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Longitudinal supports shape influence on deflection and stresses in solar receiver tubes

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Abstract. Longitudinal supports have a key role in solar central receivers, preventing tubes from excessive deflection. In this work, its influence on tube deflection and thermo-mechanical stresses has been studied. In exiting literature, the longitudinal supports are not modelled when the behaviour of solar receiver tubes is studied. In this research, they have been considered developing numerical models using a finite element analysis software. To carry out the analysis, a new geometry of the metal sheet attached to the receiver tubes has been proposed. With this new shape, different cases have been studied, varying the separation between supports and their size to study its impact on stress and deflection in the tubes. Results have shown that extremely rigid supports may induce additional stress in the receiver tube. With the geometry considered in this research, supports do not cause additional mechanical stress in tubes. Small supports are preferred to bigger ones due to the stresses arisen in the own support..

Key words. Solar external receiver, thermal stress, deflection, mechanical model, longitudinal supports.

1. Introduction

The size of cylindrical receivers in CSP plants makes impossible to not restrict the tube deflection in some way. With receiver sizes up to 20 meters, tubes must be guided to prevent excessive bowing [1], which would lead to the panel warpage, the reduction of the receiver efficiency, and ultimately to its failure.

To this end, longitudinal supports, known as clips, are used. The information regarding how the tubes are guided is scarce in the literature. McDowell and Miner [2] indicated that clips are fabricated using a machined metal piece and a piece of tube stock, (see Figure 1a). Going through the clip, the guiding rods are fixed to the receiver frame, allowing the clips to slide [3].

Longitudinal supports play a key role when thermal stress and deflection are studied in tubes of solar central receivers. Its number and position along the tube determine the value and the location of the highest stress peak [4]. A reduced number of clips would make non-viable the use of generalized plane strain assumption, which is widely used in stress calculation in solar central receivers [5, 6]. In existing literature, clips shape influence in the mechanical behaviour of the tubes has not been addressed. The longitudinal supports has been assumed as punctual supports in the tube wall, restricting the displacement perpendicular to the axial direction, but allowing the rotation of the tube [4, 7, 8]. This approach, based on previous studies of parabolic through receivers, carried out by Khanna et al. [9], underestimates the clip mechanical behaviour in solar central receivers. The actual boundary conditions of clips are more complex, since its stiffness determines how the tube behaves and stress concentrations may appear in the location of the supports. The receiver lifetime is intrinsically related with thermal stresses, so stress concentration may jeopardize the receiver integrity.

In this study, the clips geometry will be considered, obtaining the thermoelastic stresses and deflection of the tube accordingly to the clip dimensions. To carry out the research, a numerical model in a finite element software has been developed. With the temperature data provided by models of the complete receiver, the mechanical behaviour of tubes with clips attached has been addressed, studying the influence of geometrical parameters such as size and thickness, has been addressed.

This work is structured as follows: After the introduction, the studied solar central receiver and the geometry of the clip is presented. Then, the methodology to calculate thermal stresses is solar tubular receivers is shown. Results section presents the study of tube deflection and stresses for different clips sizes and distances. First, clip shape influence on displacement and thermal stresses is analysed. Secondly, the mechanical behaviour of the clip is considered, studying the stresses on its geometry. The main conclusions of this work are summarized in the last section.

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2. Studied problem and clips geometry

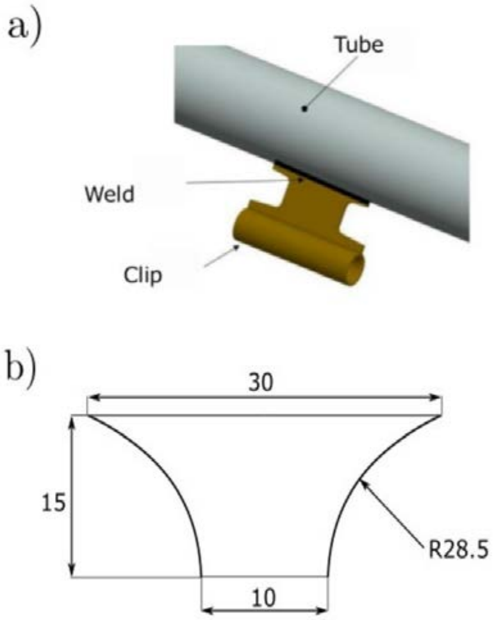


Fig. 1. a) Clip scheme [1]. b) Proposed clip geometry (in mm).

