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A Numerical Analysis of Tubular Joints under Static Loading

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Abstract: The intensive worldwide use of tubular structural elements, mainly due to its associated aesthetical and structural advantages, led designers to be focused on the technologic and design issues related to these structures. Consequently, their design methods accuracy is a fundamental aspect under the economical and safety points of view.
Additionally, recent RHS structure connection studies indicated the need of further investigations, especially for some particular joint geometries. This is even more significant when the failure mode changes and the prediction of the failure load may lead to unsafe or uneconomical solutions.
In this investigation, a numerical (non-linear finite element simulations) based parametric study is presented, for the analysis of tubular joint configurations where both chords and braces are made of hollow sections. Starting from test results available in literature and previous numerical studies, a model has been developed, taking into account the weld geometry, material and geometric nonlinearities. The proposed model was validated by experimental comparisons. The main variables of the study were: the brace width to chord width ratio and the thickness to chord face width ratio. The choice of these parameters was based on recent studies results that depicted some discrepancies on Eurocode 3 recommendations. These cases occurred for particular values of the investigated parameters and were related to issues associated to the shear to bending failure mode interaction.
The numerical results were compared to the analytical results suggested by the Eurocode 3 and to the classic deformation limits proposed in literature. This paper also presents a critical review of the results focusing on the aspects of the available analytical formulation and their practical consequences.

Key words: steel structures, tubular joints, finite element analysis, plasticity, collapse mechanisms.

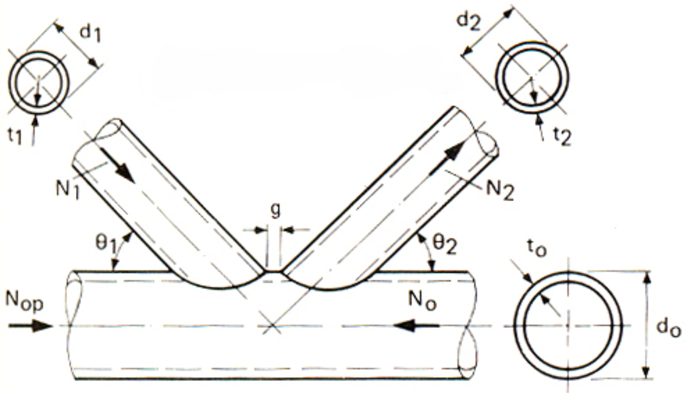
INTRODUCTION

Structural hollow sections (Fig. 1) are widely used by designers, due to their aesthetical and structural advantages [1], [2]. On the other hand, the adoption of tubular sections frequently leads to more expensive and complex connections, since there is no access to the interior of the connected parts. This problem is solved by special blind bolted connections or, more frequently, by the extensive use of welded joints. In addition to the fabrication costs, a proper connection design has to be performed since their behaviour frequently governs the overall structural response. This paper deals with the structural behaviour of CHS "K" joints (Fig. 2) in trusses under static loading. The effects of shear, punching shear and bending are considered to predict the possible joint failure mechanisms.
The circular hollow section (CHS) K-joint configuration is commonly adopted in steel offshore platforms (e.g. jackets and jack-ups) which are designed for extreme environmental conditions during their operational life. The ultimate and service strengths of such structures significantly depend on the component (member and joint) responses. Consequently, in the past few years many research programmes on tubular joints funded by oil and gas companies and national governments were initiated.
Traditionally, design rules for hollow sections joints are based on either plastic analysis or on deformation limit criteria. The use of plastic analysis to define the joint ultimate limit state is based on a plastic mechanism corresponding to the assumed yield line pattern. Typical examples of these

approaches can be found on Cao et al [3], Packer [4], Packer et al [1], Choo *et al.* [5] and Kosteski et al[6]. Each plastic mechanism is associated to an unique ultimate load that is suitable for this particular failure mechanism. The typical adopted yield lines were: straight, circular, or a combination of those patterns.

