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Reinforcement T-Joint Design and Structural Validation for a Hydroelectric Power Plant: Study Case

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ABSTRACT

Branch pipe T-joints are used to connect and bifurcate hydraulic channels in big hydraulic power plants size. These components are submitted to enormous strengths that must be counteracted by integrated structures to the T-joint, for this case specified arrangement type "Nun neck". The main objective in this work is about validate structurally by numerical analysis the branch pipe T-joint design with reinforcement type “Nun Neck” to the operational established conditions in hydraulic channel design. The structural T-joint design was made following AISI Buried steel Penstocks and ASME section VIII Div. 1 standards. The simulation process was made by Multiphysics Simulation Software, Ansys Workbench V 17. The branch pipe T-joint CAD model is set as 1700 mm in diameter to flow and 1200mm to derivation. The computational simulation process was executed using the mechanical structure module in ANSYS Workbench V17.0 commercial version. The boundary conditions settings were established based on internal operational pressure given as 353.14 mWC and fixed restrictions in the areas of contact with the pipe. Equivalent Von Mises stress contours were determined looking to validate the stress state in branch T-joint, findings demonstrate that the proposed design has structural failures that must had been reinforced by civil works.

1. Introduction

Hydroelectric power was one of the first way to generate electricity and nowadays is the second source and the most generalized way to get electric power in the world to 2017 ends, it is supposed to reach 3606 TWh in 2020 (see Figure 1) [1].

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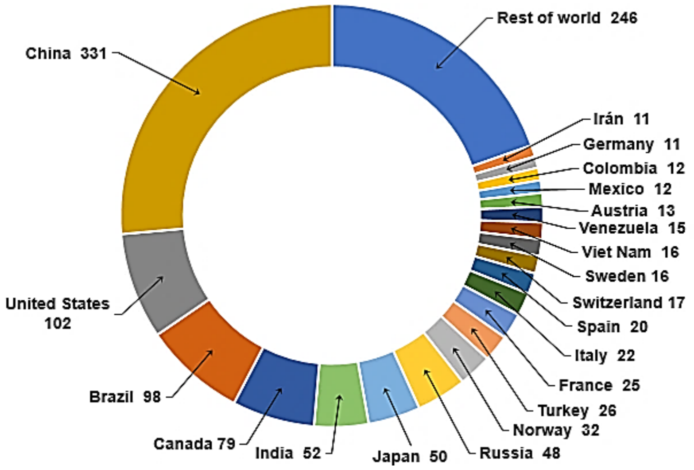


Fig. 1. Hydroelectric capacity set up in the world at the end of 2017 [1]

The big hydroelectric power plants are shown as the main electric supply source, representing since 2015 54% of world renewable energy total capacity, establishing itself as one of the proven, predictable and most profitable sources of renewable energy [2-6].

This way to generate power takes advantage of water potential energy in a dam and due to the gravity, it becomes too kinetic and pressure energy while fluid flows through the pipeline straight to the turbine's hall [7]. Figure 2 shows the main components in hydroelectric power plants.

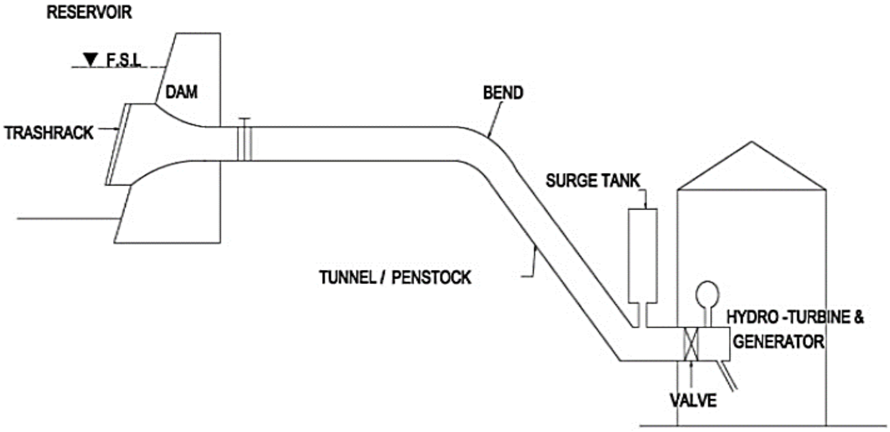


Fig. 2. Diagram of the pressure pipeline and the hydroelectric system [4]

Pressure pipeline is one of the main components in the hydroelectric power plant and it consists of straight sections, pipe elbows, pipe bifurcations and branch pipe T-joints depending on ground conditions and the flow conduction line toward the turbine's hall.

The branch pipe T-joint is characterized because the axial flow lines in the pipeline components are intercepted at 90°, which generates great stress in the structure reason why it is necessary to implement reinforcements in the perimeter zone known as nun's neck as shown in Figure 3.

