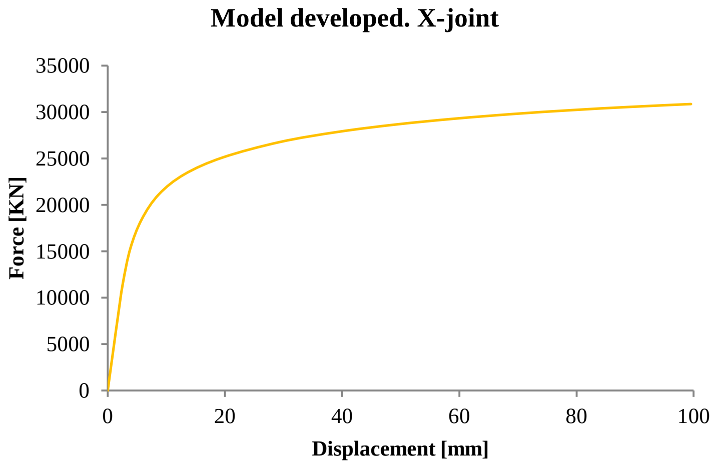


Figure 4.15 - Force-Displacement curve for X-joint (Model developed)

Finally, we can observe in figure 4.15 the Force-Displacement curve for an imposed vertical displacement of 100mm on both braces. Note that curve path follows a plastic behaviour according to the Ramberg-Osgood curve (see Fig 4.4).

4.5 Conclusions

Validation of results from numerical modelling is a very important part in research as it gives us reliability because obtains accurate or very good approximations to the real experimental results or previous research done. In addition, experiments usually are expensive or require a lot of resources which are difficult to get, so repeating it more than once might become economically unfeasible.

Therefore, once numerical analysis results are validated, it gives an alternative way to experiment and repeating it once again with changes that might be important for the purpose of that research such as the material, dimensions of the geometry, boundary conditions, loads, etc.

Regarding to our research, same steps and methodology has been done to get the same results such as material, loading, boundary conditions and discretization. Results have demonstrated a very close similarity to those from previous research.

Table 4.3 – Comparison of numerical results

	Model developed	Previous research	Difference (%)
Stresses	312.73 MPa	323.6 MPa	3.35
Displacements	2.37 mm	2.39 mm	0.83
Plastic Strain	$3.10 \cdot 10^{-3}$	$3.02 \cdot 10^{-3}$	2.58

Once results of both simulations are compared, it is stated that our validation is definitely confirmed. Then, research can be continued, as mentioned above, performing changes on the model to check how strength of tubular joints is affected by them. Thus, a parametric study is needed.

5 PARAMETRIC STUDY

These types of studies are usually done to find out the most important parameters of the problem regarding its objective. In this case, we are aimed to analyse the strength of a tubular joint and find out what are the parameters that affect the most to this strength.

The geometric parameter to be analysed is γ which accounts for the ratio of the diameter of the chord with the thickness of the chord.

$$\gamma = \frac{D}{2T} \tag{39}$$

This ratio can only vary among determined values so that the standards can be applicable.

Table 5.1- Validity Ranges for γ

Norsok N-004	ISO 19902	EC3-1-8
$10 \leq \gamma \leq 50$	$10 \leq \gamma \leq 50$	$10 \leq 2\gamma \leq 40$ $5 \leq \gamma \leq 20$

Once the ranges are established, it is seen that EC3 is very restrictive regarding the limits of γ. The reason is that EC3-1-8 (2005) makes sure to work with class sections 1 or 2 only (EC3-1-8, 2005), unlike, Norsok N-004 (2013) and ISO 19902 (2007) which are not restricted only for those classes.

Therefore, in order to understand how the analysis of γ affects the joint strength, variation among γ=10 and γ=50 is shown and more detail will be exposed from γ=10 up to γ=20 so as to find out why EC3 considers this validity range.

Each type of joint is considered in the parametric study. To proceed, the factor β maintains the same value along the study in each joint. It implies the diameter to be a fixed value and chord thickness to be the variable. Finally, design strengths (N_{Rd} or M_{Rd}) from standards will be taken into account with force-displacement curves.

5.1 Analysis for a K-joint

The example of clause 3.5.1 will be taken to proceed with the parametric study. Then, factor β is maintained equal to 0.8. The values used in the parametric study are presented in the table 5.2. Note that, Abaqus CAE is used to perform the parametric analysis.

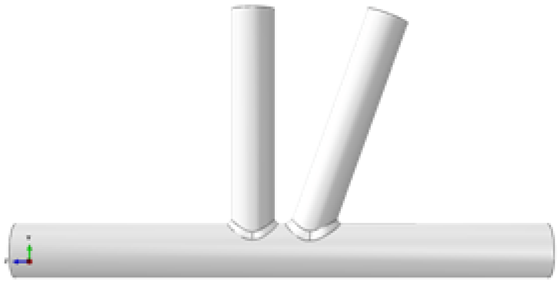


Figure 5.1- Geometry of K-joint

For the initial condition, the value admitted is γ=10. In addition, chord will be loaded with the initial ratio $N_{chord}/A\cdot f_y$ ~ 0.15 (see Table 3.11) and keep this ratio along the parametric study.

Table 5.2 - K-joint (β=0.8)

γ(D/2T)	T[mm]	t[mm]	Axial load in chord [N]	Chord Area [mm^2]
10	20	20	$-1.30\cdot10^6$	23876.10
12	16.6	16.6	$-1.06\cdot10^6$	19994.48
15	13.3	13.3	$-8.60\cdot10^5$	16157.56
18	11.1	11.1	$-7.22\cdot10^5$	13561.60
20	10	10	$-6.52\cdot10^5$	12252.21
30	6.6	6.6	$-4.34\cdot10^5$	8156.96
40	5	5	$-3.30\cdot10^5$	6204.65
50	4	4	$-2.65\cdot10^5$	4976.28

In order to obtain force-displacement curves, an imposed displacement of 50mm is applied on each brace; one in compression and the other one in tension (see Fig. 3.5). In addition, applied axial forces are shown as dimensionless in results, where N_b is the axial capacity of the brace.

