RUPTURE OF THE GIRTH GEAR / KILN SHELL CONNECTION AT AN EXPANDED CLAY FACTORY

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ABSTRACT

This communication concerns the failure of the connection between the toothed crown (girth gear) that transmits movement to kiln shell of the expanded clay factory of Leca Saint Gobain at Avelar, Portugal. The failure consisted on the breakage of 10 out of 12 spring plates (moving links) connecting the toothed crown to the kiln shell. Each spring plate is connected to the girth gear through two welded eyebars. In all of them the fracture started at the sharp corner of a rectangular cut subjected to tensile loads.
A concise reference is made to rotary kilns as used in cement or expanded clay factories, emphasizing their dimensions: in the present case, the girth gear circle pitch diameter is 4680 mm, the module is 26 mm, the shell external diameter is approx. 3,5 m, and the rotating mass may be up to 120000 kg.
The crack surfaces of the eyebars reveal the typical features of fatigue failures. The probable cause of the failure is identified, and the repair foreseen by the company technical staff is discussed and evaluated in the light of IIW recommendations for fatigue loaded weldments of different fatigue classes (FAT) and fillet weld stress analysis.
KEYWORDS: rotary kiln; fatigue failure; spring plate; eyebar; fatigue class (FAT)

INTRODUCTION

The Leca Saint Gobain factory at Avelar possesses two kilns. One was decommissioned in 2011 and therefore the production depends solely upon one kiln, which suffered an unplanned stop on December 18, 2019 due to the failure of most of the spring plates (moving links) connecting the toothed crown (girth gear) to the kiln shell, [1]. Figure 1 shows a general view of the damaged kiln (in background), where it is possible to see the girth gear attended by technical staff.

Figure 1 – Partial view of the kiln that suffered the failures, in the background. In the foreground, another kiln decommissioned since 2011.

Power for rotating the kiln is 160 kW. The kiln rotates at 2,5 rpm always in the same direction, but speed may drop to 2 rpm. The movement is imposed upon the kiln through a pinion driven by a gear reducer (gearbox). The pinion transmits movement to a toothed crown (girth gear) concentric with the kiln. A schematic representation of the girth gear is given in Figure 2, showing also the 12 spring plates (moving links) that allow for thermal expansion of the kiln shell, keeping concentricity while preserving the toothed crown which does not suffer thermal expansion as big as the kiln shell. The toothed crown is composed of two halves, Figure 3. These are from time to time rotated 180 degrees, aiming at balancing wear on both flancs of the teeth. The pinion can also be rotated 180 degrees, but given the advanced wear situation it will be substituted by a new one soon. Figure 4 illustrates the present state of the pinion.
Operation is continuous 24h per day; there are two planned stops per year for maintenance, and no more than 350 days of continuous operation are expected every year. In this context it is interesting to quote Bastier et al., [2] discussing the design of cement kilns: 'La durée de vie des éléments importants du four est calculée en années, sur une base de 300 jours de marche par an, 24 h /24, soit 7200 h.'.
The kiln shell shows some repairs of cracks detected in service. Apparently, no cracks were so far found in the original weldments. Instead, some cracks appeared in the shell plates themselves, probably as a result of (i) ovalization creating cyclic variation of stress, (ii) thickness loss due to internal wear and corrosion, and eventually due to any internal structural features creating stress concentrations. In one case observed, the repair is

simply a weldment deposited along the crack; in other cases, further to closing the crack with a weldment, a patch was welded on the outside surface, see Figure 5.

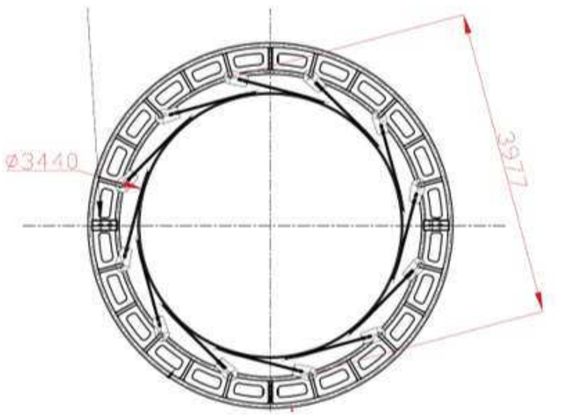


Figure 2 – Schematic representation of the toothed crown and the 12 spring plates.

