Analysis of large sheet metal tailored tubes

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Abstract. The present study was triggered by the need to verify and optimize the primary constructive solution, for custom large tubes (section lengths larger than 1000 mm), under the gravity and pressure loads. The cases presented needed to be checked for the reinforcement design. Given the complex tridimensional geometry of the axisymmetric shell structures, the basic shape of the tubes was modelled, with its actual thickness. FEA was used to check the model under static loads and buckling. In order to optimize the weight, an alternative welded reinforcement’s grid design was developed and checked for stability. Optimal welding sections along ribs in longitudinal and transversal directions were identified for easier design and further costs reduction.

1. Introduction
Several gaseous media are transported in non-standardized piping, using custom designed large, reinforced steel tubes. Thin-walled tubes have been used extensively to dissipate energy during an impact event [1] and have good behavior when exposed in out-door conditions. The main issues of such structures are the stability of certain segments, as the site topology equation certain tube length and geometry, when big gas volumes needed. These tubes work with gas at design pressures of ± 0.1 bar, temperatures under 100°C, and are built in open air, exposed to wind, rain and snow.

The primary structural calculus of such tubes takes into account the general geometry of the shell-like structure and prompts for holders and props [2]. Custom and empirical reinforcements are designed if section quotient is larger than the material (austenitic steel) thickness.

The weight to strength optimization is constrained by the thin wall and topology of the inlet and outlet to be connected. The sole resource for weight and, ultimately, cost optimization, stands in the stiffeners used along the tube. These are ribs, welded in regular patterns, as rectangular collars, in transversal position and swept ribs, following the median axis of the tube, mounted on each of the four faces at rectangular tubes. The challenge is to design the minimum number of ribs needed to reinforce the tubular structure, in order to reduce the manufacturing and material costs.

2. Rationale
The design of this axial trajectory of the tube must respect the in situ topology and the material mechanical characteristics, for the given loads. The tubes are supposed to be welded and mounted in situ, equipped with supports from extruded profiles, with concrete foundation (figure 1). The width of the square section is 1716 mm; the total length is 17500 mm. The material is chromium-nickel stainless steel SA240 304 and its mechanical properties are presented in table 1.

It was shown that the buckled wave length for a rectangular thin walled tube becomes smaller for the higher pre-buckling stress, if constrained along the boundary [3]. As such, the general design for the
stiffeners can follow the rule that their longitudinal frequenceation must be smaller than the half of the wavelength (for axial loads) and smaller than the length of the wrinkle (bump shaped) in transversal loads [4].

The present design of the structure followed the primary results of the designer for the reinforcements, correlated with the dimensioning for the supports. The square sectioned thin wall tube can be considered as a simple supported beam, loaded by its own gravity and standard out-door loads, i.e. distributed forces mainly. The studied tube has horizontal trajectory at both ends and a vertical orientation for the median part, which means that the endings are loaded under bending in two planes while the vertical part must stand mainly for the uniformly distributed axial load from the gravity. Considered as a three dimensional truss, the tube is a statically indeterminate structure.

| Table 1. ASME SA240 304 Mechanical Properties [12]. |
|-----------------------------------|
| Yield Min MPa | Tensile MPa | Elongation Min % | Hardness, max HB | Hardness, max HRC |
| 205 | 515 | 40% | 201 | 92 |

Basic static analysis of the structures indicates the main parameters for welded supports and their location. At large dimensions d and relatively small thickness t (in this case, dimensional factor K = d/t = 270), even though the pressure values are not big, but fluctuant, at some point, safety design considers that stiffeners should be taken into account, to avoid bucking in the most exposed segments [5].

Buckling assessment should take into account the sensitiveness of the critical loading with the imperfections of the shell and assembly [6, 7]. For the horizontal ends, the maximum stress is reached at extremes from the neutral axis and the top and bottom are fully stressed [8]. For thin walls, the area A and the moment I can be expressed as [9]:

\[ A = 4dt, \quad I = 2td^3/12 + 2dt[(d/2)]^2 = 2td^3 3/3 \] (1)

The buckling of the slender square tubes combines the local phenomenon with the flexural buckling of the length. It shows as local bumps on the flat sides, without roto-translation and might coexist with flexural behaviour with wrinkling on the length flat faces (figure 2). The stiffeners spacing \( s \) (figure 2) is the parameter that controls the residual stress distribution between the stiffeners [10]. Flexural buckling can be defined by the coefficient \( K \), depending of the aspect ratio width/ thickness and varies with fixture type (equation (2)).

\[ K^2 = I/A = (2d^3 t/3)/4at\approx d^2/6 \] (2)

The buckling stress is calculated with report to the tangent modulus \( E_T \) and the length of the slender strut zone, \( L \):

\[ \sigma_f = (\pi^2 E_T d^2)/(6L^2) \] (3)

In this case, each wall is considered a flat plate, supported along long edges. Axial stress induces a lateral collapse:

\[ \sigma_L = K_L E_T (t/d)^2 \] (4)
For design purposes, the local buckling coefficient \( K_L = 3.62 \), corresponding to a generic Poisson ratio \( v = 0.3 \). This \( \sigma_L \) stress should not exceed the working compressive stress, under the nominal load \( P \):

\[
\sigma_W = \frac{P}{4dt}
\]

(5)

Optimal geometry can be obtained if the buckling, axial stresses equal at most the working stress:

\[
\sigma_f = \sigma_w = \sigma_L \rightarrow (\pi^2 E_T d^2)/(6L^2) = \frac{P}{4dt} = 3.62E_T (t/d)^2
\]

(6)