Fig. 3. Branch pipe t-joint with central reinforcement [8]

In hydroelectric power plants with only one conduit is an indispensable using branch line to distribute flow to the hydraulic machines [9].

Water transport systems designs are usually made up from hydraulic and mechanic geometries. During design phase, most of small hydroelectric power plants priories mechanical strength design in pipe bifurcations. However, both hydraulic and mechanic aspects are equally important to ensure hydraulic performance and system mechanical stiffness [10].

Practices change with time, but past references are always useful. Computational techniques ease pressure pipe bifurcations design process, avoiding the troubling iterations involved on it. Hence the most important conventional design procedure with modern tools and technologies will surely help strengthen the reliability of the design [8].

Accordingly, the main research objective is validating the reinforced pipe T-joint structural theoretical design, named “Nun neck T-joint” using finite elements method (FEM) [11-13].

This paper is organized as follow. Next section discusses on detailed the branch pipe T-joint design analytic method used in this work. Initial section discusses numerical design validation. Finally, next section presents the conclusions obtained from the study and the recommendations.

2. Design Methodology

2.1 Analytical Method

The fundamental purpose in this work consists in calculate the branch pipe T-joint Wall thickness, and get to know the kind of reinforcement needed in the neck; all this based on theoretical safety factor and permissible stress established in the case of exposed metal pipe according to CECT standard [14], in addition to AISI and SPFA [15] and ASME section VIII Div. 1 [16] standards.

Branch pipe T-joint will be subdued to a permanent state of load. Whereby the safety factor is determined for service condition according to AISI Buried steel Penstocks [15] as $\mathrm{f_s} = 1.8$. Permissible stress on permanent load calculations is given by Eq. (1), Figure 4 show design parameters to the welded pipeline reinforcement.

$$\sigma_{perm} = \frac{\sigma_y}{f_s} \tag{1}$$

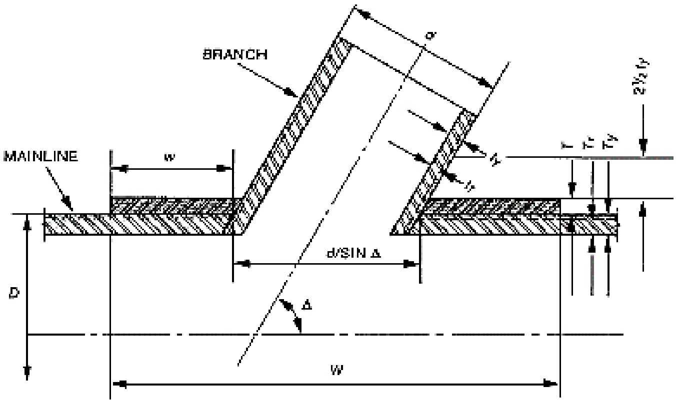


Fig. 4. Openings reinforcement in welded steel tubes [15]

The reinforcement type can be determined based on increase in pressure diameter value (PDV) and ratio between branch diameter and main pipeline diameter. Pressure diameter value can be calculated by Eq. (2) [15].

$$PV = \frac{Pd^2}{D\, sin^2\, \Delta} \tag{2}$$

where:
P = Design pressure (psi)
d = Branch outside diameter (in)
D = Main pipe outside diameter (in)
Δ = Branch diameter angle of deflection

For PDV values greater than 9000, the outlet reinforcement should consist of a crotch plate designed in accordance with the method described in Section 3.9. For PDV values less than 9000, the outlet reinforcement may be either a wrapper or collar, depending on the ratio of the outlet diameter to the main pipe diameter d/D [15].

In Branch pipe T-joint analysis case requires reinforcement partitions sheet type, which must be welded to the plating external wall. AISI Buried steel Penstock's standard recommend the reinforcement type as shown on Table 1.

Table 1
Recommended reinforcement type

PV	d/D	M	Type
>9000	All	-	Crotch plate
6000-9000	>0,7	0,000167	Wrapper
<6000	>0,7	1,0	Wrapper
6000-9000	≤ 0,7	0,000167	Collar
<6000	≤ 0,7	1,0	Collar

For T-joint is common using "Crotch plate" reinforcement type as shown in Figure 5. Wrappers and Collars reinforcement must be design according to ASME Unfired Pressure Vessel code, section VIII [16].

