

A Critical Analysis of Anchor Spacing in Refractory Lining Design

C. A. Goulart, M. A. L. Braulio, B. H. Teider, V. C. Pandolfelli

Many of the shortcomings attributed to the refractory lining materials may in fact be related to design issues, such as the anchoring one. Key aspects in the engineering of these systems, as the spacing and position of the anchors, are defined using empirical knowledge in the everyday practice of companies. This approach does not take into account factors such as thermal behaviour and strength of the anchors, and their interactions with the lining, highlighting the need for a more detailed and technical analysis of the subject. This study proposes a modification in the calculation model of anchor spacing suggested in the literature and compares the attained results with standard values presented by few companies and those used in an actual project of an alumina calciner, aiming to obtain a better modeling reference and greater reliability in the design of future projects.

1 Introduction

In many industries, such as metallurgical, cement and glass ones, the processing vessels operate at high temperatures and are

lined with refractories, in order to protect and insulate their metallic shells from mechanical, chemical and thermal stresses, to control the operational temperatures and saving energy. The performance of the refractory materials directly impacts on safety, energy consumption and quality of the process. Failures in these materials incurs the potential loss of millions of dollars due to the time and labour involved in the cooling and maintenance steps of these structures, besides the lower operational availability and consequent decrease in productivity [1]. Thus, it is important for an efficient and economically feasible operation that no sudden halts occur due to unexpected failures.

When compared to bricks, the use of monolithics as linings presents various advantages, because it allows for a diversification in the geometry of the vessels and in the installation methods, as well as a reduction in the placing time and in the number of expansion joints, providing savings of time and energy. However, the ultimate success in the application of monolithic refractory intimately depends on the anchoring system selected to keep it in the right place during

operation, considering its lack of adhesion to the vessel shell, its thickness and its self-supporting inability [2]. The anchoring system must also maintain the lining integrity, even when it is already cracked, in order to inhibit a total structural collapse [3]. Therefore, this issue is of utmost importance because failures commonly attributed to the refractory component, can be in fact, caused by shortcomings in the anchoring system.

Although practical, the anchor space design is usually based on rules of thumb or simplifications that have been developed through trial and error, disregarding important variables. Despite the wide spread use of these rules by many industries, various project particularities are not considered, which adds to the problems observed in practice. Failure prevention and an increase in the lining life are desirable and can be achieved by using engineering principles such as gravity loads, thermal stress and strain, and the mechanical and chemical behaviour of materials at high temperatures when calculating anchor spacing [4]. In this study, the fundamental features regarding anchoring systems are firstly presented. Following, mathematical models for spacing calculations are introduced and the values obtained theoretically are compared with those proposed by some companies and others used in an industrial project.

1.1 Types of anchors

Anchors are basically produced by ceramic or metallic materials and their selection is based on the equipment operating temperature range, the environmental conditions, as well as the material's behaviour before thermo-mechanical stresses [5, 6]. Generally metallic anchors are used based on their simpler installation and lower unitary prices, making their use more feasible at wider temperature ranges (up to ~1100 °C). The higher costs and the difficulties associated with the installation of ceramic anchors restrict their application to

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conditions where oxidation, corrosion and higher temperatures are present.

The number and distribution of anchors throughout the vessel impart a direct effect on the equipment lifetime. Insufficient number leads to an overloaded system, increasing the chances of failure. Conversely, adding more anchors may result in a poor refractory consolidation during installation, as the voids among them are too close and may not be completely filled in, resulting in defects, which affect the material's mechanical properties [4]. Any problems that may arise in the anchoring system, either by unsuitable material selection, design and/or installation, lead to high costs with refractory lining, maintenance and productivity loss.

1.1.1 Metallic anchors

In conditions where temperatures are lower than 1100 °C, this type of anchor is usually the selected one. Steel is the most common material used and the higher the working temperature the more particular is the alloy [6]. Tab. 1 lists some of the commercially available alloys and their maximum operating temperature.

Metallic anchors are welded directly into the vessel shell and are covered by the monolithic refractory so as the anchors' tip is embedded in the lining. Approximately 20–35 % of the lining thickness should cover the anchors' tip. If the welding is poorly carried out, it can lead to anchor (and consequent refractory) failures, due to uneven load distribution and insufficient support [7]. Metallic anchors present a wide range of available shapes and there is no consensus yet on which one provides the best performance. Many geometries are created to solve specific problems and end up remaining in the market for general purposes [2, 3]. In this field, it is usually said that a successful man, besides planting a tree and writing a book, should also create at least one anchor design in his lifetime! An example of a metallic anchor shape is shown in Fig. 1.

Anchors with larger cross-section areas provide greater holding capacity. Flexible anchors, such as a spring-type, unlike rigid and straight ones, seem to help reducing cracks in the lining [3]. Besides that, there is also evidence that anchors featuring legs with different lengths inhibit the development of preferential shear planes in the same

Tab. 1 Typical alloys used in metallic anchors and their maximum service temperature (adapted from [7])

Anchor Material	Operating Temperature [°C]
Carbon steel	430
304 Stainless steel	760
316 Stainless steel	760
309 Stainless steel	820
310 Stainless steel	930
Inconel 600	1100
Incoloy DS	1200

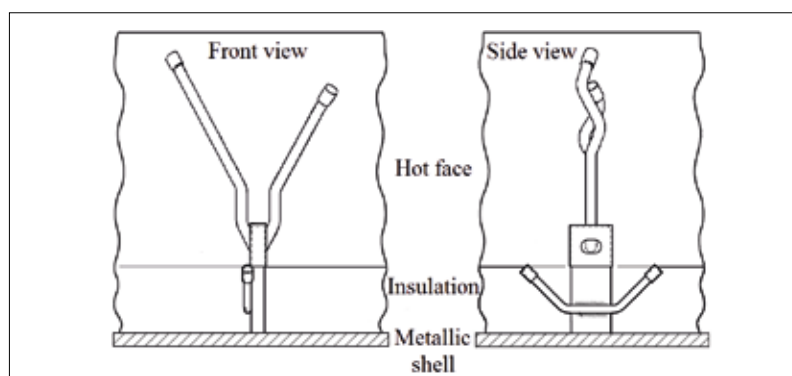


Fig. 1 Metallic anchor shape used in an alumina calciner refractory lining

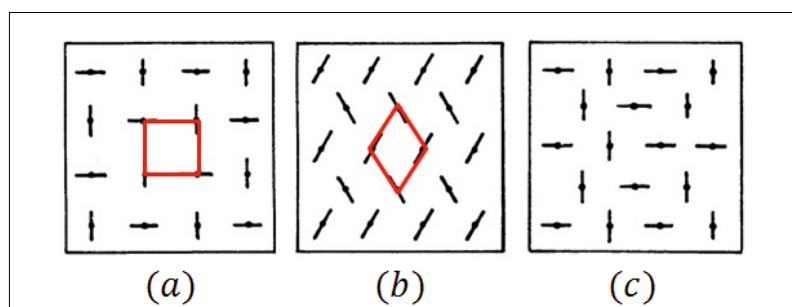


Fig. 2a–c Usual patterns of anchoring systems: (a) square, (b) diamond, and (c) staggered (adapted from [5])

directions, hindering crack propagation [6]. Anchor features such as shape, length and angle of legs, and corrugation are not normalized and their selection is usually carried out based on previous experiences. It is equally important to keep a regular pattern in anchor spacing in order to provide an evenly load distribution among them. Some typical patterns that are commonly used are illustrated in Fig. 2a–c [5].

