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Temperature-initiated buckling phenomena in stainless steel flue gas liners of double-skin chimneys

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Abstract: Buckling damage in stainless steel liners of double-skin steel chimneys have repeatedly been detected. Four case studies are presented. The main cause for these shell buckling phenomena are “thermal imperfections“ in the form of temperature strands.

1. INTRODUCTION

Free-standing steel chimneys for high temperature flue gases in modern multi-purpose heating power plants are usually constructed as double-skin chimneys with an outer structural shell as a windshield and an inner liner made of stainless austenitic steel . The liner is a long cylindrical shell either supported at the base or (less often) hung at the top. It is insulated on its outer surface in order to protect the structural shell from getting hot, and it is laterally guided against the structural shell by means of special devices, either at the top or additionally at intermediate locations.

In recent years several local buckling damage in such liners have become known. Although, at first glance, representing a serviceability problem rather than an imminent safety problem, the situation changes once the liner becomes pervious because of cracks at excessively folded local buckles. In this case, the high temperature gas would gain access to the inner surface of the structural shell creating a serious safety problem. Therefore, the damaged liners must be repaired in any case, and - even more important - know-how should be developed on how to avoid the buckling damage by means of a proper design. This paper presents the authors' knowledge about these shell buckling phenomena, as aquired on the occasion of some recent case studies and expertises.

2. OPERATIONAL AND CONSTRUCTIONAL ASPECTS

An important feature of modern natural gas power plants is their optimal energy efficiency. In a first process stage, gas turbines produce electricity, eventually combined with succeeding steam turbines. This first stage emits hot flue gas with temperatures up to 550°C. In a second process stage, the hot gas is used to produce heat for urban or industrial purposes in a waste-heat boiler. After this second stage, the flue gas has temperatures of around 100°C (called “cool“ in the following). However, there are periods in the operation of such power plants where the hot flue gas has to be released directly into the air, bypassing the waste-heat boiler, e.g. when no heat is needed.

The logical consequence would be two chimneys, one for the hot and one for the cool flue gas. Both of them would, because of corrosion reasons, require stainless steel liners. It suggests itself to combine the two functions into one single chimney in order to reduce the building costs, and also to minimize the architectural impact on the urban appearance. But that leads inevitably to the problems which are the subject of this paper: Mixed gas situations are unavoidable, either for a short time when switching from one operation type to the other, or over longer periods under a planned mixed operation.

It turned out to be impossible to regulate the gas mixing process in a manner that makes the liner tube heat up and cool down perfectly uniformly, i.e. only extending vertically and radially, but without bending. There will always be minor “temperature strands“ which result in temperature differences between opposite sides of the liner wall. They may be looked at as “thermal imperfections“. The Structural Eurocode for chimneys [1] mentions them as one of the possible actions on chimney structures. And the future European Standard dealing specifically with chimney steel liners [2] will give detailed rules for such thermal effects.

The constructional task for an engineer designing a steel liner is to develop a structural form which on the one hand provides the primary duct function, but on the other hand avoids buckling damage by unavoidable thermal effects.

3. CASE STUDIES

3.1 General

Table 1 gives the technical data and the acting stress over buckling stress ratios under self weight of four base supported steel chimney liners in which buckling during operation was observed. The material properties E_0 and $R_{p0.2}$ at nominal operating temperature T have been taken from EN 10088. σ_{xRk}^* denotes the characteristic value of the axial buckling stress when introducing E_0 and $R_{p0.2}$ as characteristic values E_k and f_{yk} into the buckling design procedure of the Shell Eurocode [3]. According to [4], σ_{xRk}^* has to be reduced to σ_{xRk} in order to cover the nonlinear stress-strain-behaviour of the austenitic steels. The last line of table 1 gives the ratios of the acting compressive axial stress under self weight at the support over the characteristic buckling stress, both without any safety factors. With this ratio being 1, buckling under self weight alone would be probable. With regard to the fabrication tolerance quality classes, it is supposed by the authors that these rather thin-walled, partially site-welded shells tend to class C rather than class B.