Figure 3 – Toothed crown (girth gear), composed of two halves; detail showing one of two connections.

Figure 4 - Toothed crown and pinion. The teeth of the pinion show plastic flow of material outside the teeth width; at a lower scale this also existed in the toothed crown but that plastically deformed material was removed during the present stoppage.

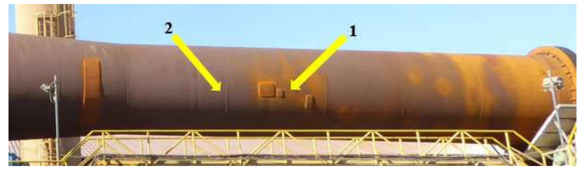


Figure 5 – Detail of Figure 1 showing the kiln shell with welded repair patches (e.g., arrow 1), and a repair consisting of a single weld bead (arrow 2).

The toothed crown transmits movement to the kiln shell via 12 welded 20 mm thick spring plates (moving links) made of St52 steel, Figure 6 a) and b). St52 is a steel designation according to the old DIN 17100 standard, [3], presently S355n according to EN 10025-3, [4]. One end of each spring plate is welded to the external surface of the kiln shell, whereas the other end is linked to a 45 mm diameter pin connected to the toothed crown via two welded auxiliary plates (eyebars), also made of 20 mm thick steel St52. Diameter from toothed crown eyebar center to eyebar center is 3977 mm.

Figure 7 is a sketch of the auxiliary plates (eyebars) mentioned, where it is possible to see the rectangular slot for fitting to the 20 mm thick spring plate. The connection to the spring plate is made with fillet welds along line ‘L’, and the acting force is therefore transmitted through a cross section (section ‘AA’ in Figure 7) that includes two sharp corners with extremely high stress concentration effect and therefore poor fatigue performance. On the plus side, the solution used includes a tapered increase in cross section, favouring a uniform distribution of shear stress in the weldments, see e.g. Moore and Wald [5], page 21.

Figure 6 – Spring plates. a) Zoom of Figure 1, showing the toothed crown and spring plates (identified with arrows), undergoing repair/assembly work by technical staff.

Figure 6 – Spring plates. b) Spring plate (arrow 1) connected to the kiln, but not yet connected to the toothed crown pins (the location of the pins is shown with arrow 2).

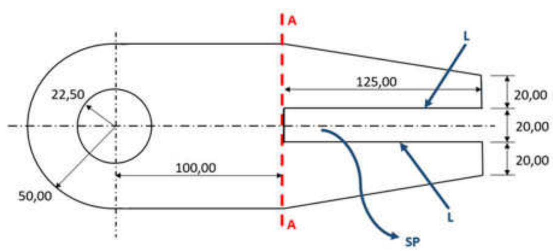


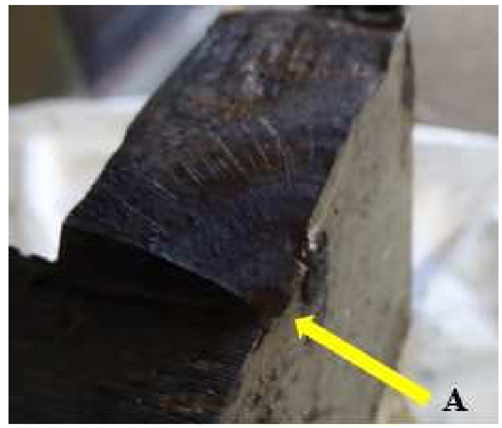
Figure 7 – Sketch of an eyebar for connecting the spring plate to the toothed crown pin. Each spring plate has two such eyebars, fillet welded along 'L' to the spring plate ('SP') that fits into the 20mm thick slot represented. The fracture of these auxiliary plates occurred always along the path schematically indicated by the interrupted line 'AA'.

THE FAILURE

On December 18, 2019 it was found that 10 spring plates suffered complete rupture, always occurring in the welded auxiliary plates (eyebars) just mentioned, implying that 20 eyebars were found broken. The rupture was of similar nature on the broken eyebars: cracks developed along the path represented by the interrupted line 'AA' of Figure 7.