1.1.2 Ceramic anchors

Ceramic anchors are refractory blocks presenting various grooves along its length which are used to withstand specific castable areas where operating temperatures are higher than 1100 °C or when working

conditions impose corrosive and/or oxidizing environments. These anchors possess greater holding capacity when compared to metallic ones due to their larger contact interface and cross-section area, which lowers the overall stress in each anchor [8]. Fig. 3 a presents the characteristic shape of ceramic anchors, which are mainly used to hold plastic refractory, but can also be applied for other types of refractories (such as castables) [2]. The highest operating condition for ceramic anchors is around 1700 °C, depending on the raw materials used in their formulations. When possible, it is desirable that ceramic anchors present similar properties to those of the lining refractory in order to minimize the thermal expansion

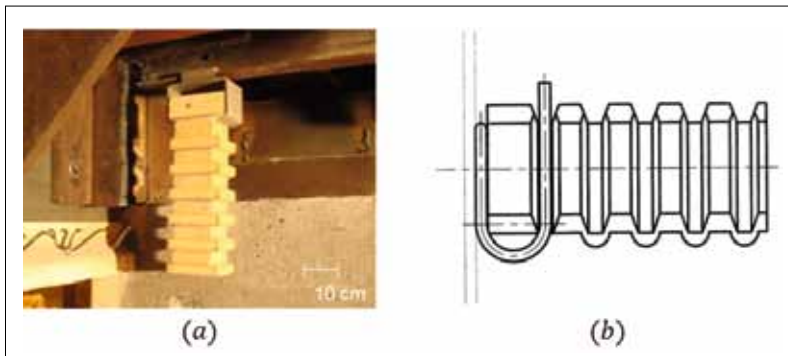


Fig. 3a–b Ceramic anchor coupled to a C-shaped clip welded to an external beam (a), and diagram illustrating the installation of a ceramic anchor with a U-shape clip directly welded to the vessel shell (b)

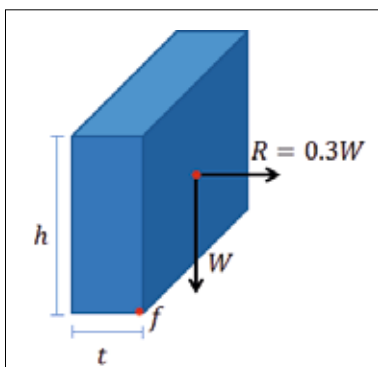


Fig. 4 Diagram illustrating an external load (R), the weight (W) of the refractory lining, and the fulcrum (f) used in the calculation of moment assuring lining stability (adapted from [2])

coefficient mismatch [9]. Unlike metallic anchors, the ceramic ones are not directly connected to the vessel shell. Instead, they are hold by metallic hangers, which in turn are welded to external beams, in the case of roofs (Fig. 3a), or directly to the shell

for walls (Fig. 3b). Such procedures increase the installation times and associated costs [8].

1.2 Anchor spacing

Their spacing is mostly determined based on previous experiences as mentioned before, which leads to the use of empirical formulas and rules of thumb. Although these practices are largely used in industries, they might ignore specific issues related to each process and material [4]. A common and widespread procedure is to establish the anchor spacing as a multiple of the total refractory lining thickness, regardless of the materials and of the working conditions. This procedure can be mathematically stated [2], according to Eq. 1–4. Given a refractory panel located on the wall of a vessel, there can be two main loads acting on it: one due to the panel own weight in the vertical direction (from its center of gravity), and another, perpendicular to the wall,

considering possible external vibrations or pressure variations, which can lead the panel to rotate around a fulcrum. A sketch of a panel in a vertical wall and the loads acting on it are presented in Fig. 4, where h is the height of the panel, t is its thickness, W the uniform load due to the weight of the lining (gravity load), R an external load and f the lining fulcrum. The horizontal load (R) is set as equivalent to 30 % of W . Thus, for the panel to remain in place without an anchoring system, the moment of the gravity load (M_w) must be greater than that of the external one (M_R), so that the lining does not collapse, as shown in Eq. 4. Thereby, it is possible to correlate height and thickness of the panel, where the former represents the spacing in which the anchors must be arranged to sustain the wall.

$$M_w = \frac{1}{2} \cdot t \cdot W \quad (1)$$

$$M_R = \frac{1}{2} \cdot h \cdot R \quad (2)$$

$$M_w \geq M_R \quad (3)$$

$$\frac{1}{2} \cdot t \cdot W \geq \frac{1}{2} \cdot h \cdot 0.3 \cdot W \rightarrow h \leq 3.3t \quad (4)$$

1.2.1 General recommendations

According to the company Shinagawa [5], the spacing for monolithic refractories should be determined depending on the place of installation, type of anchor being used and the lining thickness. Tab. 2 reports the suggested values based on the practical experience of the company.

Similarly to Shinagawa, Thermal Ceramics company [8] also suggests the use of default values, as shown in Tab. 3. It is noticeable the difference between the spacing for metallic and ceramic anchors. Whereas Shinagawa's recommendations (Tab. 2) are very similar regardless of anchor type and position, Thermal Ceramics' ones take into account the higher holding capacity of ceramic anchors.

1.2.2 Plibrico model

Plibrico company [2] stated that the anchor spacing should be based on the features of each particular project such as the mechanical properties of the anchor and the refractory lining as a function of the temperature. Considering these properties a mathematical model for the anchor spacing

Tab. 2 Shinagawa's suggestion for anchor spacing, depending on the lining thickness (adapted from [5])

Location	Lining Thickness [mm]	Anchor Types	
		Metallic [mm]	Ceramic [mm]
Walls, slopes and cylinders	50–100	–	–
	100–200	230	–
	200–300	380	380
	300–400	460	450
	400+	600	600
Roofs and bullnoses	100–200	300	300
	200+	300	300
Floors	50–100	230	–
	125–230	380	–
	230+	500	–

is proposed, where two methods are adopted for spacing calculations: (i) based on the relationship between anchor strength at operating temperature and the gravity load due to the lining weight, where the thicker the lining the greater the weight to be sustained and the lower the spacing values; (ii) based on the refractory strength at operating temperature and its own weight, so the thicker the lining the greater the strength and the larger the spacing required. The lower value obtained considering the two approaches should be adopted for spacing, as it will be shown in Section 3. Plibrico assumes L-shaped anchors in the model, as this geometry offers the least support possible. It also considers that the loads on the anchors act entirely in the vertical axis, ignoring the division of loads in different directions as in the case of V- or Y-shaped anchors, which implies in an additional safety factor.

For the spacing calculation considering the anchor strength, it is assumed that the anchors are equally positioned in all directions. The gravity load is calculated by using the dimensions and density of the refractory lining, and the anchor cross-section area. Then, the tensile strength of the anchor at the operating temperature is compared with the calculated stress. Obviously, if the anchor strength is greater than the applied load there is no failure. Fig. 5a–b illustrate the variables used in the calculations and the representation of the load due to the lining weight acting on the anchors.