Table 1. Basic data of the four liner cases

Chimney No.		**A**	**B**	**C**	**D**
Technical data	H [m]	67.0	57.5	24.5	60.0
	d [mm]	6200	4500	2900	6300
	t	8	4	2	4
	r/t	388	563	725	788
	T [°C]	515	515	550	550
	Steel No.	1.4561	1.4561	1.4571	1.4561
	$R_{p0,2}$ [Mpa]	99.4	99.4	127.0	98
	E_0 [Gpa]	164	164	161.5	161.5
Acting stress	σ_{xgk} [Mpa]	6.5	7.0	3.5	7.5
Characteristic buckling stress acc. to ENV1993-1-6	σ_{xRc} [Mpa]	255.7	176.2	134.8	124
	λ_x	0.623	0.571	0.971	0.889
	α_x 1)	0.263 – 0.173	0.224 – 0.142	0.198 – 0.123	0.191 – 0.117
	χ	0.585 – 0.446	0.397 – 0.252	0.210 – 0.130	0.242 – 0.148
	σ_{xRk}^* [Mpa]	58.1 – 44.3	39.5 – 25.0	26.7 – 16.5	23.7 – 14.5
Stainless steel reduction [ ]	ψ	0.769	0.750	0.892	0.824
	σ_{xRk} [Mpa]	44.7 – 34.1	29.6 – 18.8	23.8 – 14.7	19.5 – 11.9
Utiliz. ratio	$\sigma_{xgk} / \sigma_{xRk}$	0.15 – 0.19	0.24 – 0.37	0.15 – 0.24	0.38 – 0.63

1) Fabrication tolerance classes B to C

The four liners are supported and laterally guided by different constructional methods. Figure 1 shows schematically their structural systems, together with the flue gas entry situations which are also quite different. However, all of them represented, looked at as vertical tubular beams, statically indeterminate systems. The four cases are now discussed individually.