Fig. 1 Examples of tubular structures with K joints

Deformation limits criteria usually associate the ultimate limit state of the chord face to a maximum out of plane deformation of this component. The justification for a deformation limit criterion instead of the use of plastic analysis for the prediction of the ultimate limit state is that, for slender chord faces, the joint stiffness is not exhausted after complete onset of yielding, and can assume quite large values due to membrane effects. This phenomenon is clearly shown in the curves obtained from the material and geometrical nonlinear finite element analysis performed in the present study. It is evident that, if the maximum load is obtained from experimental curves, the absence of a "knee" in the curve could complicate the identification of this ultimate limit state point. Additionally there is still the need of further comparisons of experimental and plastic analysis results based on deformation criteria.
The deformation limit proposed by Lu et al. [7] and reported by Choo *et al.* [8] may be used to evaluate the axial and/or rotational capacity of a joint subjected to the corresponding brace axial or moment loads. The joint strength is based on a comparison of the deformation at the brace-chord intersection for two strength levels: the ultimate strength, N_u which corresponds to a chord indentation, $\Delta_u = 0.03d_0$, and the serviceability strength, N_s that is related to $\Delta s = 0.01d_0$. Lu et al. [7] stated that the first peak in the load-deformation diagram should be used if it corresponds to a deformation smaller than the limit $\Delta_u = 0.03d_0$. According to Lu et al. [7], if the ratio of N_u/N_s is greater than 1.5, the joint strength should be based on the ultimate limit state, and if $N_u/N_s < 1.5$, the serviceability limit state controls the design. In the case of CHS joints, $N_u/N_s > 1.5$ the appropriate deformation limit to determine the ultimate joint strength should be equal to $0.03d_0$.



$$\beta = \frac{d_1 + d_2}{2d_0} \tag{1}$$

$$\gamma = \frac{d_0}{2t_0} \leq 25 \tag{2}$$

$$0.2 \leq \frac{d_i}{d_0} \leq 1.0 \tag{3}$$

$$10 \leq \frac{d_0}{t_0} \leq 50 \text{ and } 10 \leq \frac{d_i}{t_i} \leq 50 \tag{4}$$

Fig. 2 Joint geometry and governing parameters [1]

EUROCODE 3 PROVISIONS

For connections between CHS joints, such as the ones represented in Fig. 1 and Fig. 2, the methodology proposed by the Eurocode 3 part 1-8 (EN 1993-1-8) [9] is based on the assumption that these joints are pinned. Therefore the relevant design characteristic (in addition to the deformation capacity) is the chord and braces strength, primarily subjected to axial forces. Eurocode 3 provisions for the evaluation of this design joint resistance assume the following failure modes:

- plastic failure of the chord face Fig. 3(a);
- chord side wall failure by yielding, crushing or instability under the compression brace member Fig. 3(b);
- chord yielding (plastic failure of the chord cross section);
- chord shear failure Fig. 3(c);
- punching shear failure of a hollow section chord wall Fig. 3(d);
- brace failure with reduced effective width Fig. 3(e);
- local buckling failure of a brace member, or of an hollow section chord member at the joint location Fig. 3(f).

