Refractory linings under thermomechanical aspects

Holger Leszinski and Martin Breddermann

Kurzfassung

Feuerfeste Auskleidungen unter thermomechanischen Gesichtspunkten

Die Auslegung feuerfester Strukturen erfolgt üblicherweise aufgrund von Forderungen, die auf die zu erwartende Ofenatmosphäre zugeschnitten werden müssen: Dichtigkeit, thermische und chemische Verträglichkeiten, Minimierung der Wärmeverluste etc.

Diesbezügliche Erfahrungswerte des Konstrukteurs und Wärmedurchgangsberechnungen am regulären Schichtaufbau sollen dafür sorgen, dass auf die fertiggestellte Anlage Verlass ist.

Thermomechanischen Vorgängen hingegen wird vergleichsweise wenig Aufmerksamkeit gewidmet. Oftmals sind es Zwangsspannungen – im Betrieb hervorgerufen durch behinderte Temperaturverformung und zum Teil um ein Vielfaches höher als Spannungen infolge Eigenlasten oder Ofeninnendruck – welche Anlagenteile „in die Knie zwingen" können. Selbst nach Eintreten derartiger Versagensfälle werden die Ursachen häufig an falscher Stelle gesucht, unter anderem weil die thermomechanischen Wechselwirkungen der einzelnen Strukturkomponenten nicht bekannt sind oder unterschätzt werden.

Selbstverständlich kann man sich dem Komplex Feuerfestbau mit seinen auch in thermomechanischer Hinsicht zahllosen Unwägbarkeiten nur annähern; dazu werden im vorliegenden Beitrag die grundlegenden Mechanismen erläutert, beispielhafte thermomechanische Betrachtungen verschiedener Konstruktionsbeispiele aufgezeigt, und die daraus ableitbaren Möglichkeiten zur Optimierung der Sicherheit und Langlebigkeit dargelegt.

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The design of refractory structures is usually based on requirements that must be matched to the expected furnace atmosphere: Tightness, thermal and chemical compatibility, minimization of heat losses, etc.

In this respect, the experience of the constructor and heat transfer calculations on the regular layer structure are supposed to ensure that the completed system can be relied upon.

In contrast, comparatively little attention is paid to thermomechanical processes. Often it is constraint stresses – during operation caused by hindrance of temperature deformation and sometimes many times higher than stresses due to dead loads or internal furnace pressure – which can "bring furnace components to their knees". Even after the occurrence of such failures, the causes are often sought in the wrong direction, among other things because the thermomechanical interactions of the individual structural components are not known or are underestimated.

Of course, it is only possible to approximate the complex of refractory construction with its innumerable imponderables, also from a thermomechanical point of view; for this, in the given article the basic mechanisms are explained, exemplary thermomechanical considerations of various design examples are shown, and the possibilities for optimizing safety and service life that can be concluded from this are presented.

1. Introduction

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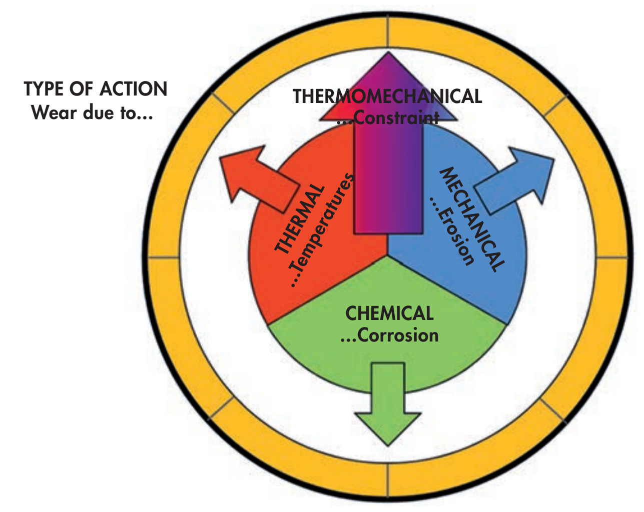

Fig. 1. Thermomechanical analyses allow to limit constraint stresses in a targeted manner.

the other hand, not all constraining forces are avoided with this measure, as will be shown later.

Of course, it is only possible to approximate the complex of refractory construction with its innumerable imponderables, also from a thermomechanical point of view; in order to advance this approximation, the basic mechanisms are explained in the following sections, exemplary thermomechanical considerations of various design examples are shown, and the possibilities for optimizing safety and service life that can be concluded from this are presented (Figure 1).

2. Thermomechanical constraint

Constraint always occurs in construction elements when their free deformations caused by load or strain are hindered by adjacent components, or when their deformations are caused by the "pushing" of adjacent components in any way.

For thermoprocessing facilities this typically means the following: As a result of the very high temperatures, correspondingly large material strains are induced; the materials expand "freely" and without stress until they face resistance from adjacent structural elements, for example by closing expansion joints. Both now "force" each other into a compatible equilibrium state. Thus, thermomechanical stresses occur only as a result of forced expansion or expansion hindrance.

The forces acting in this way depend not only on the temperature- and material-dependent expansion urge, but also on the stiffness of the structural elements involved; their key parameters are described in the following:

System stiffness

Stiffness generally describes the resistance of a body to elastic deformation due to forces or moments: In the case of strain stiffness E*A [MN] resistance to strain/compression due to tensile/compressive forces, in the case of bending stiffness E*I [MNm^2] resistance to distortion due to bending moments. It is therefore a product of the material property Young's modulus E [MN/m^2 ≙ MPa] – or more generally of the secant modulus, see below – with the cross-sectional area A [m^2] or the moment of inertia I [m^4].