The load on a single anchor (W) is given by Eq. 5, where l_a is the spacing between anchors, t_1 and ρ_1 are the refractory thickness and density respectively, and g the gravitational acceleration. In order to keep the whole system in place, the anchor tensile strength (σ_a) should be greater or at least equal to the stress in the system, as indicated by Eq. 6, where A is the cross-sectional area of the anchor. The maximum spacing is then given by Eq. 7 by replacing the variables of Eq. 1 in Eq. 6 and rearranging them. For the multi-layer lining (Fig. 5c) the spacing is calculated similarly to the single-layer case, but considering that the load acting on the anchor is given by the sum of the weights of all layers, resulting in Eq. 8. In the case where spacing is calculated based on the refractory strength, it is assumed again that the anchors are equally spaced in all direc-

Tab. 3 Thermal Ceramics' suggestion for anchor spacing, depending on the lining thickness (adapted from [8])

Location	Lining Thickness [mm]	Anchor Types	
		Metallic [mm]	Ceramic [mm]
Walls and slopes	50–100	150	–
	100–200	230	–
	200–300	300	460
	300–400	–	460
	400+	–	610
Roofs and bullnoses	100–200	180	300
	200+	250	300
Floors	50–100	300	–
	100–230	460	–
	230+	610	–

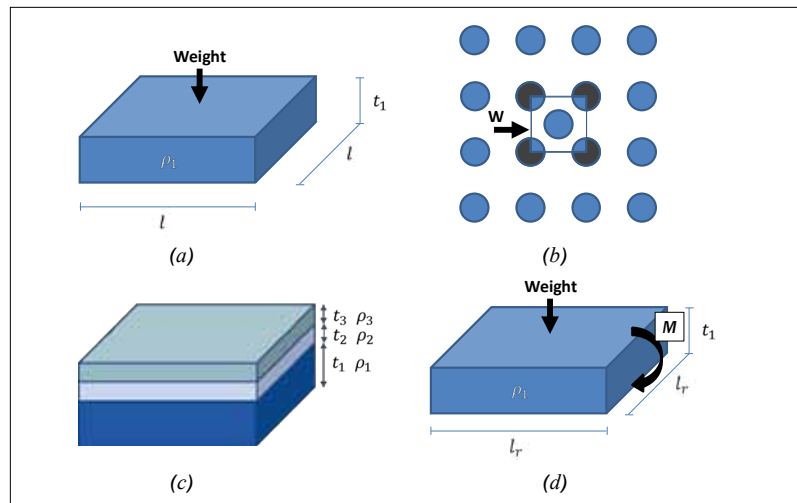


Fig. 5a–d Lining dimensions and the weight load acting on the system (a), schematic of the weight load acting on one anchor (b), multi-layer lining system (c), and bending moment diagram that arises in the lining under the action of its own weight (d)

tions. However, from the refractory perspective, the action of its own weight generates a bending moment, as it is being held in a fixed position due to anchoring system (Fig. 5d). The load in this case is obtained by Eq. 9, where l_r is the spacing between anchors. The bending moment (M) and the modulus of section $I_r \cdot t_1$ (Z) are given by Eq. 10–11, respectively. For the integrity of the system, the refractory bending strength (σ_r) should be greater or at least equal to the stress resulted by the bending moment, as indicated in Eq. 12. Thus, the maximum spacing allowed is specified by Eq. 13, and in the case of multilayer lining by Eq. 14. Regarding the walls, due to the anchor horizontal disposition and lack of mobility in the vertical axis, it is assumed that the only loads able to generate any actual stress are

the horizontal ones, which are considered as 30 % of the weight load, as shown in Fig. 4 (20 % associated with loads due to an earthquake, according to the Japanese standard for buildings, and 10 %, arbitrarily, to vibrations and thermal expansion). Thus, if the anchors used in the walls are the same as those for the roof, the spacing is given by Eq. 15–16.

$$W = l_a^2 \cdot t_1 \cdot \rho_1 \cdot g \tag{5}$$

$$\sigma_a \geq \frac{W}{A} \tag{6}$$

$$l_a \leq \sqrt{\frac{a \cdot \sigma_a}{t_1 \cdot \rho_1 \cdot g}} \tag{7}$$

$$l_a \leq \sqrt{\frac{a \cdot \sigma_a}{\sum(t_i \cdot \rho_i) \cdot g}} \tag{8}$$

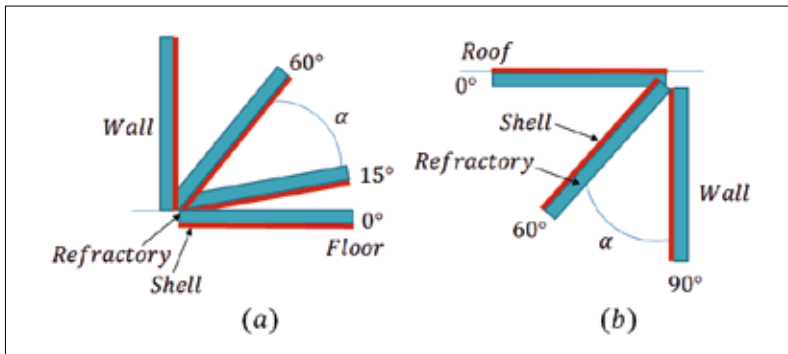


Fig. 6a–b Diagram for upward inclined lining (a), and for downward inclined lining (b) (adapted from [2])

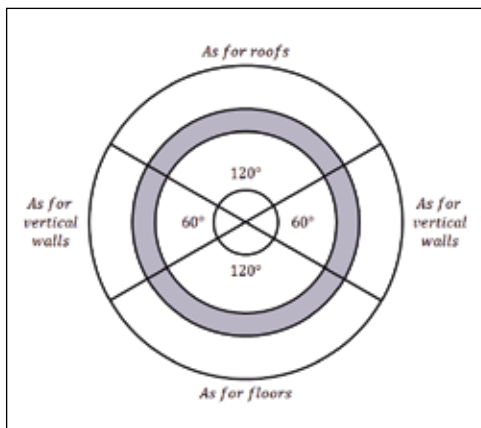


Fig. 7 Different spacing calculations depending on the area of horizontal cylinders (adapted from [2])

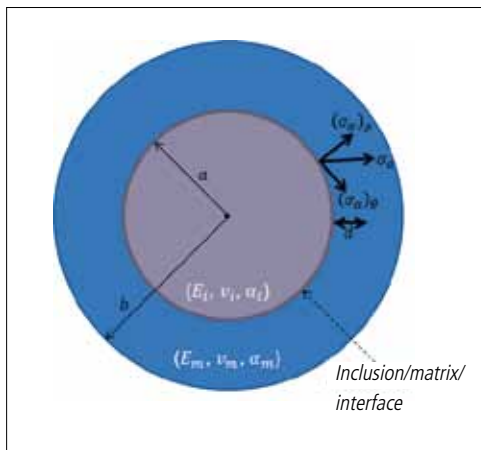


Fig. 8 Concentric spherical model (adapted from [10])

$$W = l_r^2 \cdot t_1 \cdot \rho_1 \cdot g \quad (9)$$

$$M = \frac{1}{2} \cdot l_r \cdot W \quad (10)$$

$$Z = \frac{1}{6} \cdot l_r \cdot t_1^2 \quad (11)$$

$$\sigma_r \geq \frac{M}{Z} \quad (12)$$

$$\sigma_r \geq \frac{1}{2} \cdot l_r^3 \cdot t_1 \cdot \rho_1 \cdot g \rightarrow \sigma_r \geq \frac{3 \cdot \rho_1 \cdot l_r^2 \cdot g}{t_1}$$

$$l_r \leq \sqrt{\frac{\sigma_r \cdot t_1}{3 \cdot \rho_1 \cdot g}} \quad (13)$$

$$l_r \leq \sqrt{\frac{\sigma_r \cdot t_1^2}{3 \cdot \Sigma(t_i \cdot \rho_i) \cdot g}} \quad (14)$$

$$\sigma_a \geq \frac{F}{a} \rightarrow \sigma_a \geq \frac{0.3w}{a} \rightarrow l_a \leq \sqrt{\frac{a \cdot \sigma_a}{\Sigma(t_i \cdot \rho_i) \cdot g}} \cdot 1.8 \quad (15)$$

$$\sigma_r \geq \frac{M}{Z} \rightarrow \sigma_r \geq \frac{1}{2} \cdot l_r \cdot 0.3 \cdot w \rightarrow \sigma_r \geq \frac{1}{6} \cdot l_r \cdot t_1^2$$

$$l_r \leq \sqrt{\frac{\sigma_r \cdot t_1^2}{3 \cdot \Sigma(t_i \cdot \rho_i) \cdot g}} \cdot 1.8 \quad (16)$$