Figure 8 gives one example illustrating the behaviour of all fractured auxiliary plates (eyebars). In this figure, the crack is a 'textbook case' of a fatigue crack initiated at corners of a rectangular slot, and growing as a quarter of ellipse in each side of the rectangular slot.

a) crack surface (represented by interrupted line AA in previous Figure 7).



b) Detail of the crack propagation, starting at corner.
Figure 8 – Crack surface of one of the broken eyebars.

Although the cracks observed displayed approximately the same features, the extension of the fatigue crack region seemed not to be the same in all of them. This is consistent with a scenario where not all of them suffered rupture at the same time, but instead one suffered rupture first and its load share was then transferred to the surviving plates, and so on and so forth.

After the failure, it was verified that although some of the 45 mm diameter pins could be easily extracted from the toothed crown eyebars, others suffered plastic deformation making disassembling more difficult; still others had to be physically destroyed in order to allow disassembling. This means that the damage was far from uniform along the 10 broken spring plates, which is consistent with the observation of the previous paragraph.

ANTECEDENTS AND DETAILS

According to the company internal memo., [1], the kiln was running smoothly and there was no variation in power consumption meaning that there was no major stress variation recorded prior to the breakdown. No direct antecedent could therefore be readily traced. However, the power transmission mechanism suffered a major failure one year ago, when a tooth of the gear reducer (gearbox) broke, and consequently the gearbox was destroyed. Given the huge inertia of the operating kiln (when loaded, its mass is up to 120000 kg), a sudden stop imposed upon it will create very high impact loads upon the pinion, girth gear and spring plates.

Immediately after that failure one year ago, the major focus of attention was the toothed crown and pinion, found to be in operating conditions, whereas the spring plates were only the object of a cursory exam. Nevertheless, during that impact loading, possibly small cracks initiated at the corners of some of the rectangular slots in the eyebars, given the extremely high stress concentration associated to rectangular cuts. And provided the stress intensity factor range is above the threshold value for propagation, once cracks initiate propagation inevitably follows, until final rupture when the remaining cross section is unable to transmit the applied force either because of plastic collapse or because of toughness exhaustion. With P – power, ω- rotational speed, n – rotations per minute, M_t – torque, and from P=Mω with ω=2πn/60 and P=160kW, n=2 rpm, it follows that Mt=764kNm . The radius corresponding of the external surface of the kiln in the relevant location is 3440/2 mm, and there are 12 spring plates, therefore each one will be subjected to a tensile load F of approximately

$$M_t = 12 \times F \times (3,44/2) = 764000 \text{ Nm} \rightarrow F = 37,0 \text{ kN} \quad (1)$$

The section along which the crack propagated is approximately $(100-20) \times 20 \text{ mm}^2 = 1,6 \times 10^{-3} \text{ m}^2$ per eyebar, and therefore the nominal stress in the critical cross section is

$$\sigma = 37/2 \times 1,6 \times 10^{-3} \text{ kN/m}^2 = 11,6 \text{ MPa} \quad (2)$$

A factor 2 was then applied to account for irregularities and shock, leading to the value $\sigma = 23,1$ MPa .

THE REPAIR AND CONCLUDING REMARKS

The new auxiliary plates designed by Leca / Avelar no longer display the rectangular slot, but instead they show a semi-circular slot, see Figure 9. This will dramatically reduce the stress concentration effect implied in the previous failed design, improving the fatigue life of this connection

Figure 9 – New eyebars designed by Leca / Avelar

According to Hobbacher, [6], a weld detail such as the present one may be classified as fatigue class (FAT) 50 (see Hobbacher, [6], page 68, structural detail number 612). For this fatigue class, a life of 10^7 is expected for a nominal stress range of approximately 29 MPa, approximately 1,3 times higher than the present estimated nominal stress of 23,1 MPa, and infinite life for stresses below, see S-N curve in Figure 10. In this context, it is convenient to evaluate the number of rotations involved in the present service: at 2 rpm, working an estimated 350 days /year, this involves approximately 106 rotations per year, or 2×10^7 rotations in 20 years.