The basic laws of deformation are

Strain $\varepsilon = N/(E*A)$ [-] (1)

and

Curvature $k = M/(E*I)$ [m^{-1}]. (2)

Since absolute changes in length are of interest for the calculation of refractory systems, the structural shape is also important in addition to the above laws: For example, the axial spring stiffness of an anchor, which can have a significant influence on the force variables of a lining, is reduced inversely proportional to its length

$c_A = E*A/L$ [MN/m]. (3)

A cylindrical structure reduces its resistance to expansion due to constant radial pressure in inverse proportion to the square of its radius

$c_{cyl} = E*t/R^2$ [MN/m^3], (4)

(t: sheet/layer thickness [m]).

Material stiffness

This is expressed by the secant modulus E_{sec} [MN/m^2], which describes the ratio of stress to strain at any point on the curve of a stress-strain diagram. From the origin to the strain value at which there is proportionality between stress and strain, the secant modulus corresponds to the modulus of elasticity/Young's modulus E (Hooke's law $\sigma = E*\varepsilon$).

The entire non-linear curve can only be determined in a static test, i.e. by means of compressive or flexural tensile strength tests with simultaneous recording of the deformations. In contrast, the dynamic measuring method – based on resonance frequency measurements of vibration-induced specimens – which is frequently used as an alternative, only provides the modulus of elasticity, i.e. does not take into account increasing yielding of the material, which usually occurs under operating conditions. In a later example (chapter 5) it is shown why calculations with the statically measured "complete" data provide more realistic results.

Interaction of the structural elements

The interaction of the heated rigid elements is explained in the following, based on the method described by Noakowski [1]:

If we consider a layer of thickness t [m] with a coefficient of thermal expansion α_T [K^{-1}] and a temperature change, which can be divided into a constant part T_m [K] and a gradient T_G [K], the corresponding free strain is

$\varepsilon_0 = \alpha_T \, \Delta T_m$ [-] (5)

and the corresponding free curvature

$k_0 = \alpha_T \, \Delta T_G/t$ [m^{-1}]. (6)

If we now assume ideal homogeneous systems with constant temperature profiles, in which the free deformations are completely prevented, or in other words "reset", and consider the cross-sectional properties in relation to a 1 m high/long layer, the following relationships are given:

$\varepsilon_0 = \varepsilon_R \Rightarrow \alpha_T \, \Delta T_m = n_R/(E_{sec}*t)$ (7)

$\Rightarrow n_R = \alpha_T \, \Delta T_m \, E_{sec}*t$ [MN/m] (8)

(Example: Fixed bar that does not allow uniform elongation.)

$k_0 = k_R \Rightarrow \alpha_T \, \Delta T_G/t = 12\, m_R/(E_{sec}*t^3)$ (9)

$\Rightarrow m_R = \alpha_T \, \Delta T_G \, E_{sec}*t^2/12$ (10)

(Example: Closed circular ring that cannot bend.)

Thus the normal forces and bending moments can be derived from the fact of a complete expansion hindrance, depending on the "free" expansion urge and the system stiffness.

This principle can be transferred to more complex lining systems with several layers of different material. The following system consideration and assumptions are intended to provide further explanation:

- A cylindrical layer structure consists of the inner wear layer, any number of insulation layers and the encasing steel mantle.
- Due to its high thermal conductivity, the wear layer is heated almost uniformly over the layer thickness (gradient $\Delta T_G \sim 0$). The resetting moment within this layer according to (10) can thus be neglected.
- The heating ΔT_m of the wear layer is accompanied by direct expansion hindrance of the outer layers, i.e. it is not partly compensated by expansion joints.
- Due to their nature (radial joints or separating cracks in progressive operation), the insulation layers can only transmit radial compressive forces, in contrast to the circumferentially overpressed wear layer and the steel casing.

This layered structure can be imagined as a row of springs, an inner and an outer annular spring and intermediate radial springs, whose total stiffness is equal to the sum of the reciprocal values of the individual spring stiffnesses:

$c_{cyl,W} = E_W*t_W/R_W^2$ [MN/m^3], (11)

$c_{rad,k} = E_k/t_k$ [MN/m^3], (12)

$c_{cyl,S} = E_S*t_S/R_S^2$ [MN/m^3], (13)

$\Sigma c = 1/[1/c_{cyl,W} + \Sigma(1/c_{rad,k}) + 1/c_{cyl,S}]$ [MN/m^3] (14)

The corresponding force variables are derived from

$p = \Sigma c * u_W$ [MN/m^2] (15)

and the boiler formula

$n_W = p * R_W = -n_S = -(p * R_W/R_S) * R_S$ [MN/m]. (16)

p [MN/m^2]: Radial pressure relative to the centre of gravity axis of the wear layer

u_W [m]: Actual radial displacement of the wear layer to the outside

n_W [MN/m]: Circumferential compressive force in wear layer

n_S [MN/m]: Circumferential tensile force in steel casing

In order to obtain the actual radial displacement u_W, compatibilities of the layer displacements with each other must be defined; since there is continuity at the layer boundaries, i.e. layers are not penetrated by other layers, the actual "compatible" displacements can only occur under constraint forces in equilibrium.