For the floors, as the lining is directly withstood by the shell/ground, no model is proposed and it is assumed that the anchors are not essential, except in specific situations where there are factors such as vibration and thermal expansion of the lining. For upward inclined linings the configuration can be assumed to be in between a floor and a vertical wall (Fig. 6a) and anchor spacing is given by Eq. 17–18, which are valid in the range from 15–60°. Linings with inclinations lower than 15° are regarded as floors and above 60° as walls. The spacing for downward inclined linings, in which the configuration can be considered as in between a roof and a vertical wall (Fig. 6b), is given by Eq. 19–20, which are applied for inclinations greater than 60°. Below that (<60°) the spacing is the same as for roofs. The spacing for horizontal cylinders follows the same principles previously analysed and is calculated as shown in Fig. 7. For vertical cylinders the spacing is obtained with the same equations used for vertical walls.

$$l_a \leq \sqrt{\frac{a \cdot \sigma_a}{\Sigma(t_i \cdot \rho_i) \cdot g}} \cdot 1.8 \cdot \left\{ 1 + \left(\frac{\alpha - 15}{60 - 15} \right) \right\} \quad (17)$$

$$l_r \leq \sqrt{\frac{\sigma_r \cdot t_1^2}{3 \cdot \Sigma(t_i \cdot \rho_i) \cdot g}} \cdot 1.8 \cdot \left\{ 1 + \left(\frac{\alpha - 15}{60 - 15} \right) \right\} \quad (18)$$

$$l_a \leq \sqrt{\frac{a \cdot \sigma_a}{\Sigma(t_i \cdot \rho_i) \cdot g}} \cdot \left\{ 1 + \left[(1.8 - 1) \cdot \left(\frac{\alpha - 60}{90 - 60} \right) \right] \right\} \quad (19)$$

$$l_r \leq \sqrt{\frac{\sigma_r \cdot t_1^2}{3 \cdot \Sigma(t_i \cdot \rho_i) \cdot g}} \cdot \left\{ 1 + \left[(1.8 - 1) \cdot \left(\frac{\alpha - 60}{90 - 60} \right) \right] \right\} \quad (20)$$

2 Materials and techniques

2.1 Proposed calculations

2.1.1 Thermal stresses

Thermal stress calculations for refractory lining systems containing anchors are difficult and complex as they involve those arising due to the thermal expansion coefficient mismatch among the anchor, the refractory and the vessel shell, the temperature gradient inherent to the process, and the difference between the thermal conductivity of metallic and ceramic materials [3]. Thus, the use of computational analysis becomes relevant to define the design parameters of anchoring systems and refractory structures. However, a simple mathematical model [10], which is applied for ceramic matrix composites to calculate the stresses generated by mismatch in the thermal expansion coefficients between the inclusion and the matrix, was extrapolated and used in this work to qualitatively analyse the effect of thermal stresses in anchor/refractory systems. This evaluation also provides insights about the benefits of anchor caps to reduce thermal stresses. The model is based on the stress balance between a sphere of radius *a* (representing the inclusion) inside another one of radius *b* (assumed as the matrix), and describes the stress at the inclusion-matrix interface (σ_a), considering both materials in perfect contact. It is considered that σ_a acts on the interface between the spheres in relation to the inner one and it can be tensile or compressive, depending on the relative thermal expansion coefficients of the materials. If the inclusion has a higher coefficient than the matrix the stress is tensile and is defined as negative, otherwise it is compressive and considered as positive. The surface stress varies as function of the distance (*d*) from the inclusion/

matrix interface and can be divided into two components, one radial $[(\sigma_r)_\rho]$ and another tangential $[(\sigma_\alpha)_\rho]$ (Fig. 8).

As the model was developed for spherical geometries, a shape factor is applied in order to extrapolate its use for a cylindrical one. This factor consists of an expression obtained from the division of the cylinder area/volume ratio by the sphere area/volume one, where h stands for the height and a the radius of the cylinder. The model with the shape factor is illustrated by Eq. 21 and the radial and tangential components by Eq. 22–23. The inner sphere representing the inclusion is taken as the anchor, which has properties such as elastic modulus E_i , Poisson's ratio ν_i and thermal expansion coefficient α_i , and the outer sphere, as the matrix, represents the refractory lining, with properties E_m , ν_m and α_m , respectively. In this study, the inner sphere radius (a) was set as the radius of a cylindrical anchor, and the outer sphere radius (b) as half the spacing between anchors ($b = 1/2 \cdot l$), as illustrated in Fig. 9. The calculations were based on metallic anchors and using average values for the materials properties, which are listed in Tab. 4.

2.1.2 Modified Plibrico model proposed in this work

In the original Plibrico model, when it comes to roofs, the only loads considered are those acting on the anchors due to gravity, which is just valid at room temperature. Thermal stresses that may develop during operation due to thermal expansion coefficient mismatch among the anchors, the lining, and the shell, as well as the temperature gradients, are ignored because of the associated difficulties for calculations. Therefore, the Plibrico model underestimates the total load acting on the system and changes are

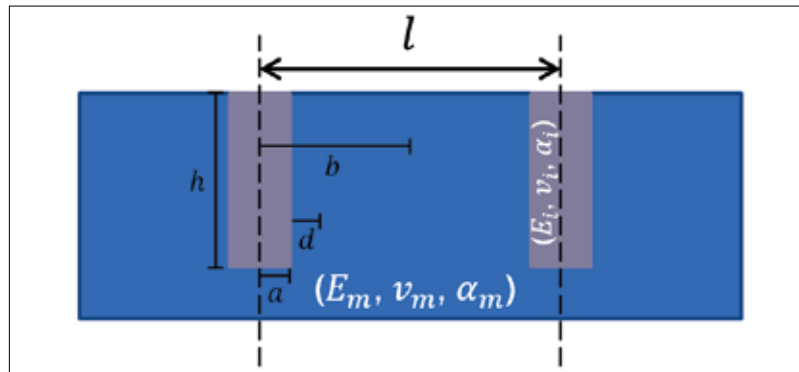


Fig. 9 Sketch of the dimensions used for the thermal stresses calculation

Tab. 4 Average material properties and conditions used for the thermal stress analysis

Refractory			Metallic Anchor				Temperature	Spacing
α_i [$10^{-6} \text{ }^\circ\text{C}^{-1}$]	E_i [GPa]	ν_i	α_a [$10^{-6} \text{ }^\circ\text{C}^{-1}$]	E_a [GPa]	ν_a	a [mm]	T [$^\circ\text{C}$]	l [mm]
6,00	20	0,20	18,7	118	0,30	8	1000	300

proposed in order to take into account the effect of thermal stresses and to improve the accuracy of the theoretical values calculated for anchor spacing. The proposal consists in calculating these stresses as a function of the lining weight load, following the idea suggested in the original Plibrico model (Fig. 4) to determine the magnitude of a horizontal one. The model defines this load as representing those related to external vibration and thermal expansion, attributing to each factor a percentage of the weight load proportional to its effects. Firstly, all potential sources of major thermal stresses were defined as follows: thermal expansion mismatch among (i) anchors and lining, (ii) refractory panels, and (iii) the shell, the lining and the anchors. Hence, each of the listed items is arbitrarily defined as proportional to 10 % of the total weight load, similarly to the original model, considering an extra load of 30 % acting on the

system. Any precautions adopted in real projects such as anchor caps, expansion joints and anchor clips, which provide anchor mobility in relation to the shell, are ignored and all the stresses are considered as if they were acting on the anchors as tensile loads. Therefore, the worst case scenario is adopted, working as an additional safety factor. All modifications to the Plibrico original model follow the conditions defined in Eq. 6 and Eq. 12. For roofs, the proposed modifications are illustrated by Eq. 24–25, in which it is assumed that the overall load acting on the system comprises the weight load and thermal stress: $F = w + T = w + 0,3w = 1,3w$, where F indicates the total load and the thermal stress is represented by T. Similarly, modifications are proposed for vertical walls, where it is also assumed the actual loads acting on the system have been underestimated by the original Plibrico model. Therefore, the total load acting on vertical walls is taken as: $F = E + T = 0,3w + 0,3w = 0,6w$, where E represents the extra load, resulting in the Eq. 26–27.