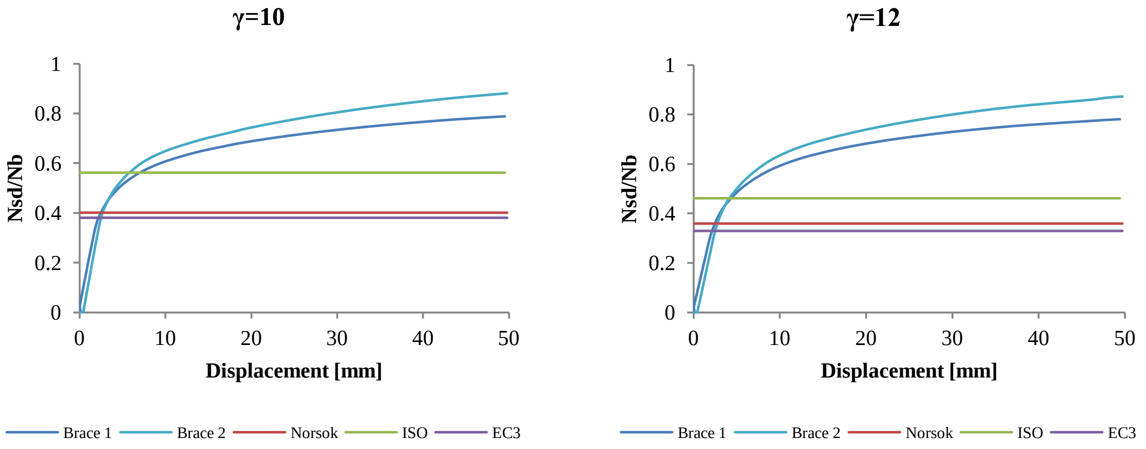


Figure 5.2- Load-displacement curves with γ=10 and γ=12

As we can see in figure 5.2, three strengths design are situated below the yielding point of the joint and axial strength from Norsok N-004 (2013) and EC3-1-8 (2005) are under ISO 19902 (2007) values. This is due to the slightly different values of partial safety factor or formulation (γ_{Norsok}=1.15, γ_{EC3}=1.0, γ_{ISO}=1.05).

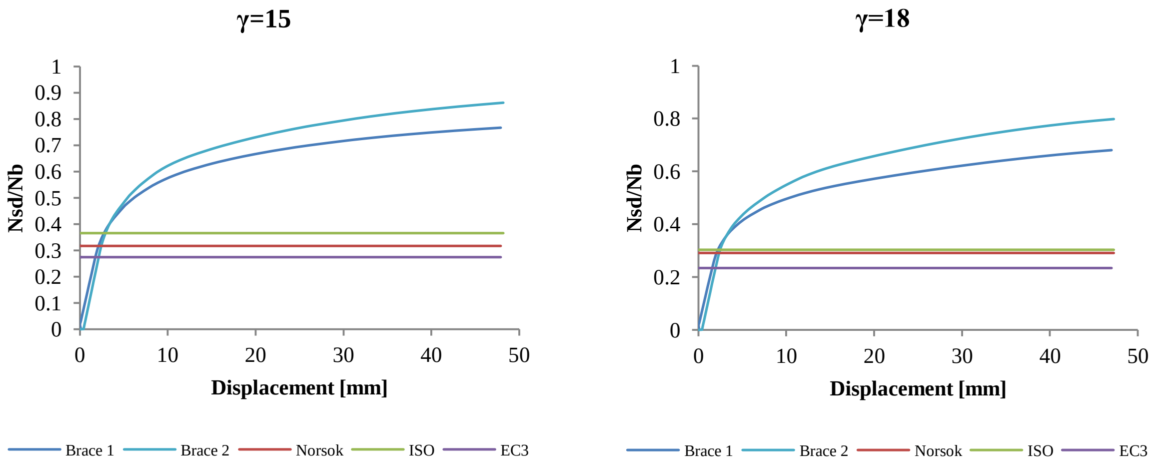


Figure 5.3- Load-displacement curves with γ=15 and γ=18

Figure 5.2 shows how strength design values approach each other due the increasing of γ and reduction of the strength is taking place as the values are under the 40% of axial capacity of the brace member.

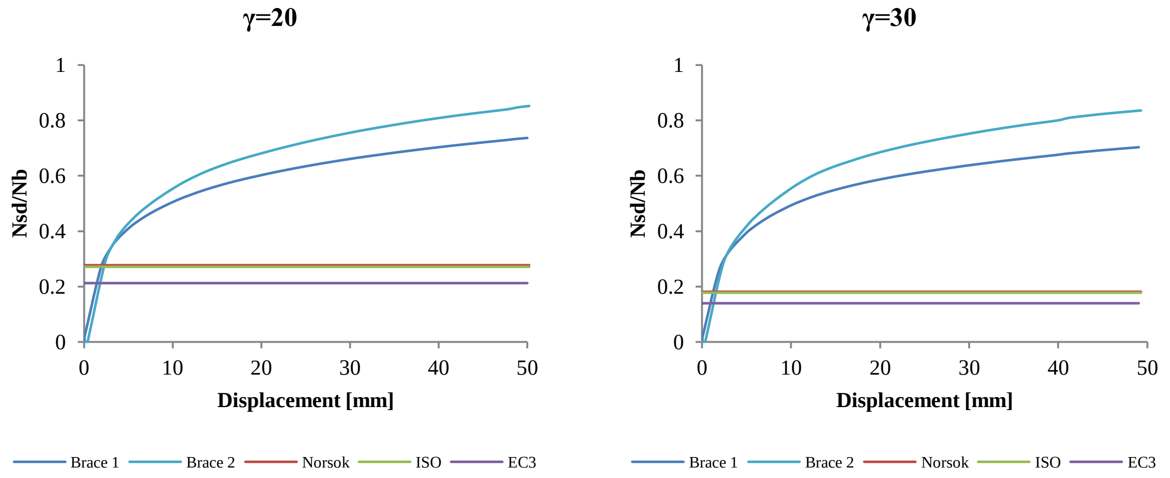


Figure 5.4 - Load-displacement curves with γ=20 and γ=30

We can appreciate that strengths design from standards gradually reduces and values of ISO 19902 (2007) and Norsok N-004 (2013) tend to have the same value (fig 5.4). When γ=30, strengths design values from standards decrease considerably, below 20% of axial capacity and EC3-1-8 (2005) even reaches 10%.