The study of the clips influence on thermal stress and deflection has been carried out in a solar power plant with an external cylindrical receiver, which uses molten salt as heat transfer fluid (HTF). It is located in Tonopah (Nevada, USA), at 38.24º north latitude, and has a nominal power of 150 Mwe. The most important parameters of the plant are summarized in Table I. The material of the tubes is Inconel 625

Table 1. Parameters of the studied solar plant

PARAMETER	VALUE
Number of heliostats	10300
Heliostat dimensions	11.28x10.36 [m]
Latitude	38.24º
Tower height	195 [m]
Receiver length	30.5 [m]
Number of panels	18
Tubes per panel	127
Tubes separation	1.8 [mm]
Tube length	20.3 [m]
Outer tube diameter	22.4 [mm]
Tube thickness	1.2 [mm]
HTF inlet temperature	563 [K]
HTF outlet temperature	838 [K]
Mass flow rate (per tube)	3.98 [kg/s]
Ambient temperature	298 [K]

The material of the tubes is Inconel 625. On the other hand, the geometry of the metal sheet in the numerical model to take into account the longitudinal supports, is depicted in Figure 1b. The metal sheet shape depicted in Figure 1.b reduces the stiffness of the clip, preventing stress concentration in the clip locations when tubes suffer considerable bending (Figure 2). The clip has a thickness of 1.5 mm.

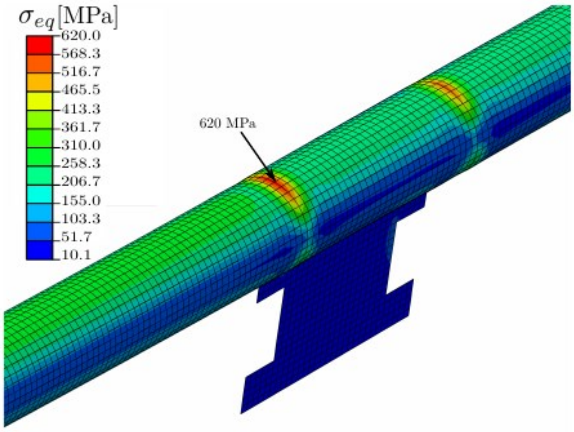


Fig. 2. Equivalent stress in the clip location, with a geometry similar to Fig. 1a, for a distance between clips of 4.5 m.

The clips are homogeneously distributed along the tube (Figure 3) each 2 m (s= 2 m), and they have been considered adiabatic, having the same temperature as the rear area of the tube. The tube own weight and the fluid internal pressure have not been considered.

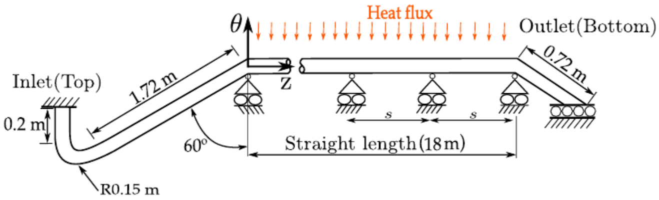


Fig. 3. Tube geometry and boundary conditions. Clips are represented as simple supports along the tube.

3. Methodology

To characterize the thermal behaviour of the receiver several published models have been employed. Firstly, an optical model developed by Sánchez-González and Santana [10, 11], named FluxSPT, have been used to estimate the incident solar flux on the receiver. Where the concentration ratio is calculated with a projection method, and the flux distribution is based on a circular Gaussian resulting from the convolution of the sun shape and the heliostat slope. This model has low computational cost and can be adapted to different solar fields and receiver geometries. Besides, it allows to modify the aiming strategy. For this work, an aiming strategy that tries to flatten the heat flux over the receiver tubes has been considered.