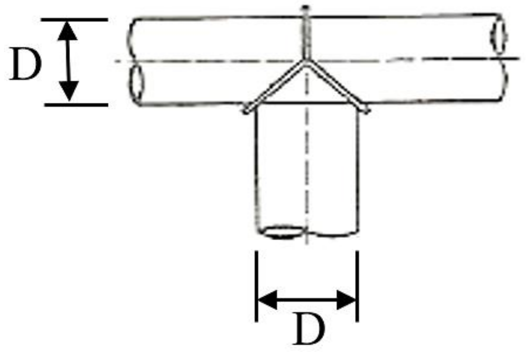


Fig. 5. Crotch plate reinforcement type

For the reinforcement design is necessary to determine the Cylinder theoretical thickness to calculate the reinforcement. The minimum theoretical thickness plating is given by Eq. (3).

$$Tr = \frac{PD}{2S_{adm}} \tag{3}$$

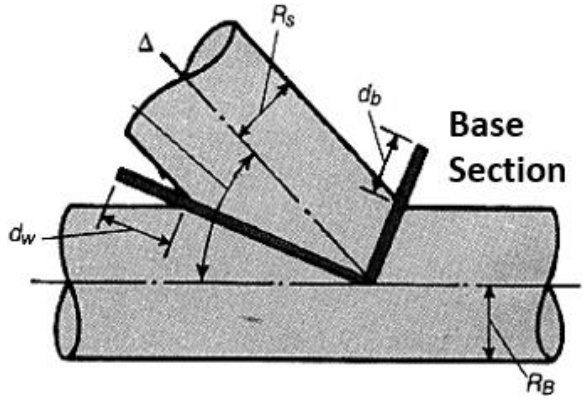
where:
P = Internal design pressure (psi)
D = Plating external diameter (in)
S_{adm} = Permissible stress (psi)

The minimum theoretical thickness T-joint is given by Eq. (4).

$$tr = \frac{Pd}{2f_s} \tag{4}$$

where:
P = Internal design pressure (psi)
d = Branch outside diameter (in)
f_s = Allowable stress (psi)

The effective reinforcement sizing is made according to Swanson *et al.,* [17]. Figure 6 shows typical reinforcement dimensions.



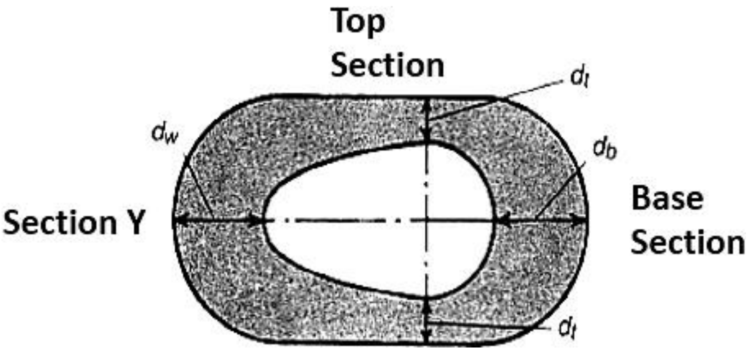


Fig. 6. Y-joint reinforcement plane and disposition “Crotch plate” [15]

Calculation process is determined for the initial reinforcement sheet thicknesses of 1 in, and 90° angle of deflection based on next steps [15].

Step 1. Using the bigger pipe diameter and design pressure, it results from Figure 7 critical plate d deepness.

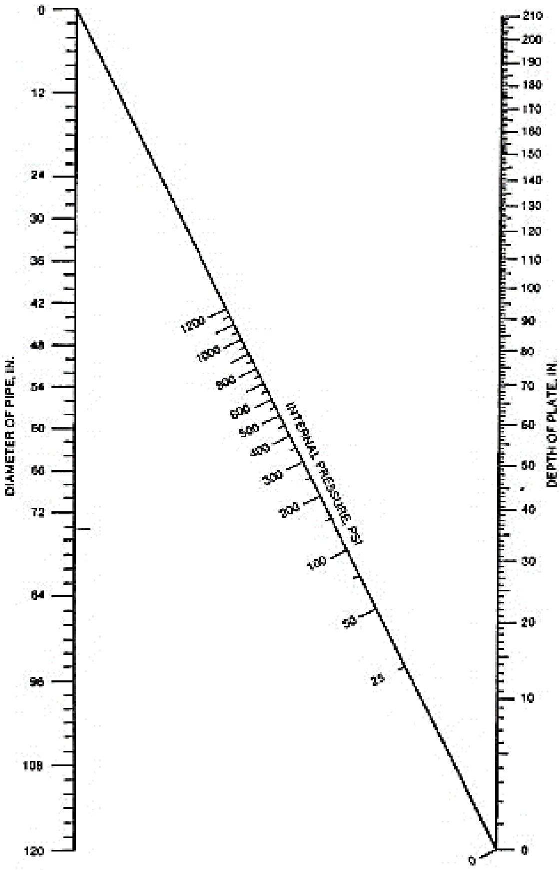


Fig. 7. Nomograph for selecting reinforcement plate depths of equal-diameter pipes [15]

Step 2. For deflection angles between 30° and 90°, N factors can be obtained from Figure 8 which applied to d plate deepness, found starting from nomograph in Figure 7 in accordance with next equations.

