Use of FRP in flue gas desulfurization applications

with temperatures up to 300°C

by Cor Rensen, Plasticon Composites

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1 Executive Summary

This document provides general information with regards to the design of a Fiber Reinforced Plastic (FRP) Chimney liner. An explanatory of the main parameters is provided to facilitate the readability of this document. A detailed explanation has been given as to how the loads on the Chimney liner are calculated through FEA analysis and how a chimney liner will be configurated to meet the specified requirements. As a conclusion Plasticon provides documented proof that the specified Chimney liner will:

- have a service life of 50 years
- resist flue gas with temperatures of 60/150 °C during decades.
- resist a short term (30 minutes) excursion temperature of 300°C without permanent damaging the laminate structure, shape or corrosion resistance.
- as proven by comparable case histories, the calculations and the FEA, the up to 300 °C requirement poses no issues for the FRP liners in the Sangaji project.

2 Introduction

2.1 Plasticon

FRP, Fiber Reinforced Plastic, is used as a construction material for tanks and apparatus since the 1950's. Plasticon Composite, established in 1956, was one of the first FRP companies in West-Europe. Today we serve the worldwide chemical and power industry with FRP tanks, apparatus and stacks and stack liners..

2.2 Plasticon and the FGD market

Increasing concern about the environmental health has prompted governments and power plant owners to reconsider the way flue gas is released into the environment. Since the 1980's hundreds of large diameter b(flue)gas scrubbers, ducts and stacks were and still are built in FRP for cleaning and transport of gasses, emitted by coal fired power plants but also waste incineration plants.

Nowadays the use of FRP is no longer limited by size, flow, process temperatures or corrosion resistance. The continuous development of raw materials, production techniques and engineering over the past 40 years enabled a vast insight in FRP and FRP became the material of choice replacing inferior and/or more expensive materials such as stainless steel, coatings and borosilicate blocks.

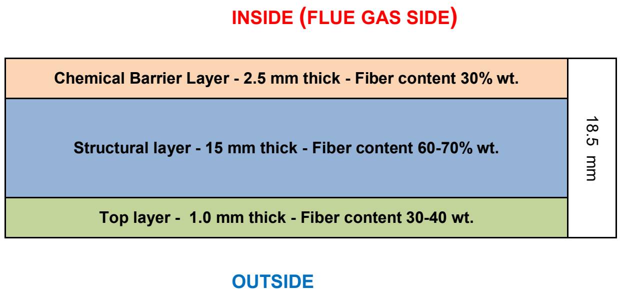
This report will give an overview of the state-of-the-art materials and design for the use of FRP in FGD installation with long term gas temperatures up to a 150°C and occasional temperature peaks up to 300°C.

3 Materials

3.1 Laminates

A laminate is a composite material built-up from a polymer matrix reinforced with glass fibers. The type and percentage of glass fibers varies from 30% wt. up to 70% wt. depending on the functionality of a layer.

A typical laminate built-up used in a FGD environment is shown below.



Note: Fiber content 30% wt. means, 30% of the weight is in glass, 70% of the weight is in resin.

3.2 Glass materials

Different types of technical glass roving's and fabrics are available on the market but for FGD applications E-CR glass is the industry standard due to its excellent performance in corrosive environments, such as the ones found in FGD applications. Requirements for the E-CR glass fibers are specified in the EN 13121-1. It is recommended that the owner specifies the use of E-CR glass over other types of glass.

Depending on the design requirements, different types of glass reinforcements will be used to build up a laminate. The most common types of glass used for FGD applications are:

Veil	a so called non-woven of 30 gr/m² made of C-glass, E-CR-glass or Nexus (synthetic).
CSM	a machine produced Chopped Strand Mat existing from randomly orientated E-CR fibers with a mass of 450 gr/m².
SPM	a Spray Mat applied by use of a chopper feed by E-CR rovings strands. Randomly orientated fibers with a mass of 450 gr/m².
BD-fabric	a Bi-Directional woven fabric consisting of E-CR glass with a mass of 800 gr/m² providing strength in x-y direction.
UD-fabric	a Uni-Directional woven fabric consisting of E-CR glass with a mass of 500 gr/m² providing strength in x direction.
Roving	a filament winding E-CR Roving of 2400 tex and a mass of 960 gr/m² providing strength in circumferential direction.

3.3 Resins

Different types of resins are available on the market. For FGD applications often Epoxy Vinyl Ester resins are used. The minimum properties of those resins are specified in the EN13121-1 code.

The resin choice is the most important aspect of a FRP design. The resin within a laminate provides the matrix for strength and stability but is also essential for the excellent corrosive resistant properties.

In a FRP construction different resins can be used to provide specific properties to a specific layer. The CBL for example can be made from a relatively elastic resin.

The resin choice for the structural layer mainly determines the allowable temperature within a stack liner. For FGD applications with temperatures up to a 100°C a so-called Bisphenol-A resin can be used. For FGD applications with (by-pass) temperatures above 100°C a Novolac-Epoxy is used due to its higher temperature resistance. Both types are also known under the collective name “*Vinylester Resins*”

The history of Vinylester resins in FGD applications goes back to the 80’s of the past century. Dozens of documented case histories are available from the resin manufacturers. Only reputable resin manufactures that such have proven history should be a qualified supplier such as Ashland, AOC and Reichold. In addition, it is important that the owner specifies the use of resins that are proven for similar operating and excursions conditions and request such confirmation in writing from the resin manufacturer.