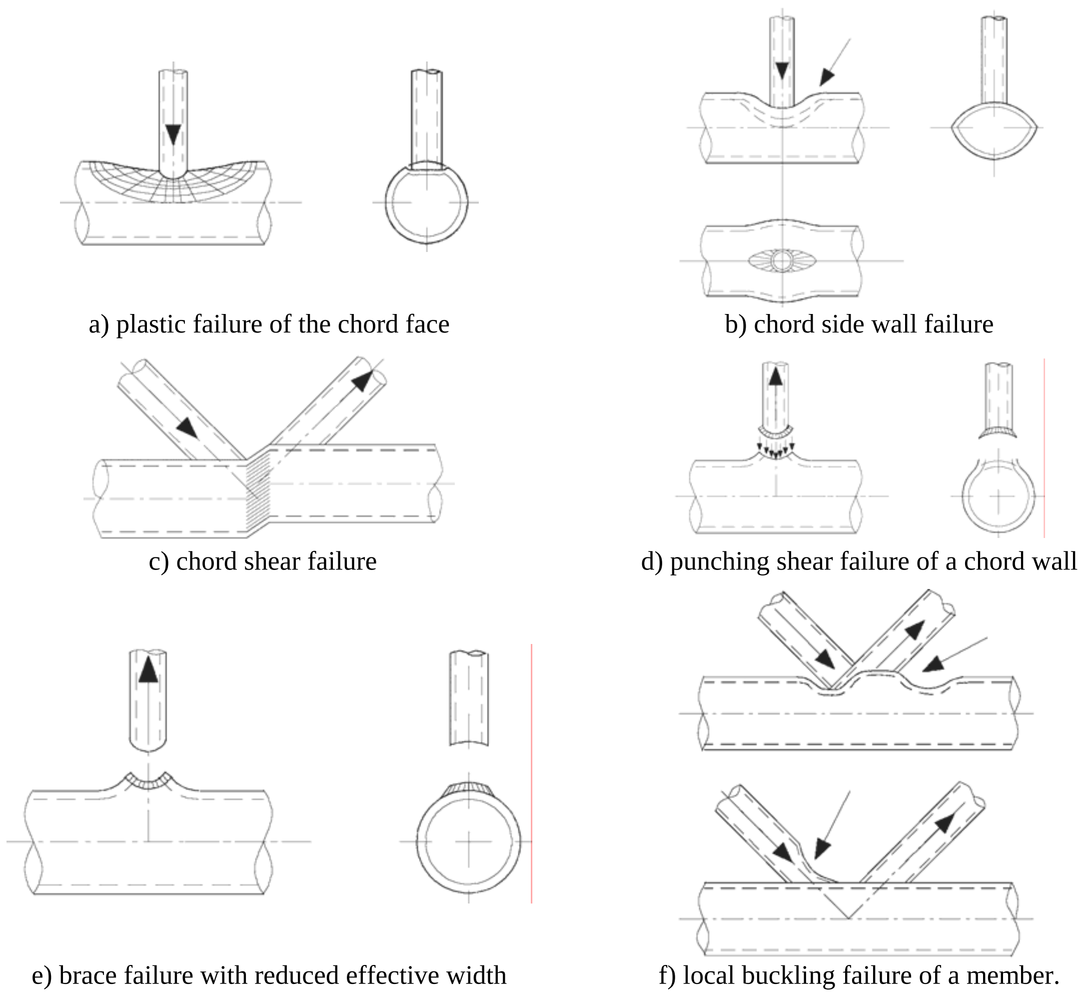


Fig. 3 Eurocode3 failure modes [4]

Equation (5) defines, according to Eurocode [9], the chord face plastic load for the investigated “K” joint with the geometric parameters defined in Figure 2. $N_{1,Rd}$ is the brace axial load related to the development of the chord face yielding or punching limit states. This value can be evaluated with the aid of equation (5) present in the Eurocode [9]:

$$N_{1,Rd} = \frac{k_g k_p f_{y0} t_0^2}{sen\theta_1}\left(1.8 + 10.2\frac{d_1}{d_0}\right) / \gamma_{M5} \text{ and } N_{2,Rd} = \frac{sin\theta_1}{sin\theta_2} N_{1,Rd} \tag{5}$$

where f_{y0} is the chord yield stress, t_0 the chord thickness, θ_1 and θ_2 are the angle between the chord and the braces, k_p =1 (for the investigated joint) and k_g can be obtained from eq. (6).

$$k_g = \gamma^{0.2}\left(1 + \frac{0.024\gamma^{1.2}}{1 + exp(0.5g / t_0 - 1.33)}\right) \tag{6}$$

NUMERICAL MODELLING

Tubular joints are most commonly modelled by shell elements that represent the mid-surfaces of the joint member walls. The welds are usually represented by shell (see Fig. 4) or three-dimensional solid elements, may be included or not in the model. It is common practice to analyse this type of joints without an explicit consideration of the weld. This is done simply modelling the mid-surfaces of the member walls using shell elements [10], [11]. Despite this fact, some authors stated that this effect may be significant [12] especially for K-joints with a gap, since the weld does not have a negligible size compared to the gap size [11]. In the present investigation the weld was modelled by using a ring of shell elements (SHELL 181 - four nodes with six degree of freedom per node), Fig. 4, similarly to the configuration proposed by Lee [11] and Van der Vegte [13].