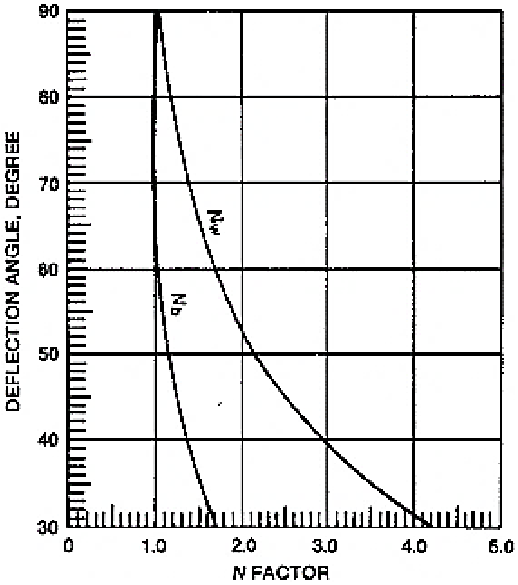


Fig. 8. N factor [15]

$$d_w = N_w d \tag{5}$$

$$d_b = N_b d \tag{6}$$

Step 3. If branch has a different pipe diameter, results obtained through steps 1 and 2 will must be multiplied by Q factors that could be found by means of single-plate stiffener curves Figure 9 and finally get dw´ and db´. These factors vary with small and big pipe radius ratio.

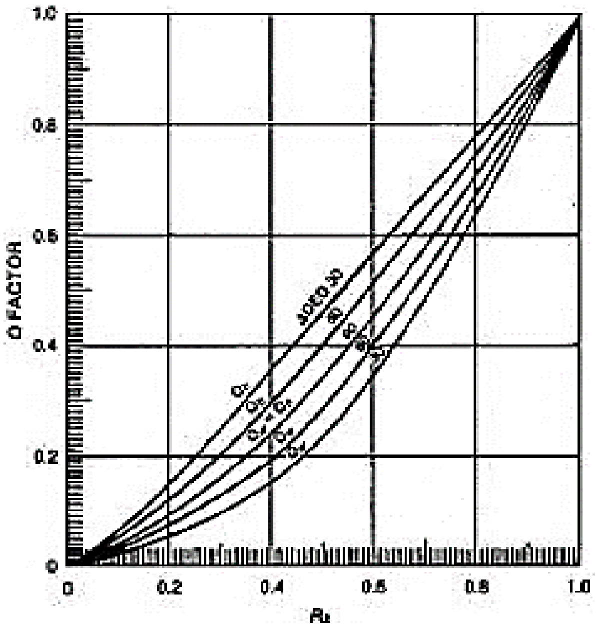


Fig. 9. Q factor [8]

$$d_{w''} = Q_w d_w \tag{7}$$

$$d_{b''} = Q_b d_b \tag{8}$$

Step 4. Depth known as dw must be limited to 30 plate thickness times. Formula is based on 1-inch plate and it could become thicker or thinner through Eq. (9). Minimum thickness must be at least 3/16 inch.

$$d' = d_1 \left(\frac{t_1}{t}\right)^{\left(0.917-\frac{\Delta}{360}\right)} \tag{9}$$

where:
d_1 = existing depth of plate
t_1 = existing thickness of plate (in)
d' = New depth of plate (in)
t = New thickness of plate selected (in)
D = Deflection angle of the wye branch

Step 5. To find the top depth dt or dt' it is use Figure 10, in which dt or dt´ represent against db or db'. This dimension gives upper and lower depths of the 90° plate.