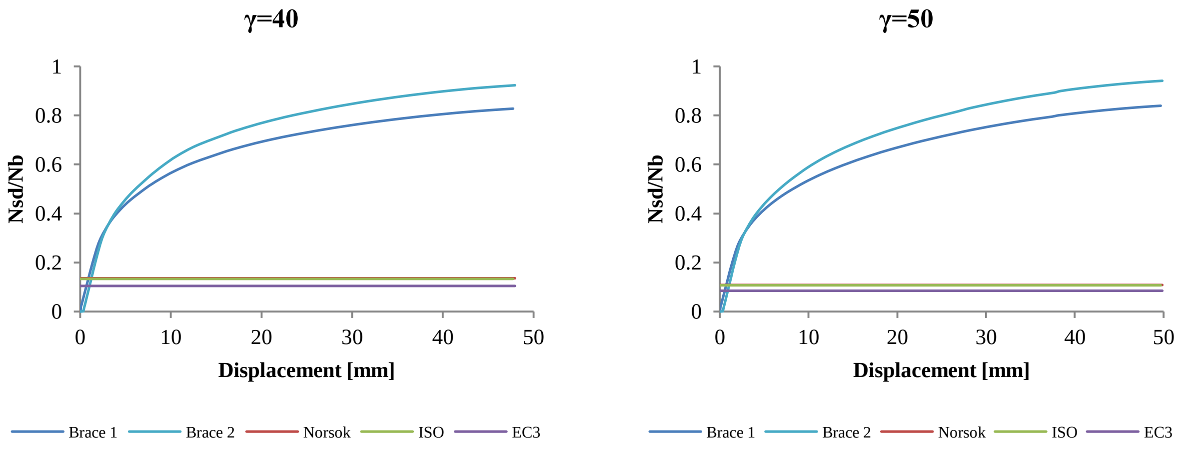


Figure 5.5 - Load-displacement curves with γ=40 and γ=50

These last figures show how N_{Rd} from standards keeps reducing its values by moving away from yield point of the joint. This fact avoids problems with sections which are prone to suffer instability before achieving yielding (class section 4). When γ=50, all axial strength design are considered to work around 10% of the axial capacity of the brace and EC3 takes the minimum value (outside of validity ranges).

Note that, the load-displacement curves belong to the joint and, for an imposed displacement of 50 mm, all of them reach plastification but, the brace member does not. This means that K-joint fails before brace member does because any ultimate strength reach the value of one for $N_{sd}/N_{Rd,b.}$ Finally, we can see the ultimate strength of the brace 2 is higher than the brace 1. This is due to steel materials are more resistant to tension loads rather than compression loads.

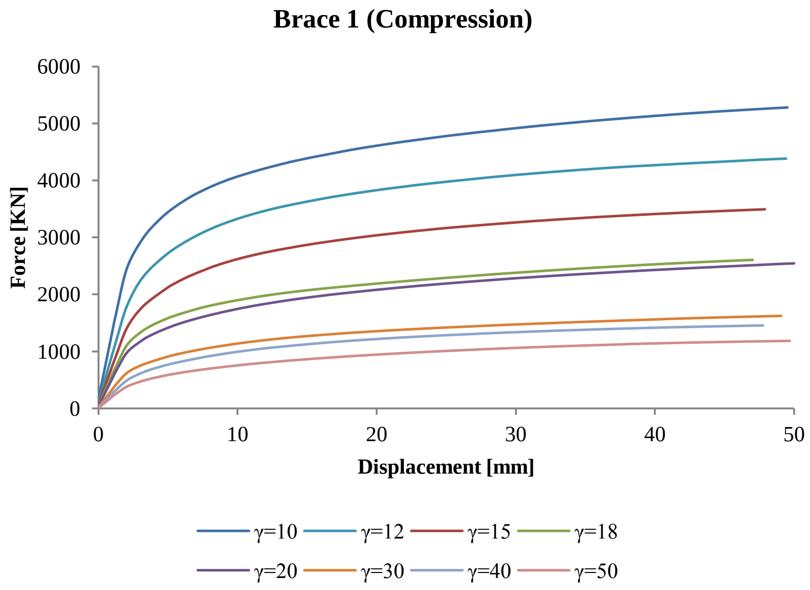


Figure 5.6- Force-displacement curve for several γ in brace 1

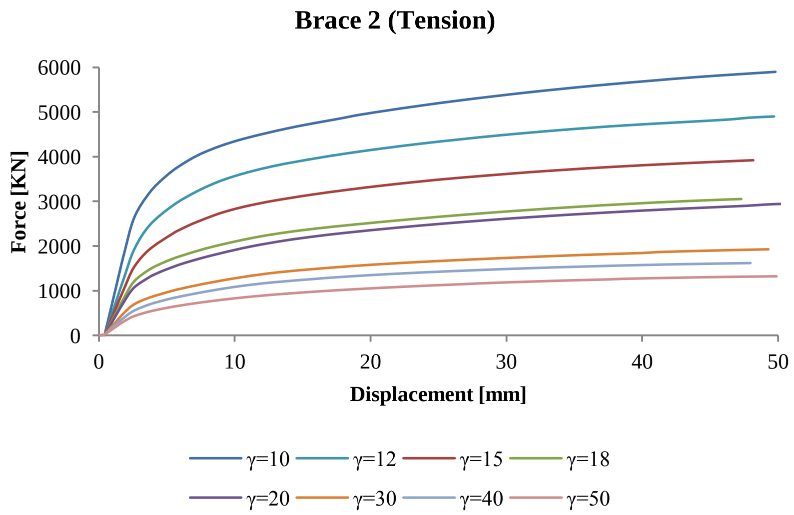


Figure 5.7 - Force-displacement curve for several γ in brace 2

Figures 5.6 and 5.7 show how force-displacement curves reduce as does its thickness. Even though, brace in tension still is more resistant to axial loads but, a reduction of stiffness in all joints is appreciated.

Note that in Figure 5.7, curves do not exactly start in zero. Considerations in the numerical analysis were split up in two phases: First compression chord and second imposed displacement at each brace. Then, at the first phase when chord is being compressed all the entire joint is being translated horizontally just few millimetres away and is more visible on brace 2 due to its inclination.

5.2 Analysis for a Y-joint

The example of clause 3.5.2 will be taken to proceed with the parametric study. Then, factor β is maintained equal to 0.8. The values used in the parametric study are presented in the table 5.3. Note that, Abaqus CAE is used to perform the parametric analysis.

For the initial condition, the value admitted is γ=10. In addition, chord will be loaded with the initial ratio $N_{chord}/A \cdot f_y$ ~ 0.30 (see Table 3.18) and keep this ratio along the parametric study.