For downward inclined linings, the same ideas for Eq. 15–16 were adopted and Eq. 28–29 are defined. As previously mentioned, Plibrico does not suggest a model to calculate floor spacing. Yet, following the same concept used for the other parts and assuming that any extra stress on the anchors can be described as a function of the weight load ($F = 0,3w$), Eq. 30–31 are

$$\sigma_\alpha = \frac{-(\alpha_i - \alpha_m)\Delta T}{\frac{2a^3(1-2\nu_m)+b^3(1+\nu_m)}{2E_m(b^3-a^3)} + \frac{(1-2\nu_i)}{Ei}} \times \frac{2}{3} \frac{(h+a)}{h} \quad (21)$$

$$(\sigma_\alpha)_\rho = \frac{-(\alpha_i - \alpha_m)\Delta T}{\frac{2a^3(1-2\nu_m)+b^3(1+\nu_m)}{2E_m(b^3-a^3)} + \frac{(1-2\nu_i)}{Ei}} \times \frac{2}{3} \frac{(h+a)}{h} \times \frac{a^3(b^3-d^3)}{d^3(a^3-b^3)} \quad (22)$$

$$(\sigma_\alpha)_\theta = \frac{-(\alpha_i - \alpha_m)\Delta T}{\frac{2a^3(1-2\nu_m)+b^3(1+\nu_m)}{2E_m(b^3-a^3)} + \frac{(1-2\nu_i)}{Ei}} \times \frac{2}{3} \frac{(h+a)}{h} \times \frac{a^3(2d^3+b^3)}{2d^3(a^3-b^3)} \quad (23)$$

$$\sigma_a \geq \frac{F}{a} \rightarrow \sigma_a \geq \frac{1,3W}{a} = \frac{1,3 \cdot l_a^2 \cdot t_1 \cdot \rho_1 \cdot g}{a} \rightarrow l_a \leq \sqrt{\frac{a \cdot \sigma_a}{\Sigma(t_i \cdot \rho_i) \cdot g}} \cdot 0,88 \quad (24)$$

$$\sigma_r \geq \frac{M}{Z} \rightarrow \sigma_r \geq \frac{\frac{1}{2} \cdot 1,3 \cdot l_r^3 \cdot t_1 \cdot \rho_1 \cdot g}{\frac{1}{6} \cdot l_r \cdot t_1^2} \rightarrow l_r \leq \sqrt{\frac{\sigma_r \cdot t_1^2}{3 \cdot \Sigma(t_i \cdot \rho_i) \cdot g}} \cdot 0,88 \quad (25)$$

$$l_a \leq \sqrt{\frac{a \cdot \sigma_a}{\Sigma(t_i \cdot \rho_i) \cdot g}} \cdot 1,29 \quad (26)$$

$$l_r \leq \sqrt{\frac{\sigma_r \cdot t_1^2}{3 \cdot \Sigma(t_i \cdot \rho_i) \cdot g}} \cdot 1,29 \quad (27)$$

$$l_a \leq \sqrt{\frac{a \cdot \sigma_a}{\Sigma(t_i \cdot \rho_i) \cdot g}} \cdot \left\{ 0,88 + \left[1,29 - 0,88 \cdot \left(\frac{\alpha - 60}{90 - 60} \right) \right] \right\} \quad (28)$$

$$l_r \leq \sqrt{\frac{\sigma_r \cdot t_1^2}{3 \cdot \Sigma(t_i \cdot \rho_i) \cdot g}} \cdot \left\{ 0,88 + \left[1,29 - 0,88 \cdot \left(\frac{\alpha - 60}{90 - 60} \right) \right] \right\} \quad (29)$$

$$l_a \leq \sqrt{\frac{a \cdot \sigma_a}{\Sigma(t_i \cdot \rho_i) \cdot g}} \cdot 1,83 \quad (30)$$

$$l_r \leq \sqrt{\frac{\sigma_r \cdot t_1^2}{3 \cdot \Sigma(t_i \cdot \rho_i) \cdot g}} \cdot 1,83 \quad (31)$$

$$l_a \leq \sqrt{\frac{a \cdot \sigma_a}{\Sigma(t_i \cdot \rho_i) \cdot g}} \cdot \left\{ 1,83 - \left[\left(\frac{\alpha - 15}{60 - 15} \right) \cdot 1,83 \right] \right\} \quad (32)$$

$$l_r \leq \sqrt{\frac{\sigma_r \cdot t_1^2}{3 \cdot \Sigma(t_i \cdot \rho_i) \cdot g}} \cdot \left\{ 1,83 - \left[\left(\frac{\alpha - 15}{60 - 15} \right) \cdot 1,83 \right] \right\} \quad (33)$$

proposed, which are valid for inclinations up to 15°. In the range from 15–60°, the equations must be adjusted to account for effects of gravity and Eq. 32–33 are proposed, whereas when the inclination increases there is a proportional decrease in the calculated spacing value, up to the point that it is the same as the one of a vertical wall. As for angles greater than or equal to 60°, the spacing should be similar to that of vertical walls.

2.2 Applying the proposed models to an alumina calciner project

Calcination is the last step of the Bayer process to produce alumina, which is characterized by a thermal treatment where aluminum hydroxide [Al(OH)₃] is transformed into aluminum oxide (Al₂O₃) at temperatures in the range 1000–1250 °C. Fig. 10 shows a schematic drawing of one of the calciners currently in operation at Alumar’s plant, in São Luis/BR. The regions operating at higher temperatures have their refractory held in place with metallic and ceramic anchors, depending on the temperature range and equipment region. For the high temperatures areas, phosphate-bonded high-alumina ceramic anchors are used. They present suitable volumetric stability, which reduces the stresses originated by the mismatches in thermal expansion coefficients. In the regions of lower mechanical stresses, Incoloy DS steel anchors are usually selected. Ceramic anchors have the same design as those shown in Fig. 2 where their lengths change as a function of the lining thickness. The metallic anchors used have the same morphology as those presented in Fig. 1. The bottom of the calciner furnace, as indicated in Fig. 10 (Region 1), was selected for analysis, as it is a region with different sorts of geometry and higher operating temperature (1050 °C). Another area of the calciner, also shown in Fig. 10 (Region 2), was chosen for analysis as it operates at temperatures around 500 °C and also comprises floors, walls and roofs.