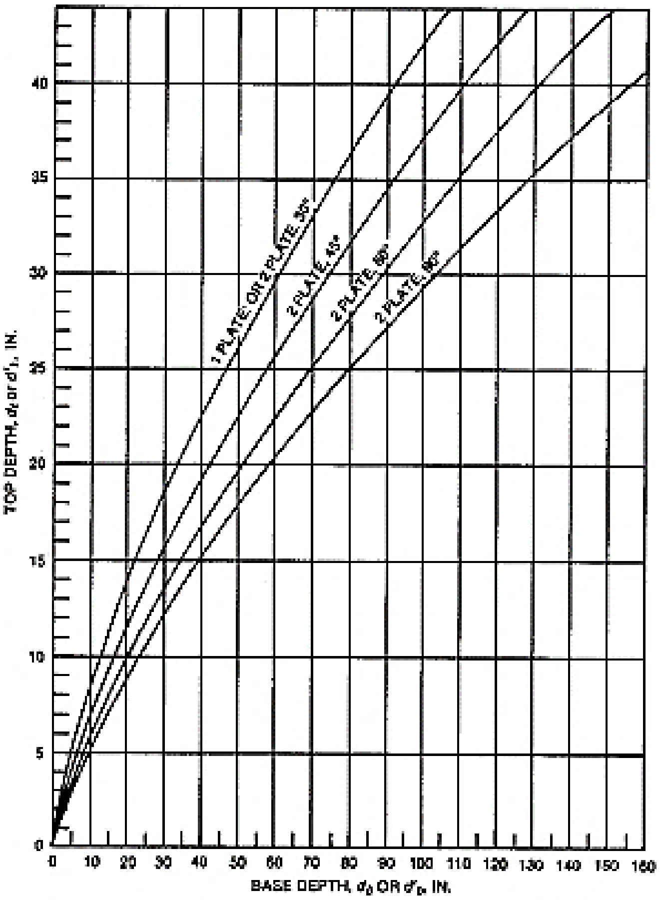


Fig. 10. Selection of top depth [15]

2.2 Structural Design

For the study case, Figure 11 shows branch T-joint geometric characteristics. The branch will be subdued to permanent load state thus safety factor is determined as fs = 1.8 to its service condition according to AISI Buried Steel Penstocks directions [15]. Branch T-joint material is ASTM Steel A537 Cl1 con $\sigma_y = 345\ \mathrm{MPa}$.

Hence, with the aim to determine thickness and reinforcement type needed in the branch area, it refers to design methodology shown in numeral 2.

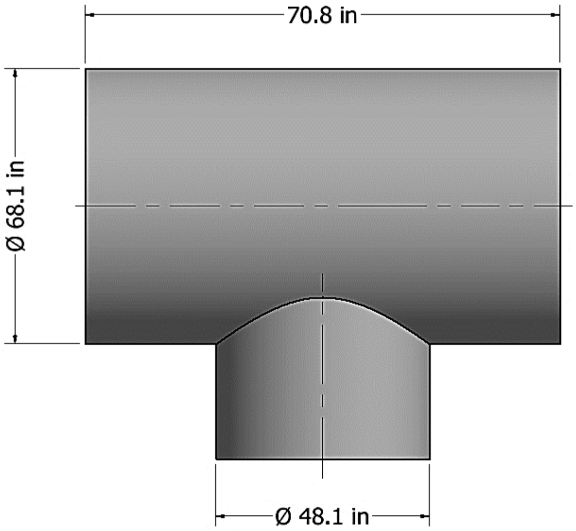


Fig. 11. T-joint geometric features

Permissible stress calculation in permanent load is given by Eq. (10), where:

$$\sigma_{perm} = \frac{\sigma_y}{f_s}$$
$$\sigma_{perm} = 27797.93\ psi \tag{10}$$

Thereby, reinforcement type required is determined by using Eq. (2) and Table 1.

$$PV = \frac{Pd^2}{D\, sin^2\, \Delta} \tag{11}$$

where:
P = 3.36 MPa (501.83 Psi)
d = 1222 mm (48.1 in)
D = 1730mm (68.1in)
Δ = 90°

$$\mathrm{PV}\left(17049.02\ \frac{\mathrm{lb}}{\mathrm{in}}\right) > 9000\ \mathrm{lb/in}$$

In this study, branch T-joint base requires sheet reinforcement type, which must be welded to the plating external wall. I accordance with Table 1, further obtained results; it is recommended implement a Crotch plate reinforcement as shown in Figure 5.

Therefore, for the reinforcement design the cylinder theoretical thickness should be solved based on Eq. (3).

$$Tr = \frac{PD}{2f_s} \tag{12}$$

where:
P = 501.83 (Psi)
D = 68.1 (in)
f_s = 27797.93 (Psi)

The minimum T-joint theoretical thickness is given by Eq. (13).

$$tr = \frac{Pd}{2f_s} \tag{13}$$

where:
P = 501.83 (Psi)
d = 48.1 (in)
f_s = 27797.93 (Psi)
tr = 0.43 in

Using nomograph from Figure 7 for the greater pipe diameter Di = 68.1 in and pressure 501.83 psi; the most loaded section width is:

$$d_o = 80\ in$$

Now, by determining branch inclination angle which is 90°, N factors from curve in Figure 8 allow to modify reinforcement widths.

$\mathrm{N_w} = 1.0$
$\mathrm{N_b} = 1.0$
$\mathrm{dw} = \mathrm{N_w d_o} = 80\ \mathrm{in}$
$\mathrm{db} = \mathrm{N_b d_o} = 80\ \mathrm{in}$

Based on derivation pipe´s and plating´s radius ratio. (Rs/Rb = 23.62/33.47 = 0.7); further, the derivation pipe inclination angle Ø = 90°; Qw and Qb factors are obtained from Figure 9.