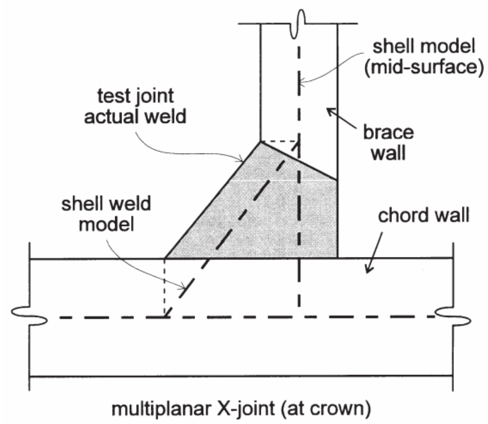


Fig. 4 Modelling of the welds by shell elements after Lee [11]

For an ultimate strength analysis, this approach is generally acknowledged as sufficiently accurate for simulating the overall joint behaviour. The decisions on the choice of element and the method of weld representation (if included), should be made in advance since it determines the model layout and the required mesh density.

The finite element models in the present study were generated using automatic mesh generation procedures. A finite element model adopted four-node thick shell elements, therefore considering bending, shear and membrane deformations. The model was composed of 9274 nodes and 9273 elements (see Fig. 5) and the analysis was performed using the Ansys 10.0 program [14].

The adopted yield and tension strengths were equal to f_y=355MPa and f_u=510MPa and were represented by a bilinear curve was used to characterise the material. The model calibration was performed on a RHS T-joint taking into account material and geometric non-linearities [12].

A refined mesh was used near the weld, where a stress concentration is likely to happen. An effort was made to create a regular mesh with well proportioned elements to avoid numerical problems. The adopted numerical procedure used boundary conditions and displacement-controlled loads at the right chord end.