In this example this displacement compatibility is defined as follows:

$$u_s = u_W + \Sigma(\Delta t_k) \quad (17)$$

u_s [m]: Actual radial displacement of the steel casing to the outside

u_W [m]: Actual radial displacement of the wear layer to the outside

$\Sigma(\Delta t_k)$ [m]: Sum of the layer thickness changes of the solely radially pressed insulating layers

$$u_S = u_{0,S} + u_{R,S} = (\varepsilon_{0,S} + \varepsilon_{R,S}) * R_S \quad (18)$$

$$u_W = u_{0,W} + u_{r,W} = (\varepsilon_{0,W} + \varepsilon_{R,W}) * R_W \quad (19)$$

$$\Sigma(\Delta t_k) = \Sigma[(\varepsilon_{0,tk} + \varepsilon_{R,tk}) * t_k] \quad (20)$$

(R_S, R_W: Average radius of the steel casing or the wear layer, t_k: Thickness of the respective insulation layers, k = 1, 2, …)

Inserting (7) in (18), (19) and (20) in compliance with a uniform sign definition for the radial displacements allows to dissolve after the compressive force in the wear layer, the tensile force in the steel casing or the radial compression in the insulation layers (Figure 2).

The assumption of mean normal forces ("rod analogy") naturally represents a simplification compared to the real conditions; however, if the diameter of the construction is much larger than the layer thicknesses, this approach according to the "spring-in-line principle" provides very good approximate results in many lining cases by capturing the relevant parameters of all components.

Conclusions

The described correlations of thermomechanically induced constraint underline the dependence of the force variables on the stiffness of all components of a layered structure. The choice of layer thicknesses, anchor cross-sections and materials therefore represents a criterion for limiting stresses beyond the usual chemical and thermal requirements.

3. Typical behaviour characteristics of refractory linings

Considering the above, it is clear that the shape and design of the structure – curvature dimensions, layer thicknesses, etc. – are of elementary importance for the determination of the force magnitudes and deformations. In the course of thermomechanical design, the "potentials" of all components are to be identified in order to determine their influences realistically.

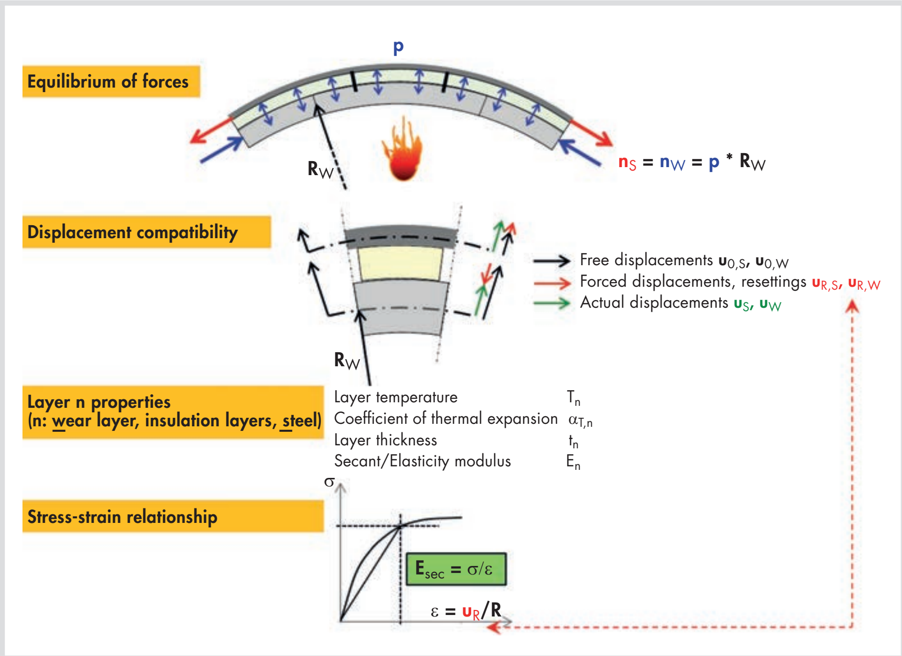

Fig. 2. Mechanical principles for the structural elements' interaction.

As an example, a system section, which comprises different zones of a circulating fluidized bed facility – cylindrical parts of the fluidized bed chamber and the cyclone, the connecting flat-walled duct and a strongly inwardly curved bullnose – is considered. The lining is assumed to be consistent over all areas with the following characteristic properties (see Figure 3a):

- Stiff back-anchored wear layer material without expansion joints or with joints that are closed during operation
- Steel casing reinforced by ribs
- One-piece anchors fixed on both sides*
- Only thermally relevant intermediate layer (very soft insulation compared to anchors)*

The resulting behavioral characteristics can be described as follows (see Figure 3b):

(a) Cylindrical areas

- Outward urge of the front layer
- "Compatible" radial displacement of the entire layer structure to the outside

* Here it is assumed that only the anchors transmit radial compression. This is due to their high stiffness in comparison to the insulation and their own tendency to expand (high α_T). Using the insulation layer as an essential load-bearing element instead would lead to unrealistic results!