$Q_w = 0.59$
$Q_b = 0.59$

Hence, reinforcement modified width will be:

$\mathrm{dw}' = \mathrm{db}' = \mathrm{Q_b} * \mathrm{do}$
$\mathrm{dw}' = \mathrm{db}' = 47.2\ \mathrm{in}$

However, the width dw’ = db’ is greater than restriction of 30 times thickness, t = 1in as mentioned on AISI Buried Steel Penstocks standard [8]. Reason why, reinforcement width dw’ = db’ = d1 requires a modification by utilizing Eq. (9).

$$d' = d_1 \left(\frac{t_1}{t}\right)^{\left(0.917-\frac{\Delta}{360}\right)} \tag{14}$$

It is used a reinforcement thickness t = 2in; where, t1 = 1in y d1 = 47.2in.

$$d' = 29.74\ in$$

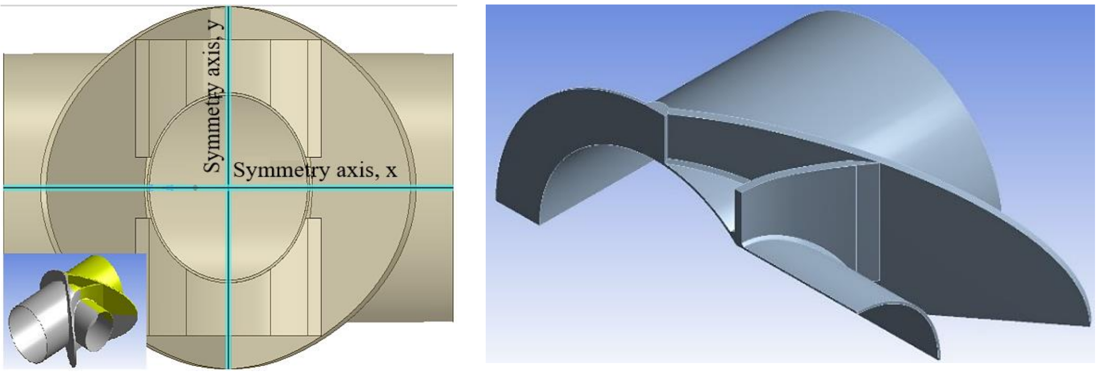
The new width d´ does not exceed 30 times thickness, which indicates, upper and lower T-joint widths can be found by Figure 10. Finally, reinforcement sheet thickness is t = 2in.

Table 2
T-joint dimensions (inches)

Parameter	Value
d	48.1
D	68.1
Tr	0.61
tr	0.43
dw'	47.2
db'	47.2
t	2
d'	29.74
dt'	12

2.3 Finite Element Analysis

As a T-joint analytic design validation, it is used a structural analysis by means of Ansys Mechanical® software V 19.1 commercial version. To run the simulation, T-joint modeling is made, considering the geometrical symmetry condition shown in Figure 12(a), it is simplified to a quarter such as shown in Figure 12(b), thus achieving to decrease simulation computational costs. CAD models include all welding geometries that is made according to structural recommendations [16]; T-joint dimensions correspond to the defined in Table 2.



(a) (b)

Fig. 12. (a) Symmetry planes, (b) Simplified CAD model

To discretize the geometry, 1.14 million cells were implemented, specifically, tetrahedral elements (Figure 13); aiming to guarantee a minimal of cells in all around the thickness.

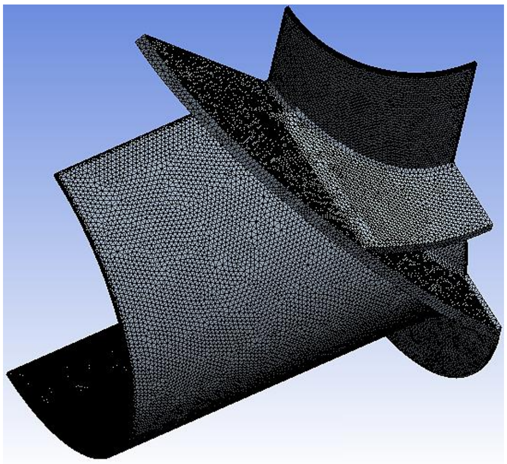


Fig. 13. Tetrahedral elements geometry meshing

Figure 14 presents boundary conditions established according to T-joint operational state correspondent to a pressure head of 354.14 mWC (3.46Mpa), a fixed backing in main branch pipe. Symmetry conditions in conformity with planes displayed in Figure 12(a) were used with the aim to guarantee the right model behaviour just as fabricated T-Joint.

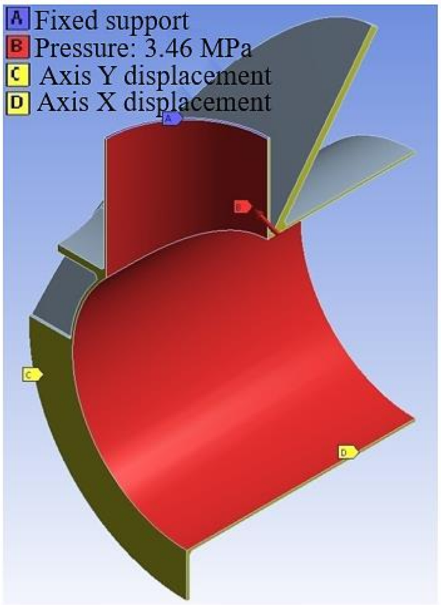


Fig. 14. Boundary conditions

3. Results

This paper presents a study case in which a structural validation is made, using finite elements analysis to the reinforced T-joint analytic design commonly used on big hydroelectric power plants.