Table 5.3- Y-joint (β=0.8)

γ(D/2T)	T[mm]	t[mm]	Axial load in chord [N]	Chord Area [mm^2]
10	20	20	$-2.51 \cdot 10^6$	23876.10
12	16.6	16.6	$-2.13 \cdot 10^6$	19994.48
15	13.3	13.3	$-1.72 \cdot 10^6$	16157.56
18	11.1	11.1	$-1.44 \cdot 10^6$	13561.60
20	10	10	$-1.30 \cdot 10^6$	12252.21
30	6.6	6.6	$-8.69 \cdot 10^5$	8156.96
40	5	5	$-6.61 \cdot 10^5$	6204.65
50	4	4	$-5.30 \cdot 10^5$	4976.28

In order to obtain a better idea about the material behaviour, moment-rotation curves are exposed. Thus, an imposed horizontal displacement of 20cm is applied on the brace; (see Fig. 5.8). In addition, resulting bending moments are shown as dimensionless in results, where M_b is the bending moment capacity of the brace.

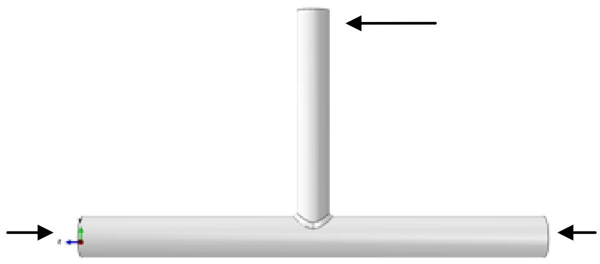


Figure 5.8- Loads on Y-joint for parametric study

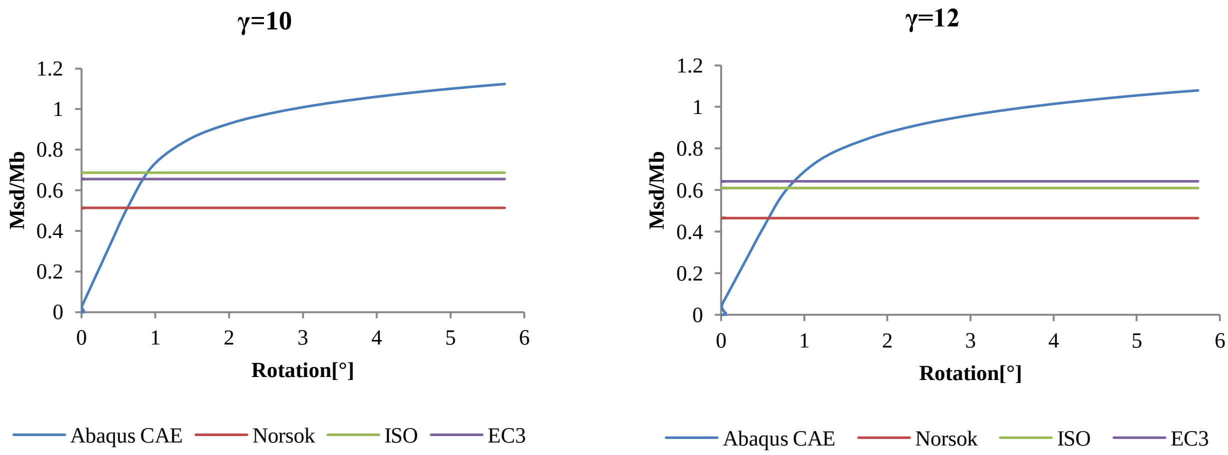


Figure 5.9 – Moment-rotation curves with γ=10 and γ=12

As we can see in Figure 5.9, three strengths design are situated below the yielding point and strength from Norsok (2013) is under ISO 19902 (2007) and EC3-1-8 (2005) values. This is due to the slightly different values of partial safety factor or formulation (γ_{Norsok}=1.15, γ_{EC3}=1.0, γ_{ISO}=1.05).

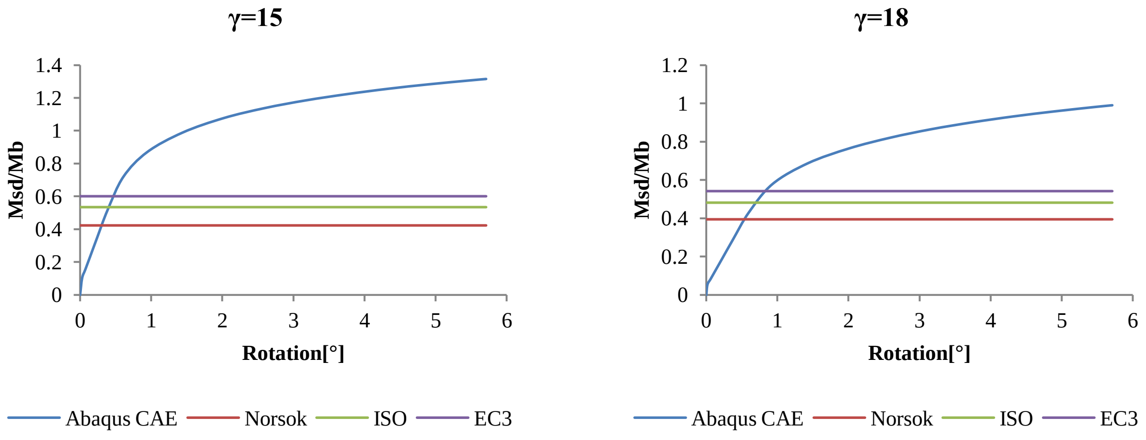


Figure 5.10 - Moment-rotation curves with γ=15 and γ=18

Figure 5.10 shows how strength design values approach each other due the increasing of γ and reduction of the strength is taking place as the values are under the 60% of axial capacity of the brace member.