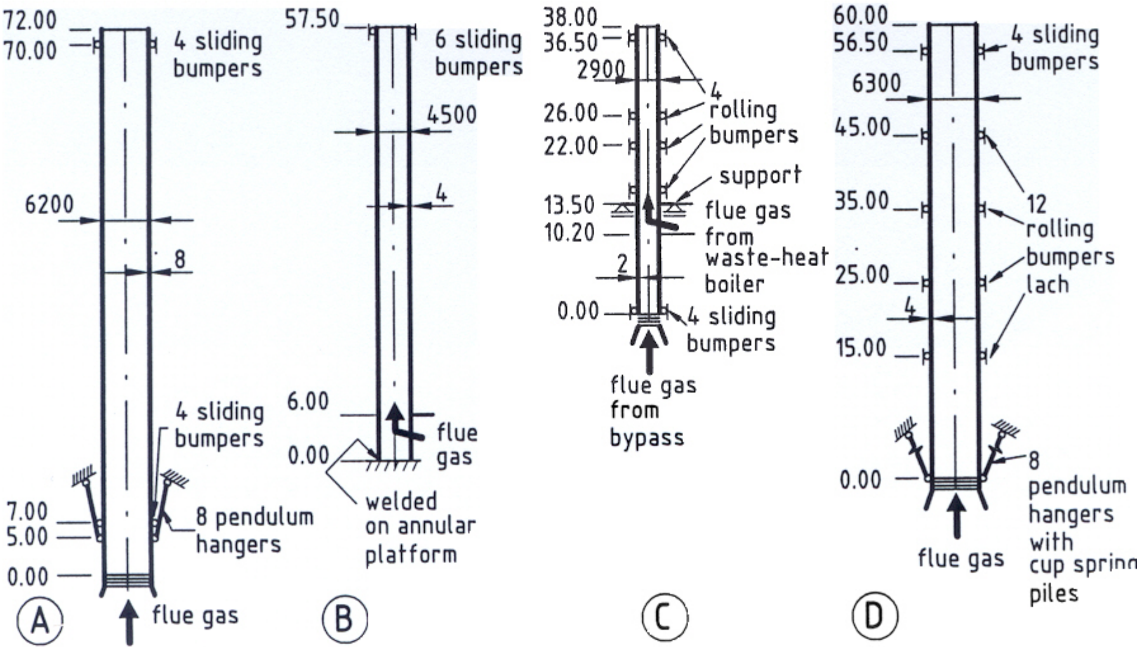

Fig. 1. Systems of the four liner cases

3.2 Liner case A

In this chimney (see Fig. 1A) both of the two flue gases, the hot one from the bypass and the “cool“ one from the waste-heat boiler, enter the liner concentrically from below. During combined operation, they are mixed by means of special baffle devices before entering the liner. It was therefore expected by the design engineers that heating up and cooling down of the liner take place in a uniform manner. None the less, the damage described hereafter occurred. Obviously there were still unavoidable temperature strands in the gas flow which yielded temperature differences between opposite sides of the liner tube.

Damage was found in the supported region of the liner. They included column buckling (!) and plastic overtensioning, respectively, of opposite hanger tie rods, a large inward buckle at a circumferential weld above the overtensioned hangers, and out-of-effectiveness of the sliding guides above the supported section. Fig. 2 demonstrates the damage process: The hanger-supported section represented for the vertical tubular beam a full bending restraint (Fig. 2b). The temperature difference between opposite liner walls produced a foot bending moment M_E. An elementary analysis shows that an assumed linear gradient ΔT across the diameter (see Fig. 2a) having an order of magnitude as small as 15K and decreasing to zero at the top of the liner would cause the observed damage (phase 1). For further increase of ΔT the statical system acted determinately (Fig. 2a); the tube could now deform unrestrained within the limits of the ventilated space between structural shell and liner (phase 2). The lower sliding bumpers then lost their horizontally supporting effect (can not be deepened here), and the tube could deform even more (phase 3).

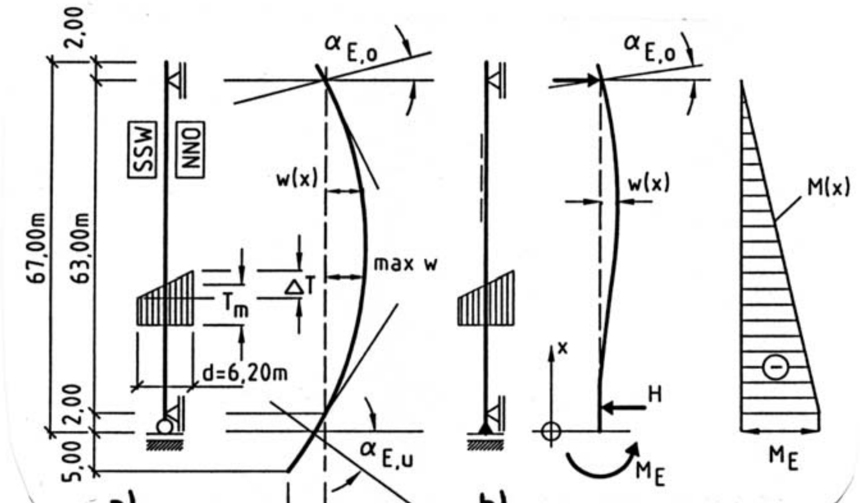

Fig 2. Statical systems of the liner A as a tubular beam

In the course of the investigation after the damage occurred it could be proved by video inspection of the ventilated space from the top of the chimney that no serious pressing contact between the outer surface of the liner insulation and the inner surface of the structural shell had taken place. Therefore the remedial measures could be restricted to the necessary repairs and - the main step - to reconstructing the liner support by including cup spring piles between the hangers and their bearings. That lead to the statically determinate beam system of Fig. 2a from the very beginning. The repaired chimney has now been operated since five years without any further trouble. The case has been reported in more detail by the first author in [5].