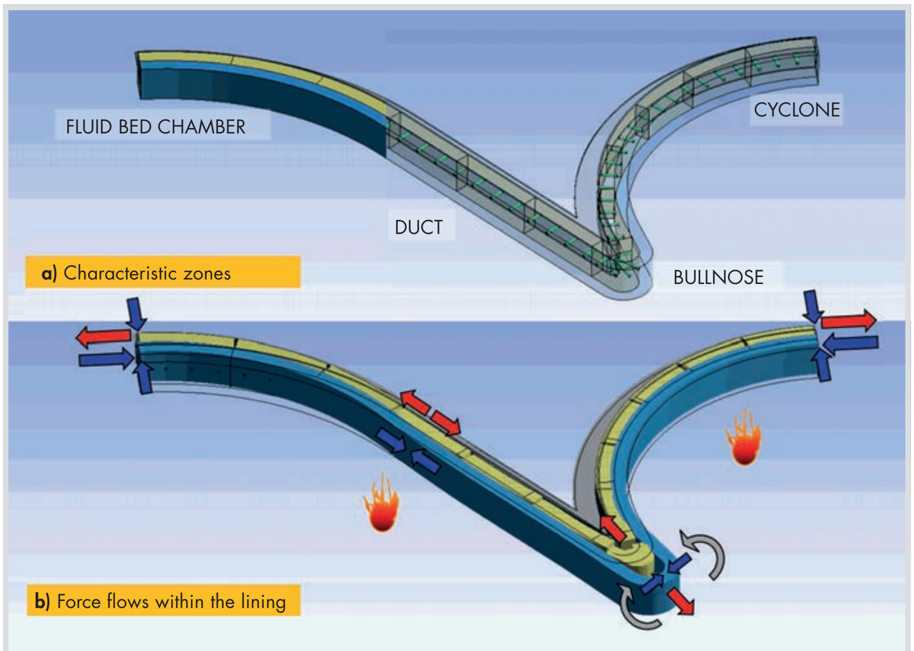

Fig. 3. Different zones result in different behavioural characteristics.

- Radial compression transmitted by the anchors
- Resetting force values primarily dependent on the expansion stiffness of the front layer and the steel casing
- Circumferentially high compressive and tensile forces due to the high stiffness of the wear layer and the rib-reinforced steel casing

(b) Flat-walled duct areas
- Urge of the wear layer along steel casing
- “Compatible” plane displacement of the wear layer relative to the steel casing
- Force coupling between wear layer and steel shell via anchor shear forces
- Force values primarily dependent on the bending stiffness of the anchors
- Compared to the cylindrical areas anchor for anchor decreasing compressive and tensile forces in wear layer and steel shell
- Shear force and bending in anchors

(c) Bullnose
- Inward urge of the wear layer
- “Compatible” rotation and inward displacement of the wear layer
- Force values primarily dependent on the axial stiffness of the anchors
- Bending and low residual compression in wear layer
- Bending in steel casing
- Anchor tension

Beyond these locally very different behavioural characteristics, the mutual influence of these regions must not be ignored; the stiffer the system is in the cylindrical zones – for instance through stiffeners – the more the wear layer pushes in the direction of the bullnose instead of outwards; its compressive stresses in the duct area are in turn co-determined by the stiffness of the bullnose anchors.

Conclusions

The determination of the behavioural characteristics requires, on the one hand, the correct assessment of qualitative force flows, which depend primarily on the design elements themselves and their respective position (for instance, can a specific anchor type transmit all types of forces?); decisive for the force magnitudes, on the other hand, is the integrative interaction of all components – the system stiffness (see Section 2). However, their analytical derivation becomes more complicated with each geometric irregularity; such complex refractory structures can be adequately solved using the finite element method.

4. Structural details and boundary conditions

As has been shown, the stiffness and expansion urge of the individual structural elements and their interaction are the relevant characteristics for a close-to-reality determination of the stresses; consequently, any change in these characteristics affects the result. The following considerations illustrate that supposed “trivialities” can have great effects:

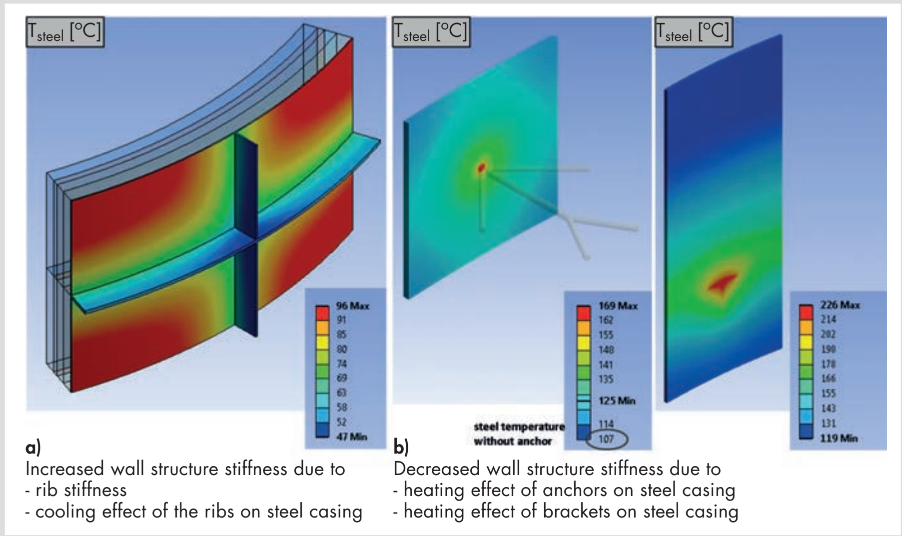

Fig. 4. Changed steel temperatures mean changed stiffness of the entire layer structure.

Stiffening effects

Reinforcing ribs (stiffeners) are usually provided for the strengthening of steel casings, especially in load transfer and transition zones (e.g. cylinder to cone). In addition to this direct structural stiffening, there is a further indirect stiffening effect due to the cooling of the shell (see Figure 4a). This reduces the urge of the steel to expand and as a result counteracts the free expansion of the wear layer with greater resistance, resulting in higher stresses in all components.