The analysis carried out compares the average spacing values used in the calciner design with those calculated with the original Plibrico model, the modified one, as well as the values suggested by few other companies, in order to study the mathematical model validity. Region 1 of the calciner

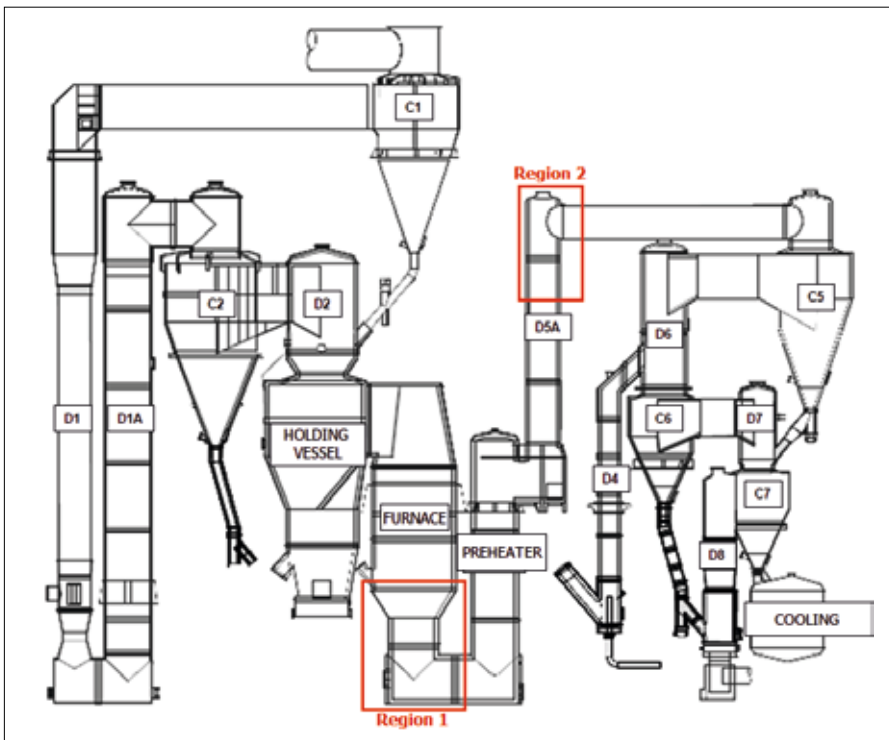


Fig. 10 Layout of a Mark VII type calciner, with indications of the analysed regions (adapted from [1])

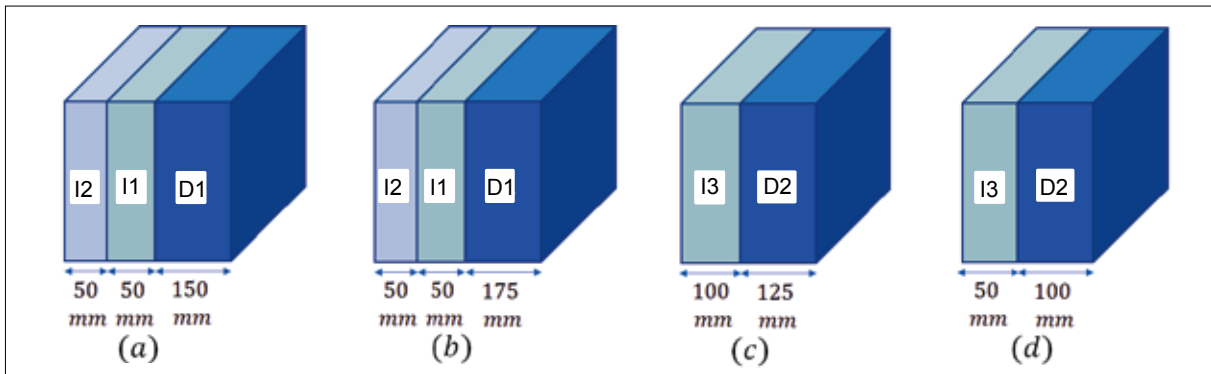


Fig. 11–d Refractory lining configuration adopted in: (a) Parts 1, 2, 4 and (b) Part 3 of Region 1 for ceramic anchors, (c) Parts 4 and 5 of Region 1 for metallic anchors, and (d) in all parts of Region 2

Tab. 5 Properties of the refractory materials used in the studied regions of the calciner

Hot Face Refractory	Density ρ [g/cm ³]	Bending Stress $\sigma_{r(1000\text{ }^{\circ}\text{C})}$ [MPa]
D1	2,46	8
D2	2,65	9
Insulating Refractory	Density ρ [g/cm ³]	
I1	1,18	
I2	0,56	
I3	1,00	

presents conical and cylindrical shapes, containing parts of roof, vertical and inclined walls, and floors. The areas in which ceramic anchors are used present a total thickness of 250 mm in one part and 275 mm in other, both consisting of a hot face refractory (D1) of 150 mm and 175 mm respectively, and

Tab. 6 Properties of the anchor materials used in the studied regions of the calciner

Anchor Type	Tensile Stress $\sigma_{r(1000\text{ }^{\circ}\text{C})}$ [MPa]	Cross-Section Area a [mm ²]
Metallic	73	50,27
Ceramic	21	5153

two insulation layers (I1 and I2) of 50 mm each (Fig. 11a–b). In areas with metallic anchors, the total thickness is 225 mm, lined only with a dense refractory (D2) (125 mm) and an insulating material (I3) (100 mm) (Fig. 11c). Region 2 also features cylindrical shapes and parts as roofs, walls and floors, hold by metallic anchors. The total lining thickness in all regions is 150 mm, in which 100 mm is related to a hot face refractory (D2) and the remaining 50 mm for the insulation (I3) (Fig. 11d). Tab. 5–6 show the values of the material properties considered in the spacing calculations.

Fig. 12a illustrates in detail the analysed calciner regions, which show a square

mesh arrangement of anchors. However, this pattern is inherent to each refractory panel and presents changes according to the vessel geometry variations, as indicated in Fig. 12b. Therefore, the general analysis is based on the average spacing values. As shown in Fig. 12a, Part 1 of Region 1 has a conical shape with a 60° slope, thus for calculation purpose it should be considered as a vertical wall. The average anchor spacing in this part is 360 mm. Parts 2 and 3 represent vertical walls with ceramic anchors and the difference between them relies on the total lining thickness, as previously mentioned. The average spacing is 362 mm for Part 2 and 340 mm for Part 3. Part 4

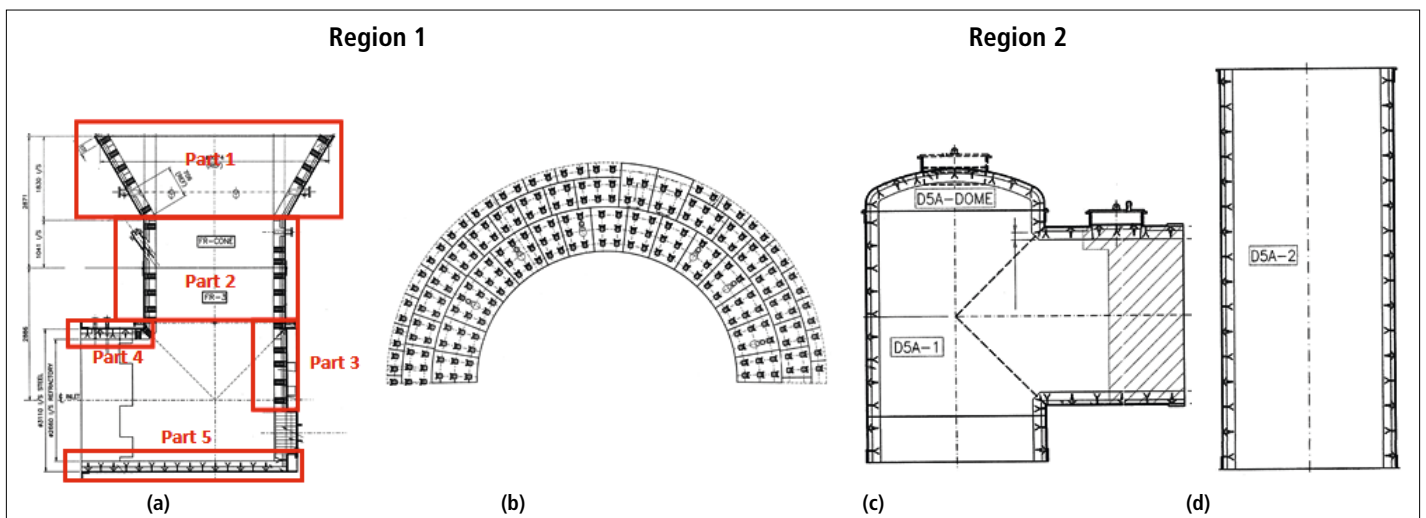


Fig. 12a–d Cross-section of Region 1 and its different parts (a), schematic view of the anchor distribution at the conical part of Region 1 (b), side view of the top (c), and side view of the bottom part of Region 2 (d)