While these considerations indicate fatigue strength to cope with a 23,1 MPa stress range, the real service conditions are likely to be rather less severe, since the stress range per rotation in routine service is likely to be rather smaller (in service, load variation per rotation is likely to vary little).

Since load is transmitted to the spring plate through 4 fillet welds per eyebar, and these fillet welds work in shear along the throat area, a matter of interest is to evaluate the length l of the necessary weldments.

We saw above that under normal continuous service $F = 37,0$ kN . Using a classical solution for shear loading in the throat of fillet welds, (throat length *a*), see e.g. chapt. 5 of Ballio and Mazollani, [7]:

$$t_{//} = F/4al \quad (3)$$

$$\sigma_{eq} = \sqrt{1,8(F/4al)^2} \quad \text{or} \quad \sigma_{eq} = \sqrt{3(F/4al)^2} \quad (4)$$

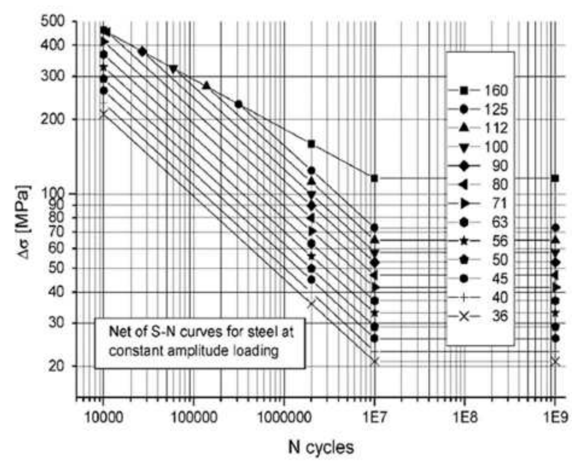


Figure 10 - Fatigue resistance S-N curves for steel, normal stress, standard applications (Figure (3.2)-1 of Hobbacher, 2008).

Bearing in mind that the material used is steel St52 with yield strength at least 345 MPa, using fillet welds with for example throat *a*=4 mm, a safety coefficient 1,5 on yield stress, and the factor 3 in expression (4),

$$F/4al = \alpha\left[(2/3)\sigma_{yield}/\sqrt{3}\right]$$

where α is a throat dependent coefficient taken as, (decreto-lei 211/86, [8], page 60),

$$\alpha = 0,8\left(1+\left(1/a\right)\right) \quad (5)$$

and using again a magnification of 2 accounting for irregularities and shock, we get for l :

$$\frac{37000}{4\times4\times l} = 1\times\frac{\frac{2}{3}345}{\sqrt{3}} \rightarrow l = 17,4 \text{ mm} \quad (6)$$
$$ie,\quad l = 18 \text{ mm}$$

Since long ago it is common practice not to consider a length 'a' in the beginning and end of the weldment (e.g. Vallini, [9], page 200); then, if a=4mm we have a 'calculated' minimum length l=18+2×4=26mm . It is also recommended that length of fillet welds should be higher that 40mm, and if discontinuous fillet welds are chosen, the minimum length per weldment should be 4 times thickness, (decreto-lei 211/86, [8], page 25).

The considerations above do not account for the very occasional increase in load due to start from rest. But very occasionally there are stoppages, and the return to normal service imposes a transient situation of higher loads. With a weldment of length l=120mm which is feasible in these components, the maximum load admissible for the very occasional start will be (120-2×4)/18=6.2 times higher than the routine service value of 37 kN, which seems to be an adequate margin. In the choice of length l attention should be given to the IIW recommendation 'Weld terminations more than 10 mm from main plate edge', see Hobbacher, [6], page 68.

An increase in fatigue performance is expected if the weldments are subjected to treatments as pneumatic hammer peening, or shot peening, Maddox, [10], Moore and Booth, [11], or MacDonald, [12].

Finally, it is recommended to periodically inspect the critical regions of the welded connection, using liquid penetrant testing, ultrasound inspection or other suitable techniques. This should be incorporated in the maintenance plan of the equipment. Such matters are discussed e.g. by Stamboliska et al., [13], dealing in detail with rotary kiln maintenance problems.

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