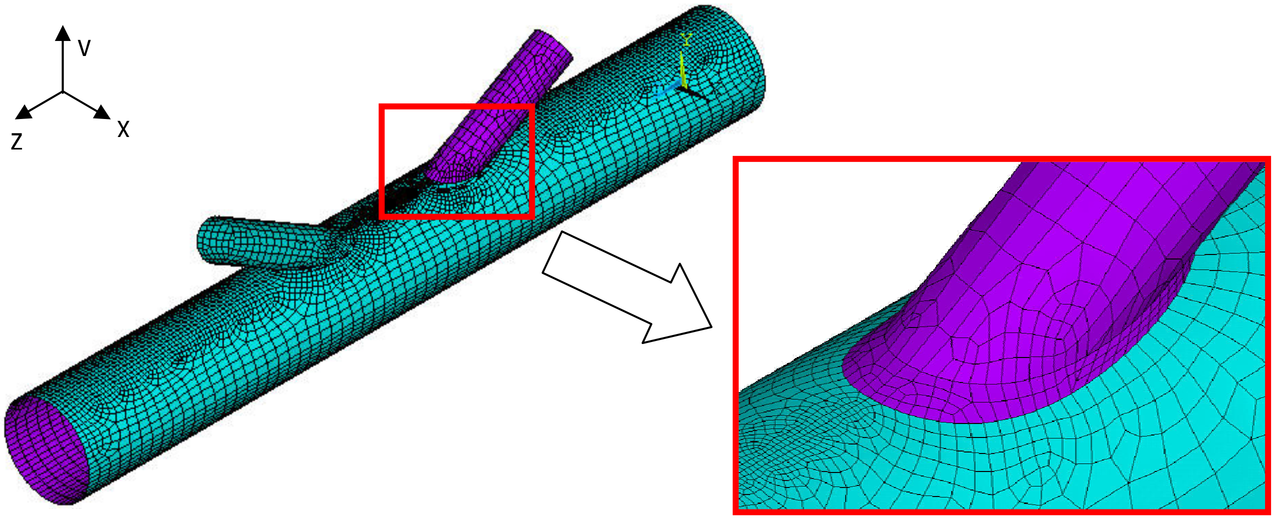


Fig. 5 Numerical model for the analysis of the "K" joints

Different boundary conditions on a K-joint may impose significant effects on the joint strength, altering chord axial stress magnitudes, chord bending stress magnitudes and introducing additional brace bending loads on the brace–chord intersection. At present, there are insufficient data from either numerical or experimental results to provide a good basis to characterise the ideal boundary conditions that could represent the effects imposed by adjacent structural members on the particular investigated joint [5].
Another issue which requires further investigation for both onshore and offshore structures is the effect of the chord to brace load interaction on the joint strength. Current design practices ignore the geometric dependence of the chord stress function, which does not consider a possible joint strength reduction resulting from the tensile chord stresses. Therefore, a better understanding of the boundary condition effects and chord stresses will provide a robust basis for safe and cost-effective designs [5].
According to Lee [15], the best way to model the boundary conditions applied to a K joint in order to simplify the test layout procedures is to consider the pinned brace ends with the translations in all coordinate directions fixed at the nodes. The load was applied by means of displacements at the nodes present at the right-hand end of the chord while the left-hand end was left unrestrained in the horizontal direction (see *Fig. 6*). Makino et al. [16] have used a similar set-up. The main difference was that instead of applying the load at one of the chord ends, the load was applied through the tension braces using a load distribution beam.

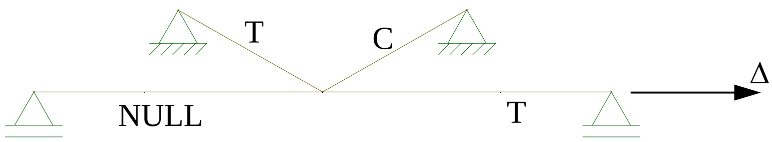


Fig. 6 Applied boundary conditions on the numerical model

The geometrical and mechanical properties of the model are presented in Table 1. These parameters lead to values of $\beta = 0.40$, $\gamma = 18 < 25$, $0.2 < d_i / d_0 = 0.4 < 1.0$, $10 < d_0 / t_0 = 18 < 50$ and $10 < d_i / t_i = 14.4 < 50$. It must be emphasized that these parameters satisfy the Eurocode 3 limits [9]. For this numerical model a full material (a bilinear material model was considered with a 5% strain hardening) and a geometric nonlinear analysis was performed.
This procedure represents the full assessment of the safety of the joints and may be summarized in several outputs, namely the stress distribution (that detects, among other data, first yielding at the connections), or the force-displacement curve for any node within the connection.
These results allow the assessment of the EN 1993-1-8 [9] performance not only in terms of maximum load (however the maximum numerical load is compared to the plastic load calculated from the Eurocode [9]), but also in terms of the load versus displacement curve. This may lead to the derivation of conclusions in terms of the stiffness and post-limit behaviour of the chord face, namely for the

assessment of the performance of deformation limits criteria for the chord face resistance, or for the evaluation of the available joint over-strength achieved by membrane action.

Table 1: Mechanical and geometrical properties

Specimen	d_0 (mm)	t_0 (mm)	d_1 (mm)	t_1 (mm)	d_2 (mm)	t_2 (mm)	θ (º)	f_y (MPa)	f_u (MPa)	f_w (MPa)
K1	406	11.28	162.4	11.275	162.4	11.28	30	355	430	600.0

RESULTS ANALYSIS AND DISCUSSION

In sequence, *Fig. 7* presents the load versus axial displacement curves for the brace members. It may be observed in the elastic range an excellent agreement of the curves was obtained. The *Fig. 8* presents the curve load versus axial displacement for the chord member.