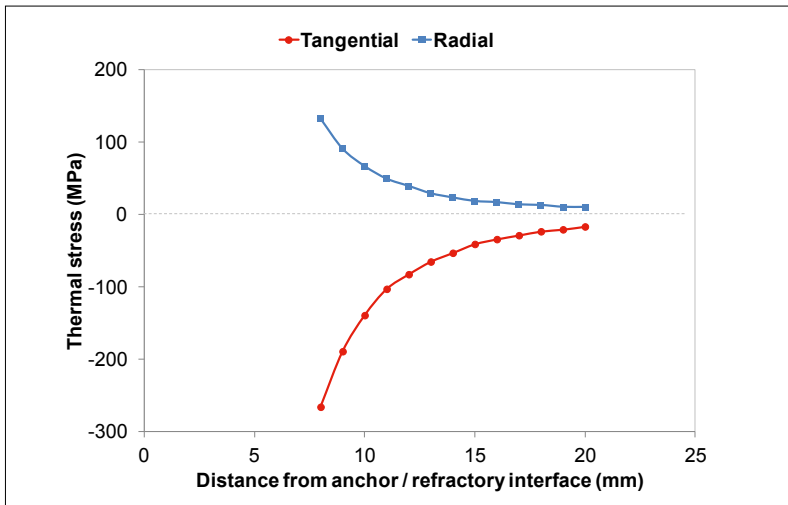


Fig. 13 Distribution of tangential and radial stresses from the interface into the matrix

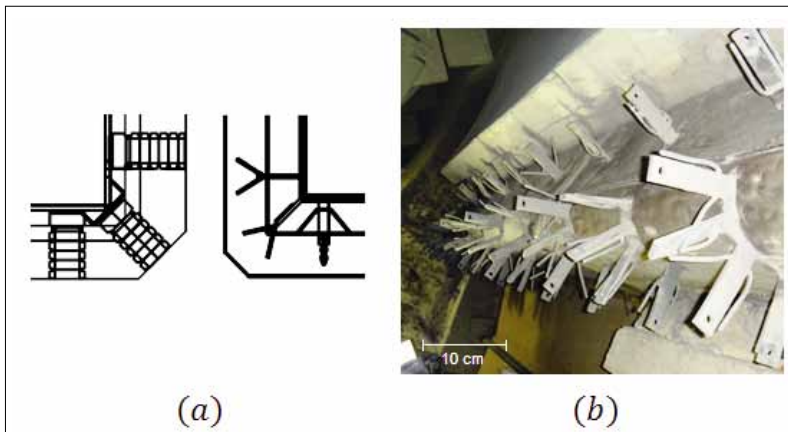


Fig. 14a–b (a) Schematic drawing of the bullnoses (Regions 1 and 2), and (b) a bullnose with metallic anchors



Fig. 15 Front view of the lining failure and crack propagation found in a bullnose area with ceramic anchors in Region 1

is a roof with metallic anchors and a small portion of ceramic ones, with an average spacing of 357 mm for the ceramic anchors. Part 5 is a floor with metallic anchors, and Part 6, which is not illustrated in the figure,

represents the walls connecting Parts 4 and 5, containing ceramic and metallic anchors, where the spacing for the ceramic ones is similar to Part 2. The average spacing for metallic anchors is 287 and 280 mm

for all parts of Regions 1 and 2, respectively.

3 Results and discussion

3.1 Thermal stresses

The thermal stress analysis, using Eq. 22–23, and the data presented in Tab. 4, provided the results shown in Fig. 13. The signs of the stresses in the graph are adjusted, so positive indicates tensile and negative compressive ones, opposite to the reference adopted in the original model.

Initially, it is possible to notice that the stresses rapidly decrease towards zero with the increasing distance from the anchor/refractory interface. However, the calculations show that null values are only reached at distances close to half of the anchor spacing used (150 mm). Thus, considering all simplifications assumed in the evaluation, especially regarding anchor shape, in which a simple cylindrical geometry adopted greatly differs from the complex shapes used in the project (Fig. 1), the actual stresses may be even greater in magnitude. So, these thermal stress profiles may indicate that in addition to problems in refractory application and consolidation during the installation step, too short anchor spacing can also lead to an interaction between the thermal stresses, which may increase the likelihood of crack generation. If by one hand the increase in the distance between anchors leads to higher stresses due to the greater weight withstood by each anchor, on the other, decrease in anchor spacing can also have harmful effects, since the thermal stresses generated at an anchor/refractory interface may extend along the lining and interact with those by its nearest neighbours. This scenario may be one of the reasons why areas with complex shapes such as bullnoses, where there is a great density of anchors, present so many cracks. Fig. 14a outlines diagrams of the bullnoses present in Regions 1 and 2, and Fig. 14b illustrates a bullnose with metallic anchors for the alumina calciner. Fig. 15 shows a common failure in the lining for the bullnose containing ceramic anchors of Region 1.

The analysis also corroborates the concept of applying degradable coatings to the anchors in order to reduce thermal stress between materials with great mismatch in thermal expansion coefficients, as the increase in the

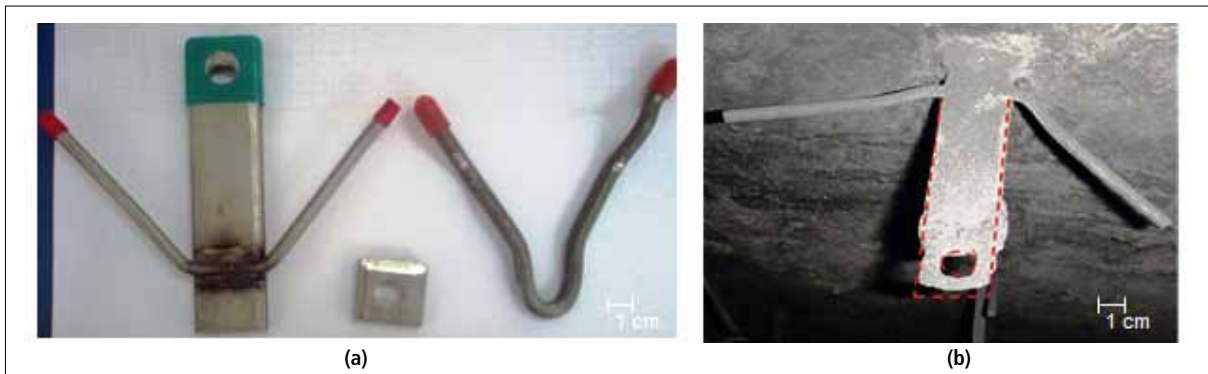


Fig. 16a–b (a) Incoloy DS metallic anchor with polymeric caps, and (b) the corrosion caused by them, after using at high temperatures

interface distance provided by the coating can reduce the initial interaction of the materials and consequently the magnitude of the stresses at the interface and throughout the lining. In this case, the coating thickness should be enough to accommodate the thermal stresses but not to the point it affects the interaction between anchor and lining, resulting in slip bond, what can reduce the holding capability of the anchor to the refractory and also lead to failures. However, the nature of the coating used should not induce anchor oxidation. Polymers can release carbon monoxide during degradation, which can oxidize and react even with high-chromium content steels [6], such as Incoloy DS alloy. This effect was observed in practice at Alumar when polymeric caps similar to those shown in Fig. 16a were used, resulting in anchor degradation as illustrated in Fig. 16b. The presence of chlorine in the coating composition is also very harmful and acts on the corrosion of metallic parts. A common installation practice consists of involving the metal clips used in ceramic anchors with chlorine-free tapes, which in addition to relieving stresses do not affect the steel properties. This is a simple procedure that could be easily replicated for metallic anchors, replacing the polymeric caps.