Once the incident solar flux on the receiver is known, the thermal model developed by Rodríguez-Sánchez et al. [12] has been used to characterize the temperature profile in the tubes. It is a simplified 2D model that only analyses one representative tube per panel, although it considers the effect of the adjacent tubes, and the circumferential temperature variation. The temperature distribution obtained with this thermal model is depicted in Figure 4.

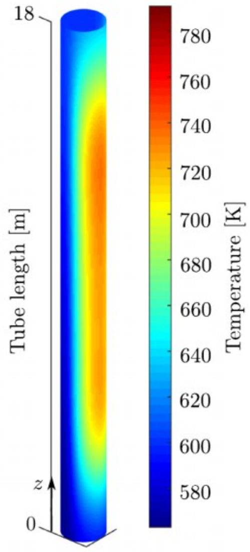


Fig. 4. Temperature distribution over the outer tube wall. Tube diameter is magnified for clarity.

The temperature distribution over the studied tube is introduced in a finite element model, developed in the commercial software Abaqus/Standard. Tubes and clip sheets are modelled using shell elements, considering the whole tube geometry, (elbows included). A coupled thermo-mechanical analysis has been carried out, obtaining the tube deflection and the stress distribution due to temperature and mechanical boundary conditions. The research workflow is summarized in Figure 4.

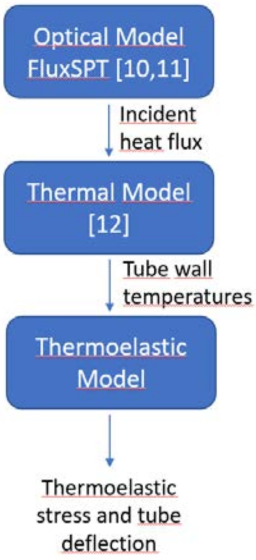


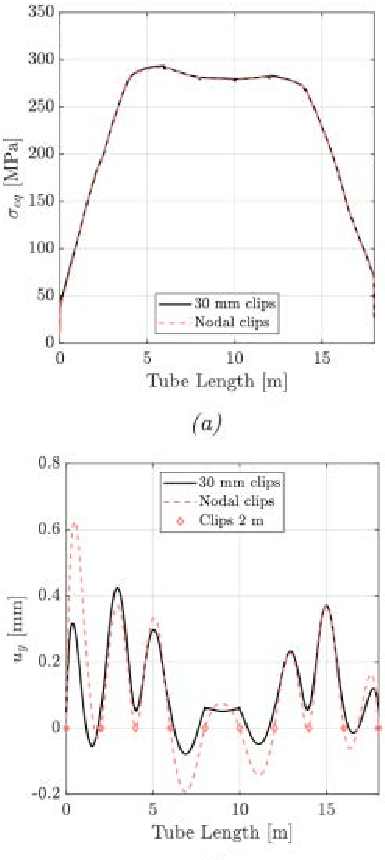
Fig. 4. Research workflow. The tube wall temperature needed by the thermoelastic model is calculated by the thermal model using the incident heat flux over the receiver obtained with the Optical model.

4. Results and discussion

In this section, the results of the study of the longitudinal support shape influence on deflection and stresses in solar receiver tubes are presented. First, a comparison between nodal clips (displacement perpendicular to the tube length imposed in the tube surface), and the model considering the clips geometry, is shown in Figure 5.

Figure 5a shows that the maximum equivalent stress is not affected due to the clip shape included in the numerical model. Note that excepting a slight variation of the stress in the position of the clips, due to its own deformation, thermal stresses do not suffer any significant changes. On the other hand, when tube deflection is compared (Fig. 4b), a displacement offset can be observed in the deflection corresponding to the case where clips are modelled. The temperature increment in the clip produces the thermal expansion of the metal sheet, something that cannot be taken into account when the boundary condition is directly imposed in the tube wall.