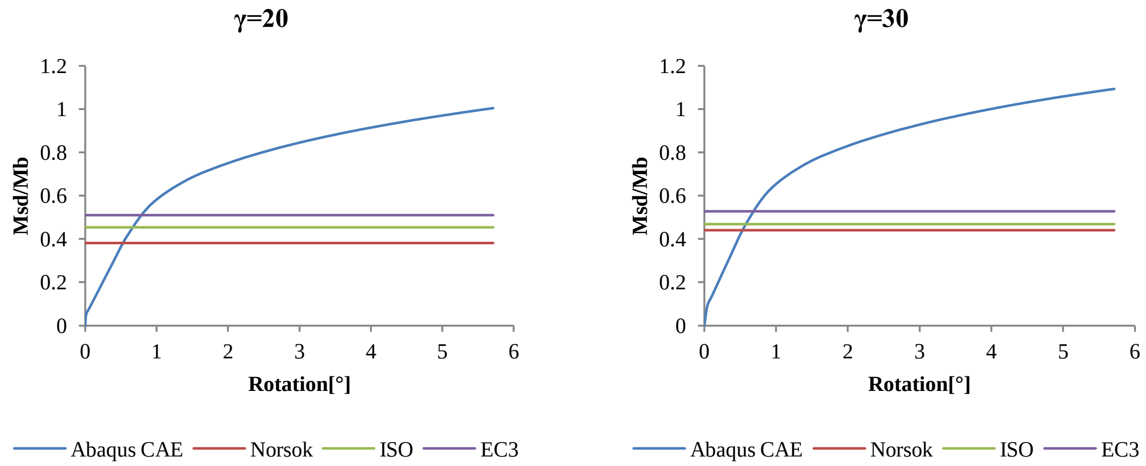


Figure 5.11 - Moment-rotation curves with γ=20 and γ=30

We can appreciate that moment strengths design (M_{Rd}) from standards gradually reduce up to stay between 40-60% of moment capacity as well as maintaining similar differences (Fig 5.11).

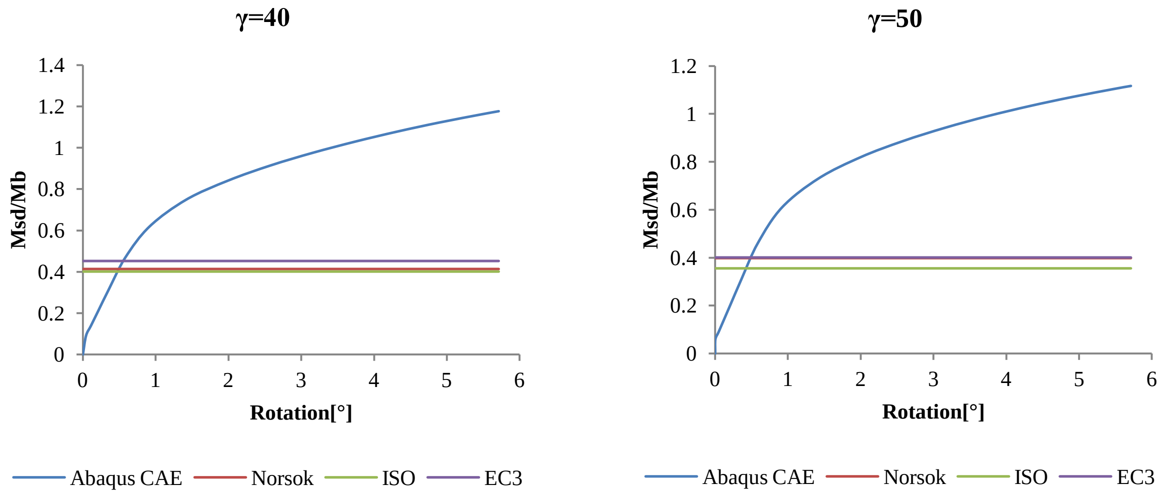


Figure 5.12 - Moment-rotation curves with γ=40 and γ=50

These last figures show how M_{Rd} keeps reducing its values by moving away from yield point. This fact avoids problems with sections which are prone to suffer instability before achieving yielding (class section 4). Mrd reaches values of 40% moment capacity of the brace.

According to the Moment-rotatin curves, a horizontal displacement of 20cm is more than enough for both joint and braces to reach yielding but, the joint still goes to failure before brace.

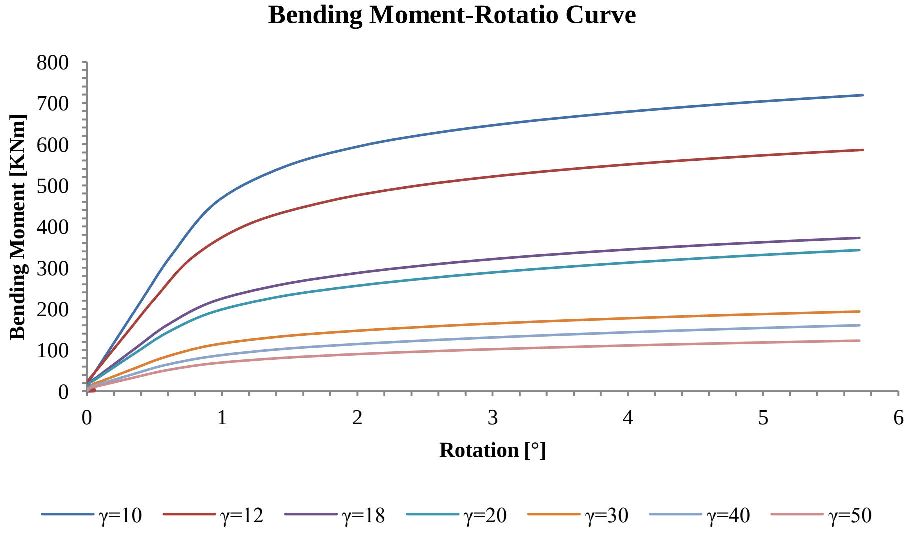


Figure 5.13 - Moment-Rotation curves for several γ

Figure 5.13 shows how Moment-Rotation curve reduces as does its thickness as well as a lost of stiffness can be appreciated. Note that, as K-joint analysis, same load phases were considered. Then, figures are showing a previous horizontal displacement just before the rotation of the brace, so that accounts for the insignificant deviation of the curves at origin.

5.3 Analysis for a X-joint

The geometry of the example of clause 3.5.3 will be taken to proceed with the parametric study. Then, factor β is maintained equal to 1.0. The values used in the parametric study are presented in the table 5.3. Note that, Abaqus CAE is used to perform the parametric analysis.

For the initial condition, the value admitted is γ=10. In addition, chord will be loaded with the section axial capacity ($A \cdot f_y$) and keep this factor along the parametric study.