Stiffness reducing effects

In contrast to the external stiffeners, typical internal steel components such as anchors and brackets do not contribute to structural stiffening. However, since they constitute heat bridges, thereby increasing the temperature and the expansion urge of the steel casing, they indirectly contribute to a reduction in stiffness of the layer structure with the effect of lower stresses in all components. Figure 4b shows the typical case of a single anchor, which increases the average temperature of the affected steel shell compared to an anchorless one. The influence of brackets, although locally limited, is even higher.

Influence of the changed system stiffness on the behavioural characteristics

The example of a heated layer structure with constant material properties in Figure 5 shows how the stiff and “cold” rib zone of the steel shell (50 °C), the regular area with medium temperature (100 °C) and the “hot” bracket zone (200 °C) affect the radial displacement and compressive stresses of the front layer. The radial displacement in the area of the circumferential ribs is about 70 % compared to the hotter bracket zone, whereas the compressive stresses increase fourfold! This is because the stresses do not correspond to the actual displacements, but to the reset ones, see section 2.

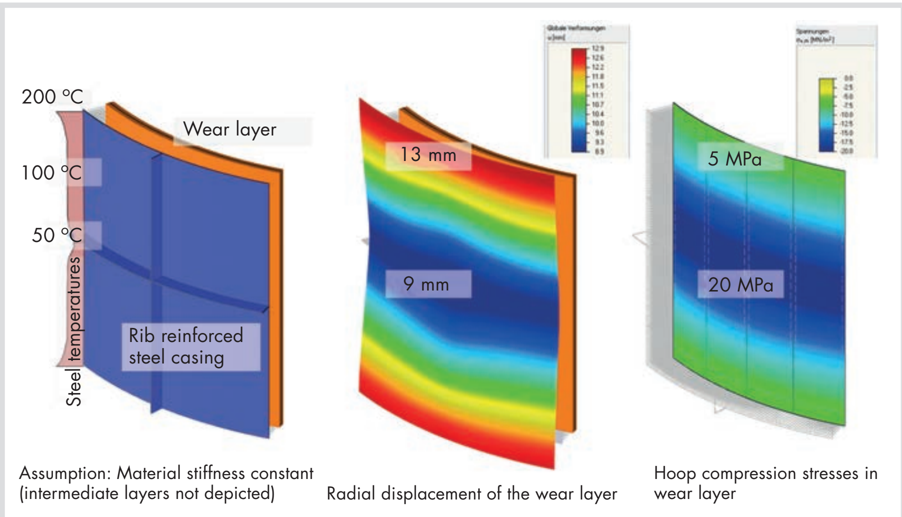

Fig. 5. Influence of the changed system stiffness on the behavioural characteristics.

Conclusions

In order to achieve realistic results, not only the consideration of the structural component stiffness, but also the identification of the prevailing temperature distribution is essential; both have a considerable effect on the computational system stiffness. Cooling effects due to reinforcing ribs and temperature increases due to anchors or brackets result in corresponding increases or decreases in component stresses.

5 Non-linear material behaviour

As with their thermal properties, refractory materials are not only subject to large scattering in terms of their stiffness, but are also dependent on temperature and stress. Depending on the compound of the material, drastic reductions in stiffness can occur under increasing temperatures and/or increasing reset strains. By means of a comparative study of two castables with different alumina contents as the wear layer of a cylindrical fluidized bed furnace with an outer diameter D = 10 m, the differences in the behavioral characteristics are to be pointed out.

System and action assumptions

Under the operating temperatures $T_i \sim 850\,°C$ the considered wear layer is overpressed despite effective expansion joint of 2 ‰ between the concrete slabs. The insulating layers transmit only radial compression, the steel shell is stiffened and cooled by ribs. At the steel there are temperatures of about 50 °C (rib area) to 100 °C (regular area).

Stiffness differences of the wear layer due to material selection

[2] gives stress-strain laws for castables at mean temperatures of 816 °C, which correspond approximately to the described system state. The 60 % Alumina Vibration Castable (“stiff lining”) behaves almost linear-elastically under any compression, whereas the 45 % Alumina Conventional Castable (“soft lining”) exhibits a pronounced plastic behaviour under comparatively low compression values (Figure 6).

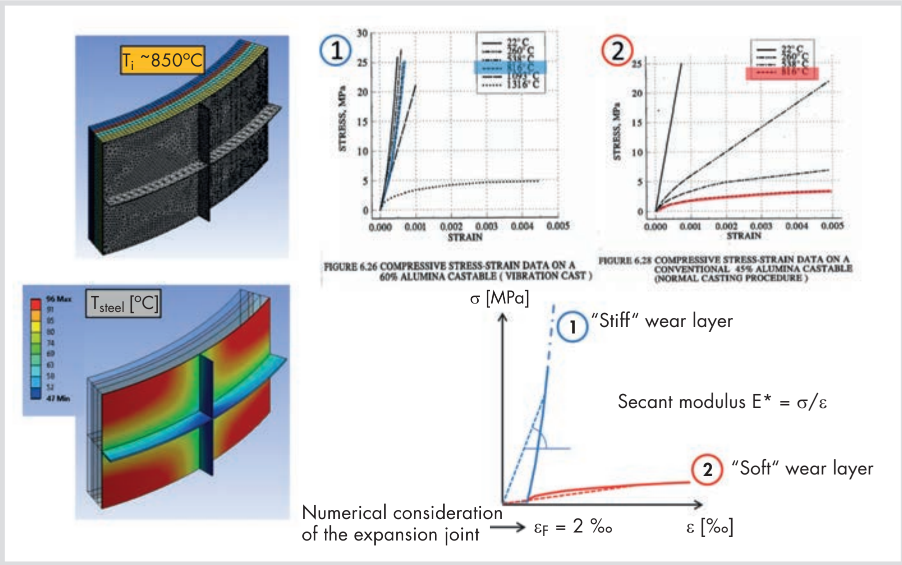

Fig. 6. System and comparison of differently stiff wear layers.