Figure 5b also shows that considering clips as nodal supports overestimates the tube deflection, as can be observed in the maximum deflection at the beginning of the straight tube length. The stiffness of the metal sheet does not allow a completely free rotation at the location of the clips, reducing maximum tube deflection. This result encourages the use of generalized plane strain methodology in the thermal stress calculation.



(a)

(b)

Fig. 5. a) Max. Equivalent stress and b) tube deflection for a clip distance of 2 m, along the straight tube length, with 3 cm clips and 1.5 mm thickness as supports.

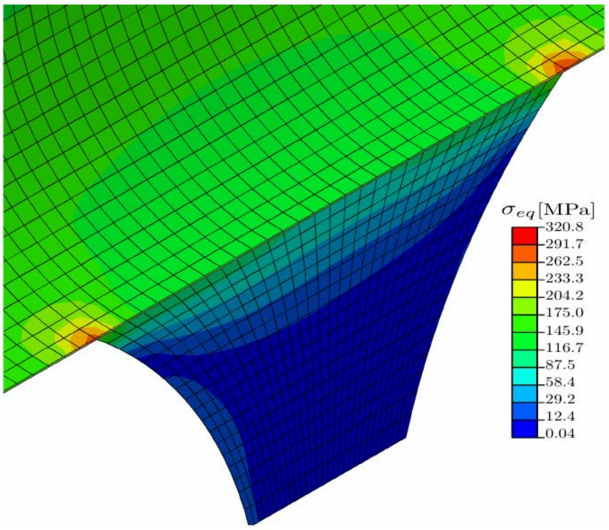


Fig 6. Equivalent stress distribution in the tube-clip weld.

As can be observed in Fig. 6, the joint between the tube and the metal sheet of the clip has been simplified and the weld has not been modelled. This, along with the use of shell elements, may lead to a stress concentration in the edges of the clips. This effect does not vary the stress in the area of the tube facing the heliostats (Fig 5.a), where the maximum equivalent stress is located.

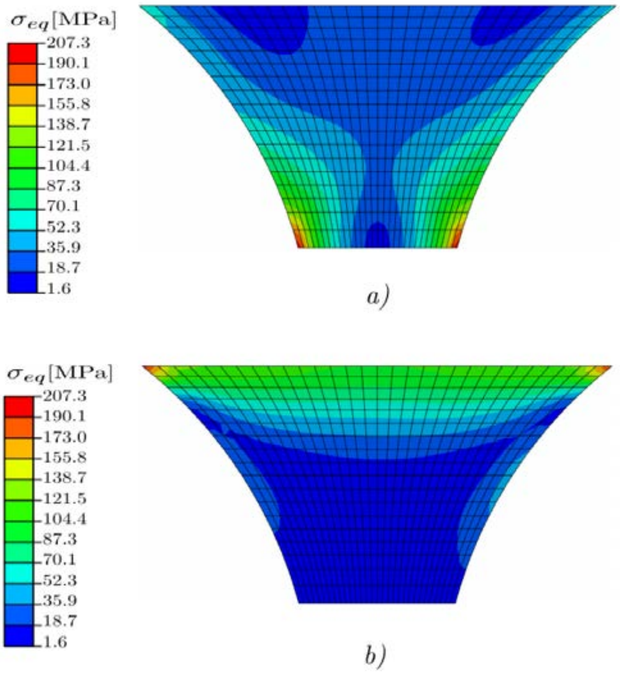


Fig 7. Equivalent stress distribution in the metal sheet of the clip in different locations: a) z=0 m, b) z=10 m.

The tube deflection deforms the longitudinal supports, being those places where tube failures can occur with the break of the clip. Depending on the clip position, maximum stress can be located in the weld between the metal sheet and the tube (z=10 m), or in the weld between the metal sheet and the tube attached to the guiding rod (z=0 m). The two cases are displayed in Figure 7.

Figure 7a depicts the equivalent stress in the metal sheet when the clips are close to the tube ends. In that area, the tube tends to rotate more and the displacement would be higher if the rotation would be allowed, Figure 5a depicts. The clip prevents this rotation partially, causing a stress concentration where the boundary conditions restricting the rotation are imposed. On the other hand, clips in the central area of the tube behave differently, since the heat flux is higher, which causes the tube bending due to the circumferential temperature variation. In this area, the part of the metal sheet welded to the tube tends to bend jointly with the tube, and the maximum stresses are located there (Figure 7b).