3.3 Liner case B

This liner (see Fig. 1B) is, as far as the statical tubular beam system is concerned, quite similar to case A. The two flue gases are also mixed by special devices before entering the liner, and the liner is also bending-restrained at its support and has only one lateral guide at the very top. However, contrary to case A, the duct entry is sidewards through a 6m high opening in the liner wall, and the base support is realized by simply welding the lower end, just below the duct entry, continuously along its circumference to an annular resting platform which is carried by brackets welded to the structural shell.

Some medium size buckles were found neighbouring close to the duct entry after the first testing operation under mixed flue gas conditions. Their inward depths were 10mm on average, their shapes were typical for local shell buckling modes under axial membrane compressive stresses. An elementary buckling analysis showed that a temperature gradient across the diameter of ΔT = ca. 20-30K would be enough to produce the necessary tubular bending moment M_E for this local buckling. With these buckles present, the liner would behave as a statically determinate tubular beam system (see Fig. 2a); one could say that the liner would have produced its wanted “hinge“ itself. After another four months testing operation period, the buckles had not enlarged. Obviously the flue gas mixing devices are in this case efficient enough to keep the unavoidable temperature strands down to the mentioned level. It was decided to leave the buckles in the wall and to check their depths after every heating period: As long as they do not enlarge they are not a problem from the standpoint of safety.

3.4 Liner case C

This is the only one of the four cases where the acting temperature gradient ΔT did not have the character of a “thermal imperfection“ but was a logical consequence of the operational design (see Fig. 1C). When, after a bypass operation period, switching to heating operation, the uniformly hot liner is directly acted upon by the cool waste-heat boiler gas from the side. This causes a rather high, quasi well-defined temperature gradient ΔT. It produced in fact two heavily buckled regions in the liner wall - just above the vertical support and just below the second lateral rolling guides - and minor buckles at the third lateral guides. Considering the threefold statically indeterminate system and the probable decrease of ΔT towards the top, the observed buckling configuration is logical.

The essential feature of the proposed remedial measures is to make the liner a statically determinate tubular system: by installing two corrugated plate compensators with low angular stiffness at the positions of the buckling damage which provides the liner with its “wanted“ hinges, and by leaving out the upper one of the two intermediate rolling bumper assemblies.

3.5 Liner case D

The lower end of this liner (see Fig. 1D) is supported by a rim of pendulum hangers with interposed cup spring piles - a technique that has proved to be a reasonable way to avoid tubular bending restraint at the base support (see case A). As a measure to avoid also lateral restraint at the vertically supported section, the first lateral guidance is located as high as 15m above the lower end. On the other hand, four further equidistant rolling bumper assemblies provided rather tight guidance for the upper three quarters of the liner. The assumed temperature configuration included a conservatively large lateral temperature gradient ΔT = 300K at the gas entry, but an unconservatively optimistic zero gradient from the first lateral guides on.

A number of typical axial compression buckles were found, rather irregularly distributed over the lower third of the liner. It is supposed that small temperature strands (15K would be enough!), together with eventual radial restraint at the rolling bumpers, and in combination with the unusually high self weight utilization (it amounts to 40 to 60% of the buckling stress, see Table 1), caused the severe buckling damages. To the knowledge of the authors, the liner was completely replaced by a considerably thicker structure.

4 CONCLUSIONS

(4.1) When designing the inner liner of a double-skin chimney which serves for flue gases with different temperatures, and where - either planned or accidentally - the differently tempered gases may mix over a more or less short period, thermal imperfections in the gas flow which produce lateral temperature gradients across the diameter have to be included in the design process.

(4.2) The liner should - looked at as a vertical tubular beam system - be made statically determinate in order to avoid local buckling damage from temperature gradients.

(4.3) When following the beforementioned advice, the ventilated space between liner and structural shell must be chosen large enough to allow for the liner’s lateral deflections from the temperature gradients, without damage of its insulation from being pressed against the inner surface of the structural shell.

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