Radial displacements of the wall structure (Figure 7a)

Stiff lining: Most of the radial displacement of the steel shell of more than 20 mm is forced by the urge of the wear layer; the refractory material “dominates” the steel shell, so that even in the area of confinement by the ribs the displacement due to the urge is very large.

Soft lining: The maximum radial displacement corresponds to the free displacement of the steel casing due to its own temperature increase

$u_R = a_T * T * R = 1.2 * 10^{-5} * 100 * 5{,}000 = 6$ mm.

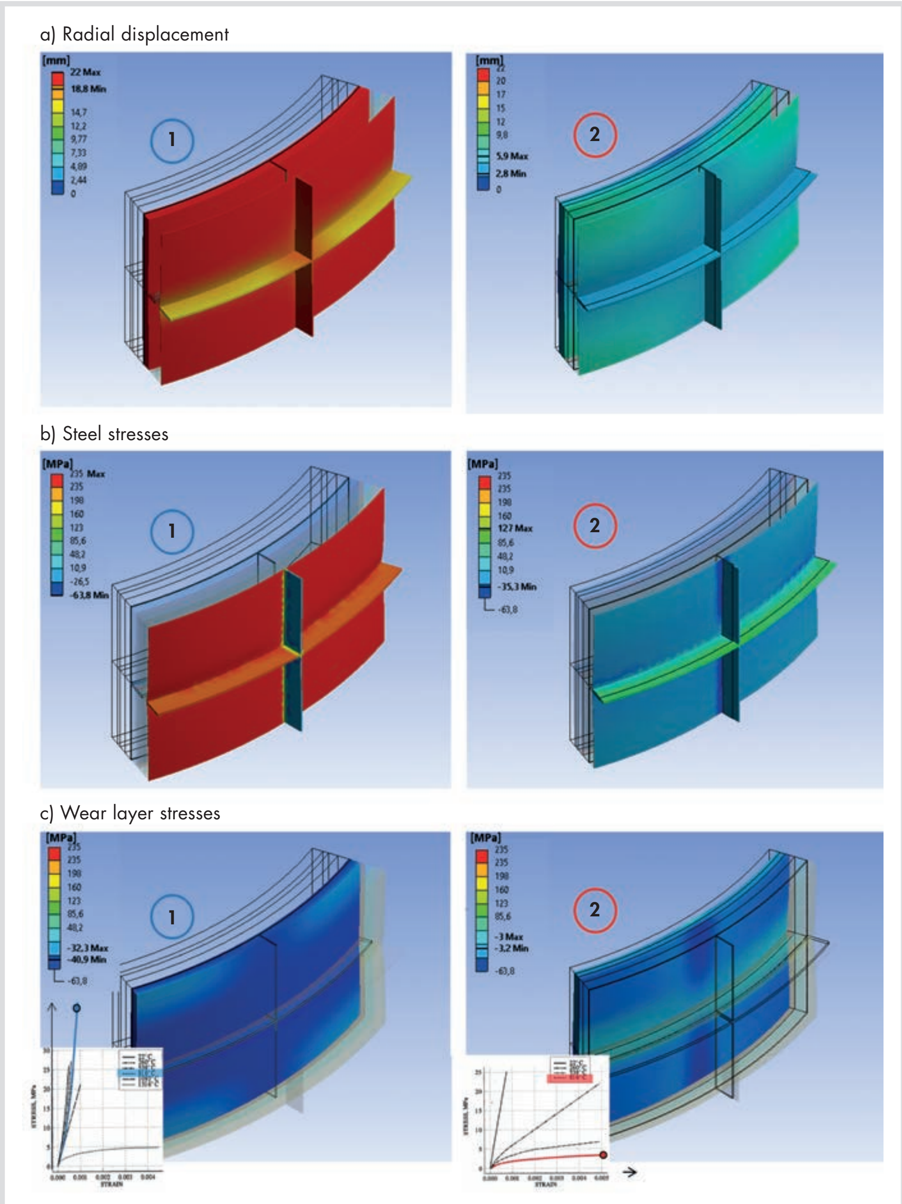

Fig. 7. Behavioural characteristics of the differently stiff wall structures.

In this case the wear layer does not exert any effective urge on the steel shell. The steel “dominates” the refractory lining.

Circumferential stresses

Stiff lining: The high compressive force from the wear layer causes the steel casing to yield. Due to the resulting irreversible enlargement of the shell diameter, open joints in the front layer occur in the cold state (Figure 7b).

Soft lining: The front layer plasticizes under its urge against the stiffer steel mantle. Due to its resulting irreversible contraction, open joints occur in the cold state (Figure 7c).

The described cases thus lead to similar consequences for the lining despite completely different irreversibilities: Open joints and an untight wear layer.

Fig. 8. Result of plasticized material: Lowering of the wear layer in a horizontal cylinder.

Conclusions

The choice of material has a great impact on the system stiffness, in the worst case resulting in permanent deformation of the layers or the steel casing. In reverse, stresses can be limited by knowing the material stiffness in the relevant operating conditions.

6. Thermomechanical design of flat structures and their back anchoring

It is considered common practice to design the anchorage of refractory concrete panels according to the panel weight and the long-term resistance of the anchor steel; in addition, the stress in the concrete is supposed to be minimized by design the panel edges as expansion joints. If this anchor design is strictly adhered to, how can ruptures of anchors be explained? And why does distinctive separation cracking in concrete occur so frequently? (Figure 9)

The reason for this lies in the lack of consideration of the influence of temperature gradients in the slab elements, which are always present – albeit in varying degrees – during the furnace campaign.