The effect of the clip size and its thickness has been also studied. Fig. 6 shows the equivalent stress and the tube deflection for a clip welded to the tube 30 mm (Fig. 1.b), and a clip twice the size, welded to the tube 60 mm. For both clip sizes, thicknesses of 0.75, 1.5 and 3 mm has been considered.

The clip size and the thickness does not have an influence on the thermal stress in the tube, as can be observed in Figs. 6c and 6d. The only noticeable change in the increment of stress variation in the locations of the clips, due to the bigger clip size, but the highest stress remains with a different lower than 1 % between both clip sizes. The clip size has a more remarkable influence in the tube deflection. As would be expected, a bigger clip restricts more the tube displacement. A comparison between Figs 6.a and 6.b shows that the 60 mm clip attached to the tube has a lower displacement than the one attached 30 mm. Doubling the clip size, decreases the maximum displacement around 12% in the case where the metal sheet thickness is similar to the tube thickness (t=1.5 mm). The maximum tube deflection for each case is summarized in Table 2.

Table 2. Maximum tube deflection and maximum equivalent stress in the metal sheets of the clips.

	30 mm Clips		**60 mm Clips**	
t [mm]	**u_y [mm]**	**σ_{eq} [mm]**	**u_y [mm]**	**σ_{eq} [mm]**
0.75	0.44	252.8	0.41	303.9
1.5	0.421	207.3	0.37	254.3
3.	0.41	150.6	0.32	183.5

The clip thickness does not affect considerably the tube deflection when the clip has a size similar to the tube diameter. The difference in displacement between thicknesses of t=0.75 mm and t=3 mm is around 0.03 mm, while this difference goes up to 0.09 for a bigger clip. Although increasing the clip size reduces the deflection, the stress in the clips is higher for the metal sheets of 6 cm (Table 2). Restricting the displacement in a wider tube length makes the clip deform more, therefore for constant thickness, the stress will be lower in smaller clips. Being difference in tube deflection between both sizes small, it would be recommended to user small clips with lower stresses, to avoid the failure of the weld between tube and metal sheet.