The objective function of independent structural variable is referred as the weight \( W \), which is less when the stress in the sectional area \( A \), along the length \( L \), under the load \( P \), is maximum [10]:

\[
W = \rho AL = \rho (P/\sigma) L
\]

(7)

A normalised weight parameter \( n \) is defined for depicting the optimum weight range:

\[
n = \frac{1}{\rho} \frac{W}{L^3}
\]

(8)

This parameter will be used to control the results of ribs optimal placement and optimal number. Equation 6 is used for optimal dimensioning of the width \( d \) and thickness \( t \) [11]:

\[
d_{opt} = 0.743((PL^3)/E_T)^{1/5}, \quad t_{opt} = 0.371((P^2 L)/[E^2]_T)^{1/5}(1/5)
\]

(9)

With these parameters, one can follow Elwi and Kulak recommendation for rational design [12], and assume, further, a stiffener distribution, then check for stability, ensuring that failure should occur rather between the stiffeners than outside. Choosing shell buckling or general buckling for the calculus, one will decide the ribs distribution. At this time, important supplementary aspects as imperfection and residual stress (as a result of welding and assembly on long paths) must be taken into account [13].

3. Method and analysis

3.1. The tube without ribs
The solid model was developed as a swept feature, from the normal cross-section, along the three dimensional path axis. First, parametric CAD INVENTOR ® was used for solid modeling, FEA was performed with Autodesk Simulation Mechanics®, while CATIA® digital prototype was used for double checking the static analysis results. In both models, local constraints were declared on the supporting lines, where the tube will be fixed on the position. Gravity, wind and interior pressure of
0.1 bar load the model. The median surface for shell meshing was generated. Minimum element size (as fraction of average size) is 0.2, while average element size in the mesh is 0.05.

The total mass of the tube without stiffeners is 4984 kg. This value will be used as reference for further study of the optimal stiffeners displacement.

As can be seen in figure 3 (stress and displacement), the critical points stand in the middle of the curved sections of the tube, but the equation univalent stresses remain in the safe zone, under the yield limit. The large displacements present in the flat horizontal faces remain under the material capacity. This steel is designed for vessels under pressure and working at high temperatures. The need for reinforcement is obvious, mainly in the critical zones. The goal is to ensure a safety factor of 4 at least, for the stiffened structure (figure 4).

![Figure 3. a-Von Mises Stress diagram.](image)

![Figure 3. b-Displacement 10x.](image)

3.2. The ribbed tube

The tube was designed with stiffeners that will be modelled as circumferential zones with no radial and torsional displacements. The ribs are separate parts (figure 5), as ribbons of 1716x100x6 mm welded in linear sections, as a circumscribed matrix along the tube. In fact, locally, the tube rectangular cross-section changes, and the flexural buckling coefficient increases with 12%. With stiffeners, as designed initially, the mass reaches 7165 Kg, comprising the welding. The normalized weight parameter increases 43.7%.

A second model was built from the initial tube, with ribs, located with a s pitch of 500 mm along length and dividing the sides in three, swept along the tube. Even though modelled for the welding assembly calculus, the stiffeners were declared as formal restrictions in the normal and lateral direction to the surface, and no twisting along the symmetry axis. Otherwise, the complexity of the details would have induced errors at mid-surface shell generation and meshing, altering the results. The stiffeners break the flat surfaces in smaller plates constrained along the edges. The stiffeners alone can improve the bucking behaviour which means that is sufficient to weld the ribs on the shell and not to the web.
Finite element analysis for the ribbed tube, with frictionless contacts defined on the surfaces of the model, reveal the important decrease of the stresses and, practically, the annulation of the static displacements, which barely reach 0.04 mm (figure 6).

3.3. The square tube with spaced hoop stiffeners
This initial design was checked for optimization resources. The zones with the lowest stress condition and displacements were considered. The axial stiffener was kept along the tube, due to the uniformity and symmetry of the welding residual stresses and considering the general buckling.

Hoop ribs were reconsidered and spaced at the end and middle of linear zones and discarded on the rest of faces.

As a result, the reinforcements were placed only on the upper plates of the horizontal zones and the laterals of the vertical, where the maximum displacement was identified. The remaining stiffeners are used also for technological reasons, for reliable contact with supporting frame. Each section of the geometry of the tube is supported by a pair of horizontal frame members. The ribs will be used for weldment assembly.

The static analysis indicated a good behaviour and very small displacements, with a small increase in the equivalent stress.

This indicates that the rib design can be changed, for the same pattern along the tube length. The maximum stress is displaced on the bottom flat zones, between the supports, as a result of the load distribution. The stress configuration in the new rib design stays within material potential limits.
The redesign of the stiffeners intended to identify the less stressed zones and to eliminate the disposable ribs. The new design was verified under the same loads, with constraints displacement modified (dark ribs in figure 7).

4. Conclusions

Thin wall slender tubes are prone to buckling deformations under their own mass and designed pressure action. Large deflections of the side walls of the tubes can be prevented with stiffeners. These are ribs welded as a matrix around the perimeter of the tube and along its length. The initial design indicated that the normalized mass parameter $n$ increased up to 43%. Studying the stress distribution and buckling behaviour, a new distribution of the ribs was found (dark zones eliminated in figure 12), that eases the whole structure, reducing the weight parameter $n$ with 25%.

Corresponding stiffeners manufacturing effort decreases with 42%, thus optimizing the objective function. An optimization potential was found in a slender cylindrical tube with high slenderness factor. Given the small values for the stress and displacements, a thickness reduction was applied and checked. The normalized mass parameter $n$ decreased with 25%.

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