Table 5.4 - X-joint (β=1.0)

γ(D/2T)	Tcan [mm]	Tnom [mm]	t [mm]	Axial load in chord [N]	Chord Nominal Area [mm^2]
10	45	25	25	$3.38 \cdot 10^7$	68722.34
12	37.5	25	25	$2.44 \cdot 10^7$	68722.34
15	30	20	20	$1.96 \cdot 10^7$	55292.03
18	25	18	18	$1.77 \cdot 10^7$	49875.92
20	22.5	15	15	$1.48 \cdot 10^7$	41704.64
30	15	10	10	$9.93 \cdot 10^6$	27960.17
40	11.25	8	8	$7.96 \cdot 10^6$	22418.41
50	9	6	6	$5.98 \cdot 10^6$	16851.50

In order to obtain load-displacement curves, an imposed displacement of 50mm is applied on each brace; both of them in tension (see Fig. 3.9).

As stated before, EC3-1-8 (2005) does not consider chord can in its formulation, so we will also compare both results (can and no can) to find out how different they may be. In addition, applied axial forces are shown as dimensionless in results, where N_b is the axial capacity of the brace.

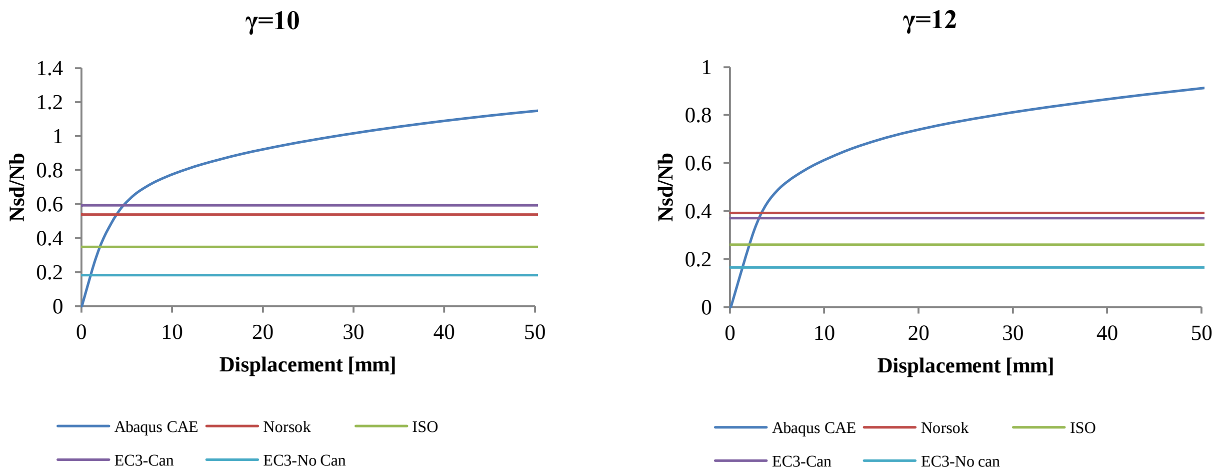


Figure 5.14- Load-displacement curves with γ=10 and γ=12

As we can see in Figure 5.14, three strengths design (N_{Rd}) are situated below the yielding point of the joint.

Axial strength design of ISO 19902 (2007) is very conservative as is only working with around 30% the axial capacity, unlike Norsok and EC3-1-8 (2005) (can) values around 60 % and 40%. This is caused by the differences in the formulations for an X-joint, see tables 3.1 and 3.3.

Moreover, both EC3-1-8 (2005) values are very different. The one who considers the can thickness along the entire chord is overestimating the strength of the joint and the other one is underestimating the joint strength working around a 15% of brace axial capacity. Fortunately, sections form figure 5.13 represent section class 1 with enough rotational capacity to be overloaded.

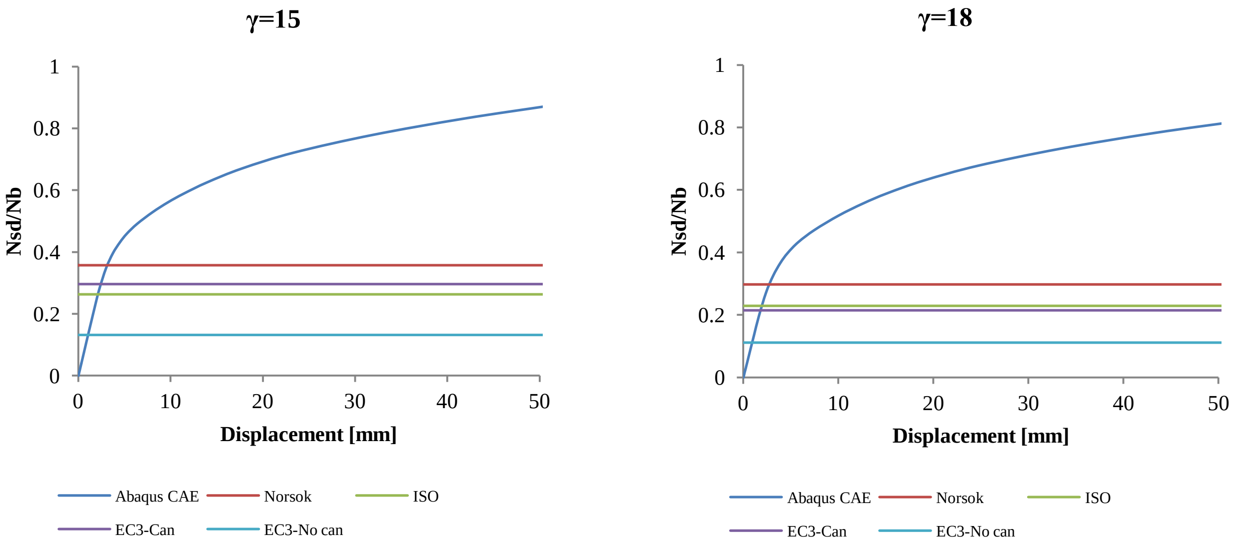


Figure 5.15 - Load-displacement curves with γ=15 and γ=18

Figure 5.15 shows how strength design values approach each other due the increasing of γ and reduction of the strength is taking place as the values are under the 40% of axial capacity of the brace member.