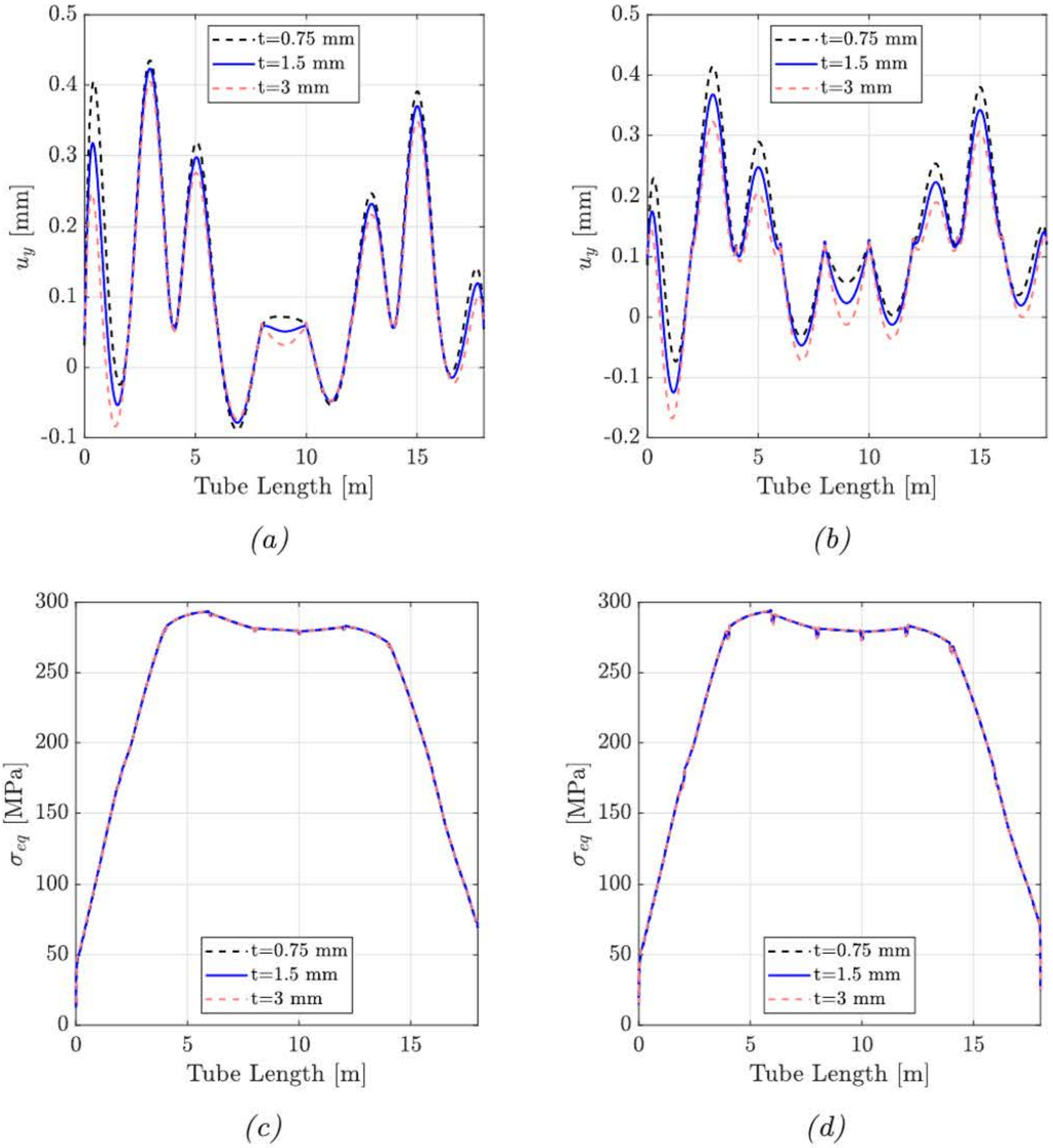


Fig. 6. Along the straight length of the 18 m tube different tube thicknesses, tube deflection a) and equivalent stress c) for a 3 cm clip. Tube deflection b) and equivalent stress d) for a 6 cm clip.

5. Conclusions

In this work, the geometry of the longitudinal supports has been considered, and its influence in thermal stress and tube deflection has been studied in tubes from solar central receivers. To avoid stress concentration in the location of the clips, a geometry that partially allows the tube rotation in the supports have been proposed. The numerical model presented has been considers the shape of the clips as a metal sheet attached to the tube. An analysis with flat heliostat aiming strategy has been carried out, with different distances between the clips considered and sizes.

Compared with a simpler numerical model, where clips are modelled as punctual supports in the tube rear wall nodes, the deflection is lower when the clips geometry is considered, since preventing the tube rotation reduces the maximum displacement. Thermal stress results do not present significant changes, excluding stress concentration where the metal sheet is welded to the tube, due to the simplifications made in the union. These stress peaks are not higher than the maximum stress in the tube area facing the heliostats. These different boundary conditions do not affect the thermal stress calculation.

Thermoelastic stress in clips depend on the clip position. Clips at the tube ends have their maximum stress close to the guiding rod, due to the tube rotation. Clips in the central area of the straight length have their maximum stress in the tube union, due to higher circumferential temperature variation that bends the tube, deforming the top part of the metal sheet. Increasing the clip size and thickness does not have a significant impact on tube thermal stress, only reducing slightly the tube displacement.

The presented research could be a starting point to optimize the cost of solar receivers, regarding the optimal number of clips along the solar receiver tubes. Reducing the number of clips would decrease the economic cost of each receiver panel, but an in-depth thermos-mechanical analysis would be needed to ensure their safety. On the other hand, the influence of clips shape in heat loses has not been considered, so experimental and numerical studies where clips are not considered adiabatic are encouraged.

Acknowledgement

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