The furnace campaign of back-anchored slab elements (Figure 10)

Like any other furnace component, the concrete panel goes through the process of heating or reheating, a period of maximum temperature and the cooling process. Whether the panel reaches its steady state temperature naturally depends on the temperature cycle. What is certain is that, depending on the time of the cycle and depending on the thermal conductivity, specific heat capacity and density of the material, linear or curved temperature distributions will occur over the panel thickness, which will cause it to bulge. The anchors counteract this urge with their spring stiffness $c_A = E^*A/L$ [MN/m] and prevent free bulging. The panel with its bending stiffness EI [MNm²] in turn forces the anchors to be lengthened or shortened: The result is normal forces in the anchors and bending moments in the slab element.

Fig. 9. Anchor ruptures and separation cracks in refractory concrete as a result of hindered slab curvature.

During heating, the positive gradient, i.e. the difference between the hot inner surface and the colder outer surface, will reach its maximum value. The free convex curvature of the panel is hindered by "external constraint", i.e. the central anchors are pulled the most and the external anchors are compressed the most. Accordingly, the positive bending moment also reaches a maximum.**

During regular operation – in this example lasting long enough to reach the steady state temperature – the positive gradient is lower. If, however, the expansion joints to the adjacent panels are overpressed due to the highest mean temperature, this compression on the pre-bent panel results in an increase in the bending moment (II. order moment), which is in balance with the resulting increased compressive and tensile forces of the anchors.

**The transient-related curvature of the temperature distribution has no influence on the forces and the bending moment, but imposes internal stresses which are in equilibrium over the thickness of the panel ("internal constraint"). For the determination of these stresses, see [1]).

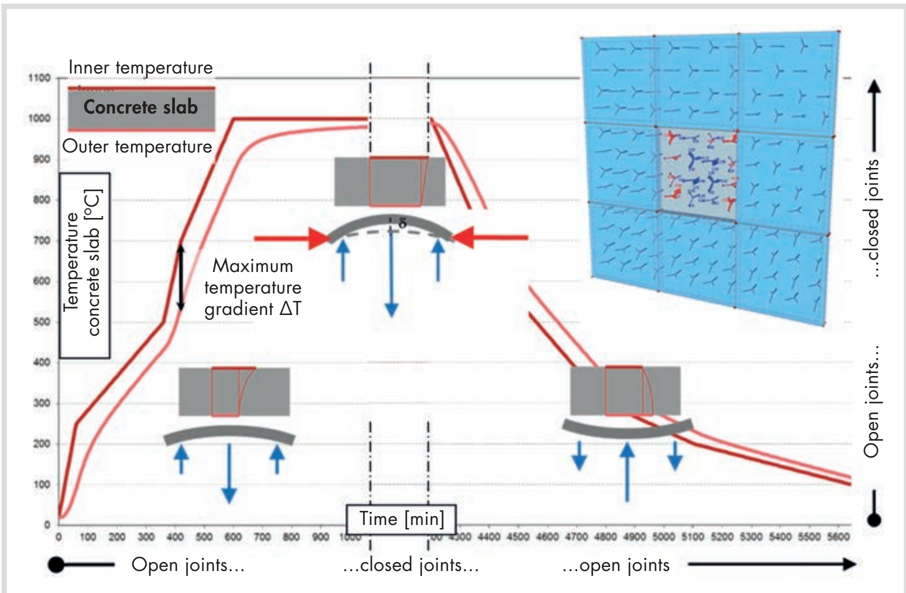

Fig. 10. Furnace cycle of a back anchored concrete panel.

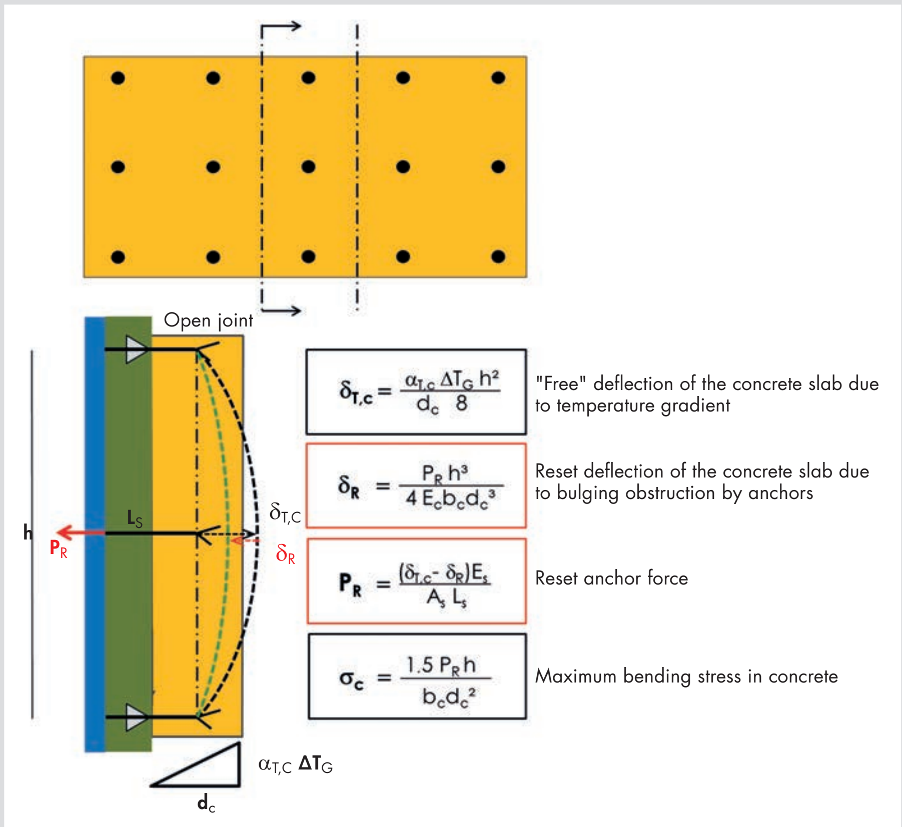

Fig. 11. Computation principle for determining anchor forces and layer stresses.