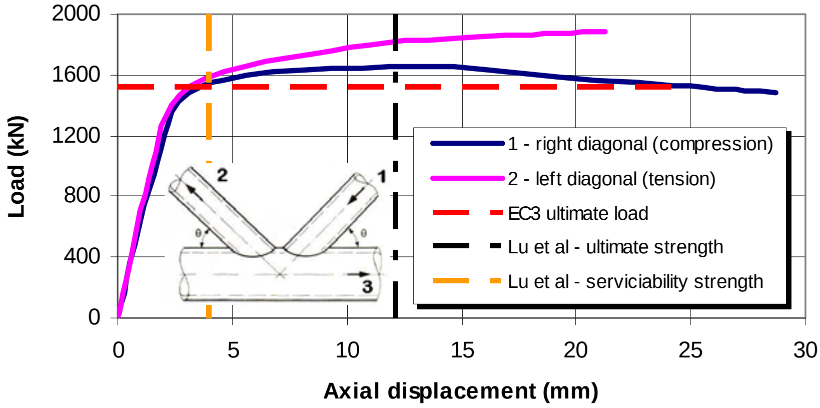


Fig. 7 Load versus displacement curves for chord members (1) and (2)

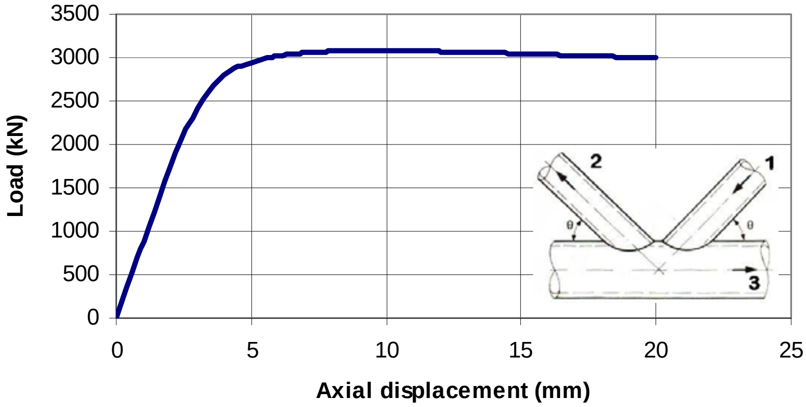


Fig. 8 Load versus displacement curves for brace member (3)

According to the deformation limit proposed by Lu et al. [7] and reported by Choo *et al.* [8], the joint strength is based on a comparison of the deformation at the brace-chord intersection for two strength levels: the ultimate strength, N_u, which corresponds to a chord indentation, $\Delta_u = 0.03d_0$, and the serviceability strength, N_s, that corresponds to $\Delta s = 0.01d_0$.

In the definition by Lu et al. [7], the first peak in the load-deformation diagram should be used if it corresponds to a deformation which is smaller than the deformation limit $\Delta_u = 0.03d_0$. Following these recommendations it can be observed that in *Fig. 7*, $N_s = 1550$kN and $N_u = 1650$kN.

Using Eurocode 3 [9] provisions, the joint ultimate load, also represented in *Fig. 7* is equal to 1522kN being an inferior limit to the numerical model results. The joint ultimate load was controlled by the chord local buckling at the compression brace member region (see *Fig. 9*, where the von Mises stress distribution of the model that did not explicitly considered the welds are presented).