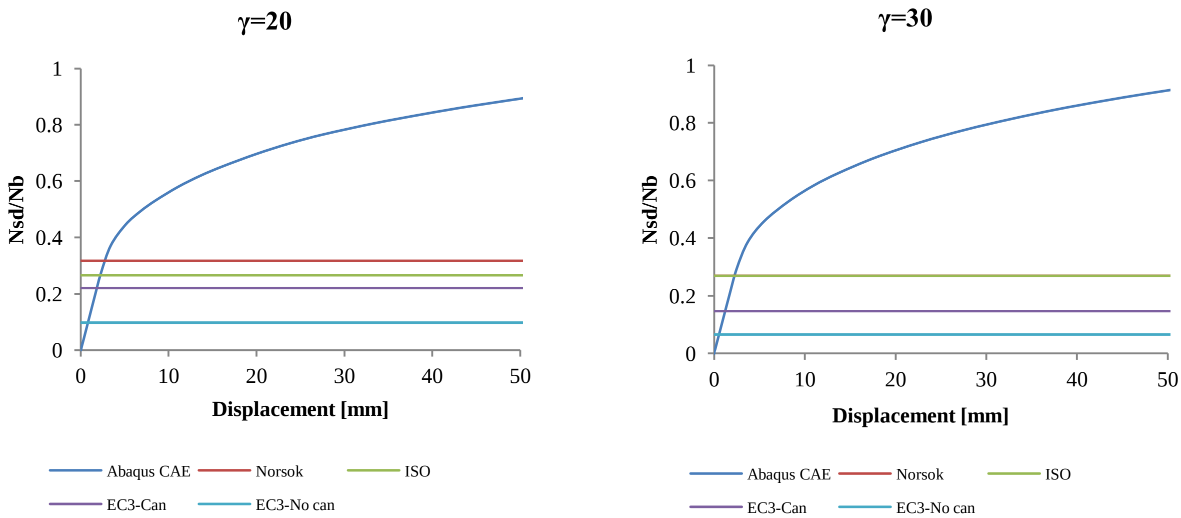


Figure 5.16 - Load-displacement curves with γ=20 and γ=30

We can appreciate that strengths design from standards gradually reduce and ISO 19902 (2007) and Norsok N-004 (2013) tend to have the same value (Fig. 5.16) maintain similar differences. Both tests of EC3-1-8 (2005) keep in the same difference and emphasising it when γ increases.

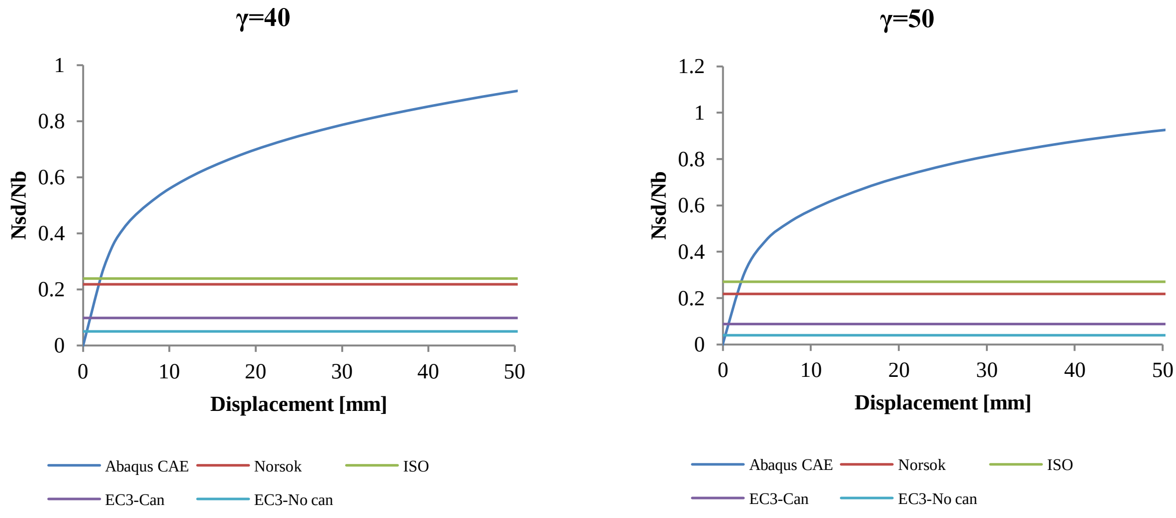


Figure 5.17 - Load-displacement curves with γ=40 and γ=50

These last figures show how N_{Rd} keeps reducing its values by moving away from yield point of the joint. This fact avoids problems with sections which are prone to suffer instability before achieving yielding (class section 4). Moreover, results from EC3 stopped being considered, as in last figure 5.17, gives results which are quite conservative and below all of them.

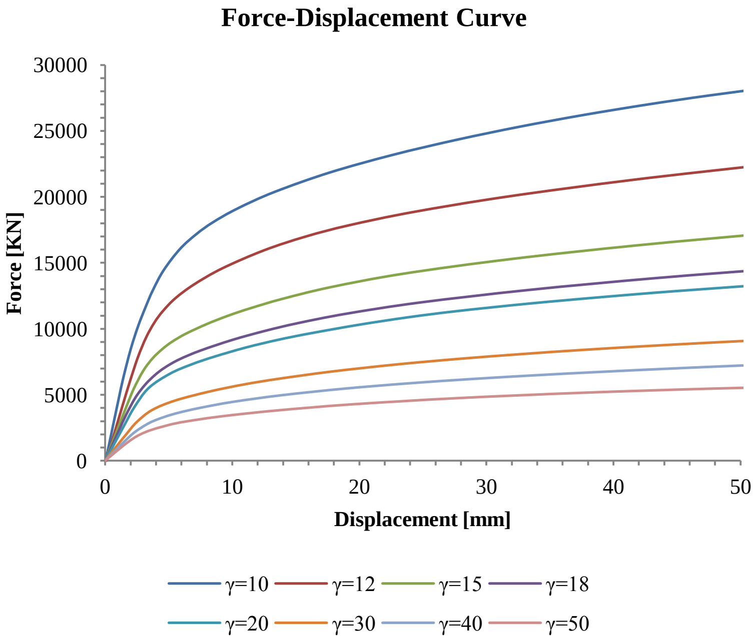


Figure 5.18 - Force-Displacement curve for several γ

Figure 5.18 shows how Force-Displacement curve reduces as does its thickness as well as the lost of stiffness.

5.4 Conclusions

Parametric study is very useful to find out how specimen behaves when any of its parameters changes and then let us know their high or small influence on final results.

In this case, parameter γ, which contains the chord thickness in its formulation, is a very important factor as it affects directly the joint strength. It is quite clear that the thicker the chord, the stronger the joint. However, in order to know the limits and from which point our design is safe, joint strength design from standards need to be taken into account.