Figure 15 shows equivalent Von Mises stress state for simulated structure. It is possible to observe there are stresses values greater than 191Mpa, which represents is the minimum stress using a safety factor lower than 1.8 just as standards followed [15].

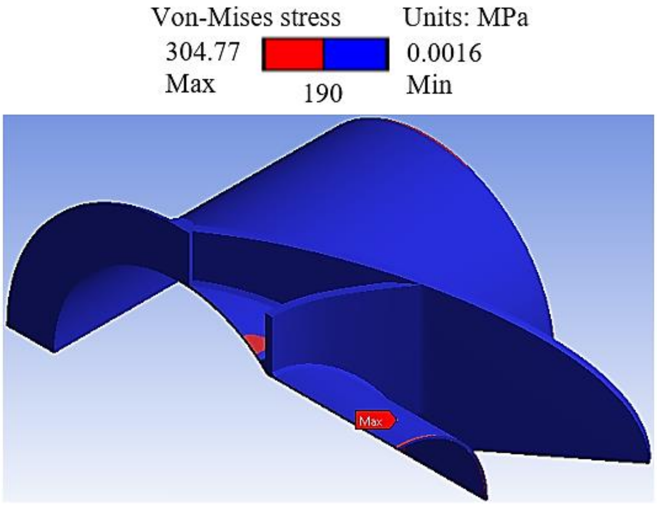


Fig. 15. Equivalent Von Mises stress contour

Looking at stress contours, it is evident that zones, where permissible stress is upper than allowed, are rather low, this can be attributed to stress concentration criteria. Figure 16 stands out regions where permissible stress is upper than 191 MPa, confirming than displayed regions have a stress increases associated to numerical singularities because of geometry issues.

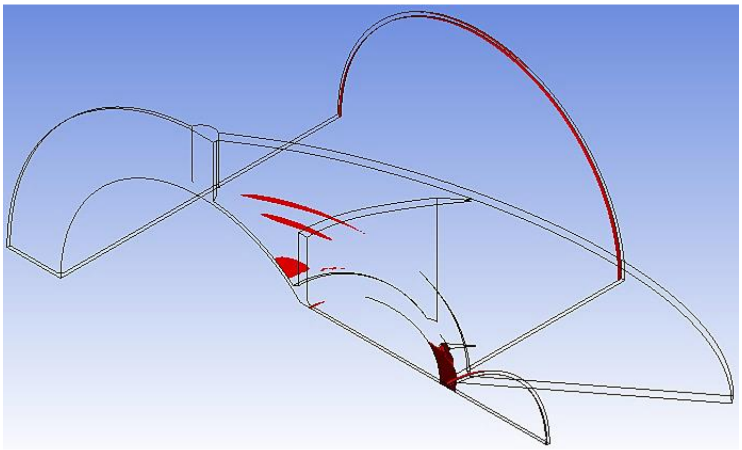


Fig. 16. Volume of material which presents an equivalent Von Mises stress up to 190 MPa

As a result obtained in this study, it can be inferred used geometry does not comply stress conditions for which reinforcement T-joint sizing has been made, standing out main pipeline and branch deviation intercept each other abruptly, quite different than conic type progressive way, recommended by standards [10]. By permitting reduce stress concentration caused because of abrupt direction change as shown on Figure 17.

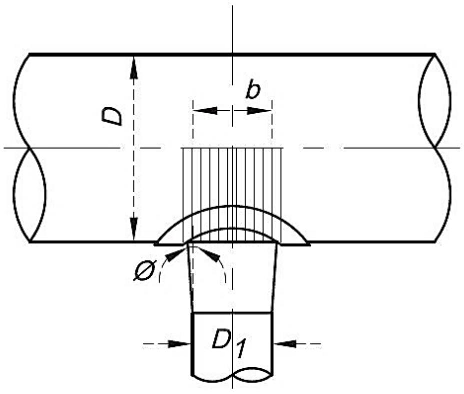


Fig. 17. T-Joint branch recommended geometry

4. Conclusions

By way of finite elements analysis, it is possible to validate the right performance of analytic designs as structural elements T-Joint types used in big hydroelectric power plants, which helps to find design shortcomings before fabrication and assembly processes start, thus guaranteeing the hydroelectric and surrounding communities' safety.