During cooling, the negative gradient reaches its highest value, the free concave curvature of the panel is hindered by "external constraint", i.e. the central anchors are compressed the most and the external anchors are pulled the most. Accordingly, the negative bending moment also reaches its maximum.**

Computation principle for determining anchor forces and layer stresses (Figure 11)

Based on the consideration of a vertical wall strip cut out of a very wide wall (wall width >> wall height) – the width corresponding to the horizontal anchor spacing – the interaction of the refractory concrete layer with its back-anchoring is shown below; the principle follows the calculation method presented in Section 2 with the correlations of free deformation, system stiffness and resetting described there.

For the sake of simplicity, the compressed edge anchors, which have the same free thermal expansion as the central pulled one, are assumed to be infinitely stiff; this approximation is due to the fact that compression normal to the panel surface can be absorbed by anchors and layers, whereas

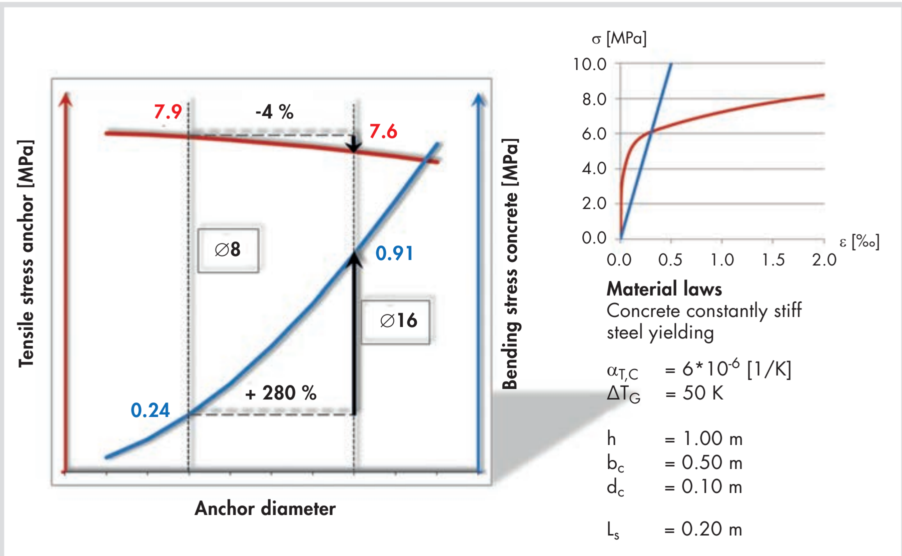

Fig. 12. The use of more powerful anchors does not necessarily bring only advantages!

only the anchors are capable of withstanding tension normal to the panel.

From the data for height, width and thickness of the panel strip, the anchor length and its cross-section as well as the material stiffnesses, the resetting force of the central anchor can be determined and from this, in turn, the bending stress in the concrete panel can be derived.

Against the background that these constraint stresses can be many times the stresses due to dead load, it is tempting to ensure the load-bearing capacity by increasing the anchor cross-sections. This can prove to be counterproductive in that it results in the often observed through cracking of the concrete slabs. While the tensile stress in the anchor hardly drops, the bending stress in the concrete rises drastically. To the same extent as the resistance of the anchor increases, the constraint under which the concrete "suffers" increases due to the higher anchor stiffness (Figure 12).

Conclusions

In order to adequately design plane refractory plates and their anchoring, the thermomechanical effects, above all the bulging hindrance through the anchors, must be taken into account in addition to the dead loads. As in curved systems, the force parameters depend on the deformation urge and the system stiffness; if the component stiffnesses are matched to each other appropriately, the tendency to form separation cracks can be reduced and the anchor rupture avoided.

7. Summary

Every industrial facility with a refractory lining is subject to thermomechanical loads during operation. Constraint stresses occur primarily as a result of hindered thermal expansion and affect not only the refractory layers, but also the anchors and casings by interacting with each other. The type of forces and their magnitudes depend on the system stiffness, which in turn is comprised of the geometry and position of the lining components, their coupling with adjacent components and their material properties. As has been shown, cooling effects, through stiffeners for example, and thermal bridges through anchors, brackets, etc. also contribute to the overall stiffness.

The materials used generally have non-linear properties – depending on both temperature and stress. If the calculation is linear, misinterpretation of results and incorrect dimensioning can be the consequence. In addition, the considerable scattering of refractory materials and the operational imponderables should be taken into account. Here, parametric studies help to verify the results; besides, the lining components can be better balanced and optimised in this way.

Finally, in addition to the thermal and chemical suitability of the materials with regard to their intended application and the largely ensured tightness of the lining, the limitation of stresses should be the primary objective in the design of refractory linings. Using thermomechanical analyses this criterion can be ensured; the possible increase in reliability and durability compared to an experience-based design is also reflected in higher economic efficiency of the furnace.

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