Exposed results are inside the limits of applicability of three standards, although one of them is more restrictive than the other ones. Then, comparison among the standards, tell us more about their efficiency and structural point of view. We can conclude that three norms obtain a safe strength design regarding to Force/Moment-Displacement/Rotation curves as all of them do not surpass the yielding zone.

Regarding the differences, results tend to work nearby the yielding zone when dealing with sections between γ=10 and γ=20 which are usually class section 1 or 2 and where plastic strength design can be considered. However, once results approach to sections with γ=50, strength reduces drastically and standards consider a strength design (N_{Rd} and M_{Rd}) that works in a point which is much lower than the yielding point. Then, this is the way standards avoid considering local failure for those sections which are usually class section 4.

Norsok N-004 (2013) results are usually working under the yielding area and beneath the other strengths values due to its partial safety factor which is bigger, γ_M=1.15 except for a X-joint whose value is bigger than other ones, most likely because its formulation. Moreover, its formulation increases or reduces the strength design regarding the which kind of section is dealing with (γ=10 up to γ=50)

ISO 19902 (2007) gives also safe results as Norsok N-004 (2013), but its formulation only distinguishes sections with different γ when a K-joint is being analyzed and giving conservatives results when considering other joint types as its strength design usually remains in the same zone, around 40% of the brace capacity. Therefore, ISO 19902 (2007) does not consider a correct gradual variation of strength regarding sections γ~50 for X- and Y-joints.

EC3-1-8 (2005) is strictly applicable with class section 1 or 2(see clause 3.3.6). However, once the structure to be analyzed is out of these ranges, results stop being reasonable and do not make sense as tend to be very conservative. Moreover, chord can reinforcement is commonly used in offshore jacket structures and EC3-1-8 (2005) does not consider this at all, giving results that cannot be applicable to design a joint in the offshore area.

Regarding K- and Y-joint (unreinforced), EC3-1-8 (2005) showed good results; considering a 60%-70% of the brace capacity for γ=10 and γ=12 and decreasing the strength design for section that were out of its ranges.

6 RESULTS AND CONCLUSIONS

The present clause aims to analyse the work and results of this thesis. A general overview about offshore structures has been done as it is usually the area where tubulars joint are mostly used. The simple geometry, no critical corners, low drag coefficient (water, air, etc) and aesthetic appearance allows them to be the most optimum solution for most engineering projects.

Strength capacity is a very important part to analyze because every time complexity on new designs and projects is increasing. In order to know the structural behaviour, regulating standards such as Norsok N-004 (2013), ISO 19902 (2007) and EC3-1-8 (2005) are studied and analyzed. It is found that each standard has several formulations to estimate the axial and moment design strength of the joint and the reader might have problems to understand the important parts of these formulations. However, several things were discovered in this thesis just to help and give a better idea about how they work. Despite of having complex and several formulations, there are common factors among those formulations which usually account for the design strength of the joint. Those factors are Q_f and Q_u (ISO 19902, Norsok N-004) which accounts for the loads on the chord, type of joint and type of loading on the brace as well as the factor k_p which is the equivalent to Q_f but used in EC3-1-8 and all those three factors depend on the basic geometric parameters γ, β, g, τ which are ratios that consider the thickness, diameter, space between braces, etc of the joint. Case studies for each joint were performed to estimate the design strength and find out more differences and similarities. It was found that results usually were similar among them however; there was always one of them that were significantly higher or smaller than the other two (see Table 3.30) and those differences were accounted for either Q_f or Q_u or just simply because of the partial safety factor: $\gamma_M = 1.15$ (Norsok N-004, 2013), $\gamma_{Rj} = 1.05$ (ISO 19902, 2007) and $\gamma_{M5} = 1.0$ (EC3-1-8, 2005) which might rewards more conservative results.

In order to know and obtaining a better behaviour of the joint, a finite element analysis was performed. Then, a static plastic analysis of a reinforced X-joint was carried out by Abaqus CAE. As every numerical model, it needs to be validated so we compared our results (stresses, displacements and plastic strain) with a previous research (Ghanemnia N., 2012). Finally, results were quite similar (see Table 4.3) despite of not having simulated the weld. Then we concluded to continue our research.

After validation, parametric study was performed to find out what are the most important parameters which have more influence in the joint strength. The parameter γ was chosen as it considers the chord thickness in its formulation. Validity ranges was checked to know the boundaries of our parametric study: $10 \leq \gamma \leq 50$ but EC3-1-8 (2005) is more restrictive $5 \leq \gamma \leq 20$ (see Table 5.1). So we deepened in more detail in the range of $10 \leq \gamma \leq 20$ with $\gamma=12$, $\gamma 15$, $\gamma=18$. Then the variation of γ was done for every type of joint (X-, Y-, K-) by a numerical analysis to obtain the Force/Moment-Displacement/Rotation curves then locate the design strengths on those curves so as to find out the point they consider for structural design.

Consequently, it was found that for small values of γ, joints tend to behave with a good axial and moment capacity and design strength from standards tend to locate nearby the yield zone. However, for small values of γ, joints tend to have a poor axial and bending capacity, and then joint strength curve reduces drastically and they become to be prone to local failure. Thus, design strengths from standards tend to reduce its value and moving away significantly from the yielding zone as local failure might occur before yielding.

In conclusion, formulations from regulating standards are generally capable to distinguish the strength capacity of the joints thanks to good calibrations of the geometric parameters (γ, β, g, τ) in their formulations. However, some results might not differentiate well enough as they locate and remain relatively in the same position i.e: Norsok design strength for a Y-joint (see Table 5.9 to Table 5.12) and that detail deserves special attention.

7 RECOMMENDATIONS FOR FURTHER WORK

Main objective of this thesis was the assessment of the behaviour of tubular joints and compare the results with the regulating standards in order to know how they really work according their formulations, types of joints and loading.

The parametric study only focused on the parameter γ. Then, it could be helpful to continue this study with other parameters such as β, τ , different loads on the chord and others type of brace loading.

Unique loads were analysed in this thesis and carry out a research about how tubular joints behave under combined loading would help to understand their structural behaviour.

Finally, a static plastic analysis was performed so go to cyclic or dynamic analysis is a very interesting option to find out how tubular joints behave under critical conditions with plastic strains (low cycle fatigue) and then a good assessment of the weld would be needed.

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