This study case reports T-joint analysis through ANSYS Mechanical ® V 19.1 software commercial version, verifying than stress values upper to 191 MPa are presented, which correspond to safety factor Fs = 1.8. Increasing stress value can be mainly attributed to implemented geometry in pipe branch design, which does not have a conic transition to reduce stress concentration in pipelines intersection zone.

Similar studies can be developed for different structural elements like Yee-Joints, elbows and pressure pipes in order to validate the correct theoretical design according to the operational conditions.

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References

[1] Capuano, Linda. "International Energy Outlook 2018 (IEO2018)." *US Energy Information Administration (EIA): Washington, DC, USA 2018* (2018).
[2] Woldemariam, Endashaw Tesfaye, Hirpa G. Lemu, and G. Gary Wang. "CFD-driven valve shape optimization for performance improvement of a micro cross-flow turbine." *Energies* 11, no. 1 (2018): 248. https://doi.org/10.3390/en11010248
[3] International Hydropower Association. "Hydropower Status Report 2017." *IHA, London* (2017).
[4] Singhal, Mukesh Kumar, and Arun Kumar. "Optimum design of penstock for hydro projects." *International Journal of Energy and Power Engineering* 4, no. 4 (2015): 216-226. https://doi.org/10.11648/j.ijepe.20150404.14
[5] Penagos-Vásquez, Diego, Jonathan Graciano-Uribe, and Edward Torres. "Characterization of a Commercial Axial Flow PAT Through a Structured Methodology Step-by-Step." *CFD Letters* 14, no. 1 (2022): 1-19. https://doi.org/10.37934/cfdl.14.1.119
[6] Rahman, Mohammad Nurizat, Mohd Shiraz Aris, Mohd Haffis Ujir, Mohd Hariffin Boosroh, and Dinishkaran Pillai a/l Velayutham Pillai. "Predictive Numerical Analysis to Optimize Ventilation Performance in a Hydropower Surge Chamber for H2S Removal." *CFD Letters* 13, no. 10 (2021): 69-80. https://doi.org/10.37934/cfdl.13.10.6980
[7] Khattak, M. A., N. S. Mohd Ali, N. H. Zainal Abidin, N. S. Azhar, and M. H. Omar. "Common Type of Turbines in Power Plant: A Review." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 3, no. 1 (2016): 77-

100.

[8] Koirala, Ravi, Sailesh Chitrakar, Hari Prasad Neopane, Balendra Chhetri, and Bhola Thapa. "Computational design of bifurcation: a case study of Darundi Khola hydropower project." *International Journal of Fluid Machinery and Systems* 10, no. 1 (2017): 1-8. https://doi.org/10.5293/IJFMS.2017.10.1.001

[9] Aguirre, Carlos Andrés, Ramiro Gustavo Ramirez Camacho, Waldir de Oliveira, and François Avellan. "Numerical analysis for detecting head losses in trifurcations of high head in hydropower plants." *Renewable Energy* 131 (2019): 197-207. https://doi.org/10.1016/j.renene.2018.07.021

[10] Task Committee on Steel Penstock Design of Pipeline Planning and Design Committee of the Pipeline Division of ASCE. "Steel Penstocks." *American Society of Civil Engineers*, 2012.

[11] Kumar B, Ravi. "Investigation on buckling response of the aircraft's wing using finite-element method." *Australian Journal of Mechanical Engineering* 18, no. sup1 (2020): S122-S131. https://doi.org/10.1080/14484846.2018.1483467

[12] Molatefi, H., S. Najafian, and H. Mozafari. "Fracture mechanics of planetary gear set by using extended finite element method-linear elastic fracture mechanics approach." *Australian Journal of Mechanical Engineering* 13, no. 2 (2015): 87-96. https://doi.org/10.7158/M13-077.2015.13.2

[13] Abidin, Mohamad Naufal Zainal, and Md Yushalify Misro. "Numerical Simulation of Heat Transfer using Finite Element Method." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 92, no. 2 (2022): 104-115. https://doi.org/10.37934/arfmts.92.2.104115

[14] CECT. "Recommendations for the Design, Manufacture and Erection of Steel Penstocks of Welded Construction for Hydro Electric Installations." *European Committee of Boiler, Vessel and Pipe Work Manufacturers* (1980).

[15] AISE, and SPFA. "Buried Steel Penstocks." *Steel Plate Engineering Data* 4 (1998).

[16] ASME, "Design, Construction and Inspection of Tanks and Pressure Vessels," in Design, Construction and Inspection of Tanks and Pressure Vessels.

[17] Swanson, H. S., H. J. Chapton, W. J. Wilkinson, C. L. King, and E. D. Nelson. "Design of wye branches for steel pipe." *Journal (American Water Works Association)* 47, no. 6 (1955): 581-630. https://doi.org/10.1002/j.1551-8833.1955.tb19181.x