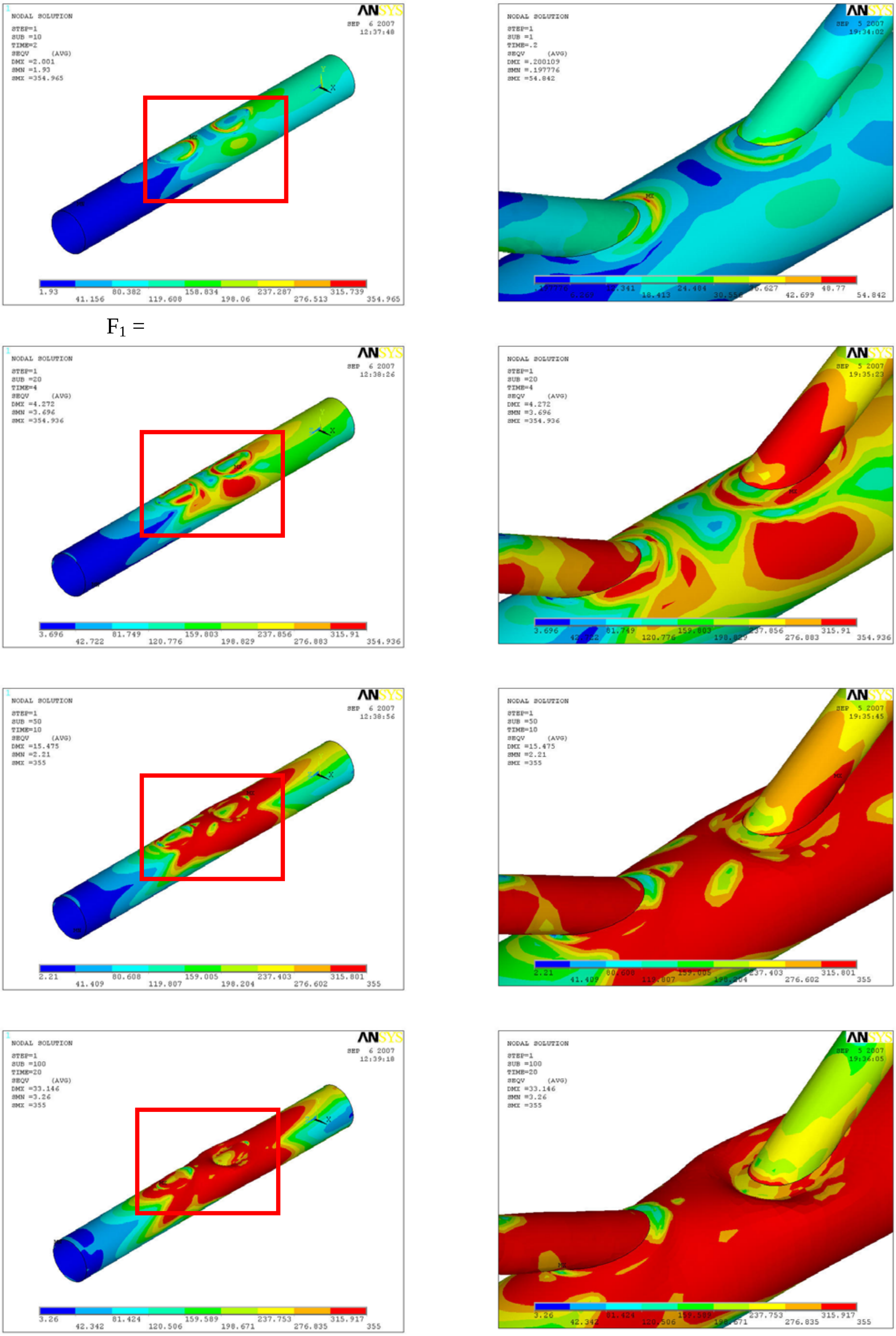


Fig. 9 Von Mises stress distribution (in MPa) – deformed scale factor = 2

FINAL REMARKS

A finite element model was developed to simulate the K joints behaviour using four-node thick shell elements, therefore considering bending, shear and membrane deformations. In this investigation, a full geometrical and material non-linear analysis was performed.

Deformation limits criteria were used to obtain the joint ultimate load. This criterion usually associates the ultimate limit state of the chord face to a maximum out of plane deformation of this component. The reason for using a deformation limit criterion instead of the use of plastic analysis for the prediction of the ultimate limit state is that, for slender chord faces, the joint stiffness is not exhausted after the complete yielding onset due to membrane effects.

The results of the analysis were used to assess the EN 1993-1-8 [4] performance not only in terms of maximum load, but also in terms of the global load versus displacement curves to fully characterise the joint structural response in terms of stiffness and ductility capacity.

Through the observation of the analytical curves, it could be concluded that the numerical results achieved a good agreement with the Eurocode 3 [4] previsions for the joint resistance combined with a deformation limit criterion for the deformation of the joint chord face.