3.2 Anchor spacing

The results for anchor spacing obtained using the modified and the Plibrico original model were compared with those proposed by few companies and the ones currently applied in the calciner. Two different calculations are carried out for the theoretical models, one with anchor strength as limiting factor and another based on the refractory strength, being the lowest value found taken as valid, as illustrated in Fig. 17.

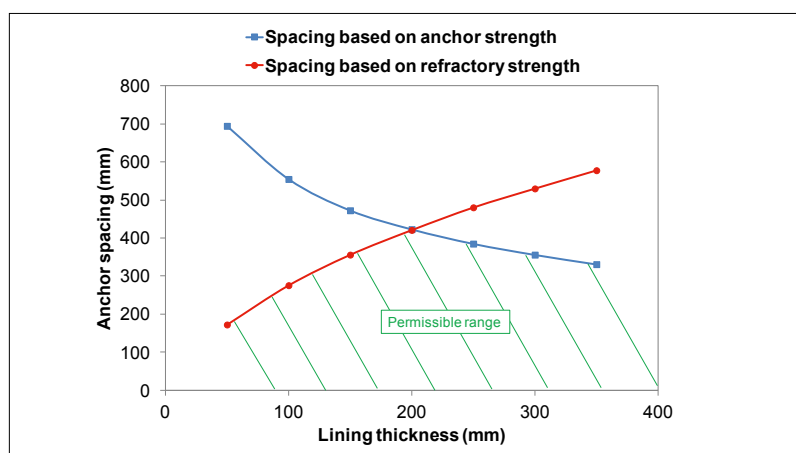


Fig. 17 Relationship between lining thickness and anchor spacing calculated with the modified Plibrico model and using the materials described in Tab. 4–5

Tab. 7 Average spacing in [mm] for ceramic anchors of Region 1, working around 1050 °C

	Plibrico Model		This Paper		Shina-gawa	Thermal Ceramics	Project (Alumar)
	Anchor Strength	Refractory Strength	Anchor Strength	Refractory Strength			
Roof	546	406	479	356	300	300	357
Wall 1	999	744	704	524	380	460	362
Wall 2	938	815	661	575	380	460	340

Tab. 8 Average spacing in [mm] for metallic anchors of Region 1, working around 1050 °C

	Plibrico Model		This Paper		Shina-gawa	Thermal Ceramics	Project (Alumar)
	Anchor Strength	Refractory Strength	Anchor Strength	Refractory Strength			
Roof	295	372	258	326	300	180	287
Wall	539	681	380	480	380	300	287
Floor	–	–	539	681	380	460	287

Tab. 9 Average spacing in [mm] for metallic anchors of Region 2, working around 500 °C

	Plibrico Model		This Paper		Shina-gawa	Thermal Ceramics	Project (Alumar)
	Anchor Strength	Refractory Strength	Anchor Strength	Refractory Strength			
Roof	345	348	302	306	300	180	280
Wall	631	637	445	449	230	230	280
Floor	–	–	631	637	380	460	280

Tab. 10 Likely reduction for non-critical areas of Region 1 with ceramic anchors

		Spacing [mm]		Number of Anchors		Reduction [%]
		Actual Project	This Paper	Actual Project	This Paper	
Wall 1	Cone	362	524	213	150	30
	Vertical cylinder 1	362	524	81	36	56
	Vertical cylinder 2	362	524	131	61	53
	Horizontal cylinder	362	524	62	35	44
Wall 2		384	575	32	15	53

Tab. 11 Likely reduction for non-critical areas of Region 1 with metallic anchors

	Spacing [mm]		Number of Anchors		Reduction [%]
	Actual Project	This Paper	Actual Project	This Paper	
Wall	287	380	56	44	21
Floor	287	539	160	40	75

Tab. 7 shows the results for the areas containing ceramic anchors of Region 1, where the Roof is associated with Part 4 of Fig. 12a, Wall 1 to Parts 1 and 2, and Wall 2 to Part 3, respectively. The results for metallic anchors are presented in Tab. 8, in which the Roof relates to Part 4, the Wall to Part 6 and the Floor with Part 5. The results for Region 2 are indicated in Tab. 9.

For Region 1 the anchor spacing values obtained with Plibrico original model differed largely from all the others, what indicates this model overestimates the permissible spacing, restricting its practical use. There was a good agreement between the values of the modified model (this paper) with those used in the calciner design for the roofs, which are one of the most critical areas concerning anchoring systems, providing some evidence for the model validity. In relation to the walls and floors, the values attained are higher than those actually used. Thus, considering correct the modified model, there may be opportunities for potential changes for the spacing used in practice and a consequent reduction in the number of installed anchors, which can lead to savings. The same trends regarding the values proximity for roofs and differences for walls and floors is observed for Region 2. In addition, the comparison between the results for Region 1 and Region 2 provides further and stronger support to the idea of reducing the number of anchors used in less critical areas, given that the average oper-

ating temperature of Region 2 is 500 °C, making this region much less critical, and that the data used in the calculations refers to the materials strength at 1000 °C, which is an additional safety factor. This assessment shows the possibility to decrease anchor consumption in less demanding areas and opens opportunities for conscious and grounded cost savings. Considering that in some cases the price of ceramic anchors can surpass the one of the refractory materials themselves, the importance for optimization related to the number of used anchors is relevant. Besides that, many failures observed in regions working at moderate temperatures are related to other aspects than the anchor spacing, for example the refractory panel size and the lack of expansion joints. Tab. 10–11 show the possible reduction in the number of installed anchors in case the spacing values used were the ones predicted by the modified model.

4 Conclusions

The values for anchor spacing used in the actual design of refractory lined vessels can greatly differ from those attained with the available theoretical models, especially for non-critical areas. Generally, there is a trend of replicating the anchor spacing used for roofs in walls or even floors, which represent an opportunity to decrease the number of applied anchors, without affecting safety. Their spacing in less critical areas, where the loads in action are less intense, can be increased without reducing the expected life-

time of the lining. Decreasing the number of anchors saves costs on materials and on the installation time. Regarding the anchor mesh pattern, there are changes in the regularity along the refractory panels due to the transition of geometry of sections in the vessel. This scenario may induce irregular load distribution on the anchors, and could be bypassed through a suitable design of the lining as a whole, including the arrangement and position of expansion joints, the panel size and the anchoring system. This study provides a preliminary, nevertheless incremental and relevant, understanding on the parameters involved in the design of anchoring systems. The mathematical models herein presented offer an interesting basis and a simple and practical way for calculating anchor spacing using ordinary properties of materials.

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