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REFERENCES

[1] Packer, J. A., Wardenier, J., Kurobane, Y., Dutta, D. and Yoemans, N., 1992. Design Guide for Rectangular Hollow Section (RHS) Joints Under Predominantly Static Loading, CIDECT - Construction with Hollow Steel Sections, Verlag TÜV Rheinland.

[2] Tabet, F., Lima, L. R. O. de, Vellasco, P. C. G. da S., Andrade, S. A. L. de, Silva, J. G. S. da, Neves, L. F. da C., Avaliação do coeficiente de eficiência em ligações “T” com perfis tubulares através do método dos elementos finitos, *Proceedings of the XXVII CILAMCE - Iberian Latin American Congress on Computational Methods in Engineering*, September 3-6, Belém-PA, Brasil, pp 1-14 (in portuguese).

[3] Cao, J.J., Packer, J.A., Young, G.J., 1998. Yield line analysis of RHS connections with axial loads, *J. Constructional Steel Research,* vol. 48, nº 1, pp 1-25.

[4] Packer, J.A., 1993. Moment Connections between Rectangular Hollow Sections, *J.Constructional Steel Research 25*, pp 63-81.

[5] Choo, Y. S., Qian, X. D., Wardenier, J., 2006. Effects of boundary conditions and chord stresses on static strength of thick-walled CHS K-joints. *Journal of Constructional Steel Research,* vol.62, pp. 316-328.

[6] Kosteski, N., Packer, J.A., Puthli, R.S., 2003. A finite element method based yield load determination procedure for hollow structural section connections, *Journal of Constructional Steel Research,* vol. 59, nº 4, pp. 427-559.

[7] Lu LH, de Winkel GD, Yu Y, Wardenier J. Deformation limit for the ultimate strength of hollow section joints. In: Proceedings of Sixth International Symposium on Tubular Structures, Melbourne. 1994.

[8] Choo, Y. S., Qian, X. D., Liew, J. Y. R, Wardenier, J., 2003. Static strength of thick-walled CHS X-joints - Part I. New approach in strength definition. *Journal of Constructional Steel Research,* vol.59, pp. 1201-1228.

[9] Eurocode 3, EN 1993-1.8, 2005. *Design of steel structures – Part 1.8: Design of joints* (“final draft”), CEN, European Committee for Standardisation, Brussels.

[10] Lee, M.M.K., 1999. Strength, Stress and Fracture Analyses of Offshore Tubular Joints Using Finite Elements. *Journal of Constructional Steel Research*, vol. 51, pp. 265-286.

[11] Lie, S-T, Chiew, S-P, Lee, C-K and Yang, Z-M, 2006. Static Strength of Cracked Square Hollow Section T Joints under Axial Loads. II: Numerical. Journal of Structural Engineering, 132:3(378-386).

[12] Lima, L. R. O. de, Neves, L. F. da C., Silva, J. G. S. da, Vellasco, P. C. G. da S., Andrade, S. A. L. de. Parametric Analysis of RHS T Joints Under Static Loading. In: 11th International Conference on Civil, Structural and Environmental Engineering Computing - CC2007, 2007, Saint Julians. Proceedings of the 11th International Conference on Civil, Structural and Environmental Engineering Computing - CC2007. Edimburgo: Civil Comp Press, 2007. v. 1. p. 1-15.

[13] Van der Vegte GT, de Koning CHM, Puthli RS, Wardenier J., Numerical simulation of experiements on multiplanar steel X-joints. International Journal of Offshore and Polar Engineering 1991, 1(3), pp 200-2007.

[14] ANSYS, 1998. Swanson analysis systems, Inc., P.O. Box 65, Johnson Road, Houston, PA, 15342-0065, version 5.5, Basic analysis procedures, 2nd edition.

[15] Lee, M. K. K., Wilmshurst, S. R., 1995. Numerical Modelling of CHS Joints with Muitiplanar Double-K Configuration. *Journal of Constructional Steel Research,* vol.32, pp. 281-301.

[16] Makino, Y. et al., Ultimate capacity of tubular double K-joints. In *Proceedings of 2nd International Institute of Welding Conference on Welding of Tubular Structures*. Pergamon Press, Boston, 1984, pp. 451-8.