The final resin choice is always depending on the composition of the flue gas and the temperature range of the FGD’s process. In all cases the resin supplier will need to confirm in writing the suitability of a resin for a specific application.

4 Construction

4.1 Laminate built-up of the liner wall

The total wall thickness of a flue gas liner can be split up in 3 different areas, each having their own function.

Chemical Barrier Layer (CBL):	layers which protect the structural layers against influences from the inside flue gas
Structural layer (SL):	layers carrying the loads
Top layer:	layer protecting the SL against influences from the outside

4.2 The chemical barrier layer

The function of the chemical barrier layer (CBL) is to protect the SL against the corrosive environment inside the liner. The CBL has no structural function and is not considered as load carrying element in the structural design. The CBL can be made from a different resin then the SL. The 2.5 mm CBL is built-up as follow.

The glass reinforcement in the CBL is randomly oriented and therefore properties are more or less isotropy. If needed the CBL can be executed with a carbon veil to discharge static electricity generated by the gas flow.

The transition between the CBL and the SL is very important. The bounding between the CBL and the SL should be optimal to prevent debounding. Therefore, it is mandatory to produce this transition wet-in-wet. This means by use of a technique where the CBL and SL are brought directly after each other and before the resin starts to polymerize. Beside an optimal bounding the technique also guarantees a gradual increase of the fiber content between CBL and SL. As a result of that interlaminar thermal stresses are minimalized.

4.3 Structural layer (SL)

The function of the SL is to give the construction sufficient strength and stability against the loads from the process and/or the interface with the concrete chimney. The SL is mainly built up from Roving and UD-fabrics.

Within the composite matrix, the glass fibers absorb the load and give strength and stiffness to the construction. By applying different amounts of fiber per main stress direction the mechanical properties of the laminate can be influenced per stress direction. For pressure vessels for example a 2:1 ratio is optimal due to the difference in stress between circumferential and longitudinal direction.

The possibility to influence the amount of glass fiber per stress direction, to add stiffeners and the low density of the GRP give the overall construction an excellent mass/strength/stiffness ratio compared to concrete or steel linings.

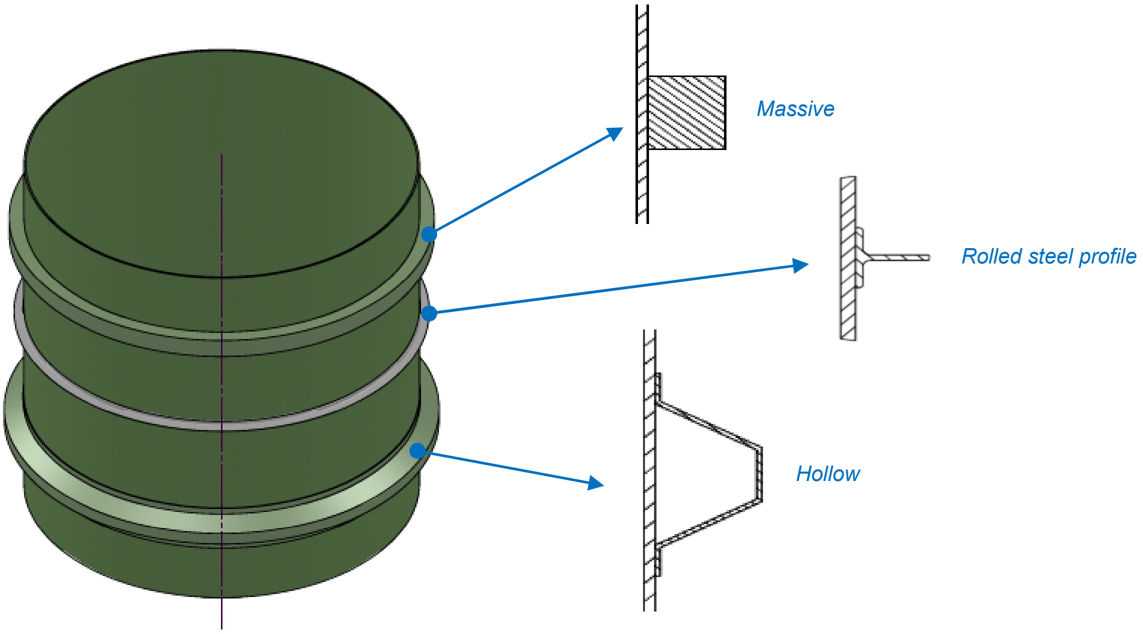
4.4 The top layer.

The function of the top layer is to protect the SL against influence from the outside. This includes the addition of a UV-inhibitor to the resin so that when the laminate is cured there will be no damage from UV radiation. In addition,it is possible to give the product a color (environment, UV-radiation etc.) and the possibility to give the product a color. However this is typically only for aesthetic reasons and not recommended if not exposed as it limits visual Quality Control.

The thickness and exact built-up is depending on the environment where the liner is installed.

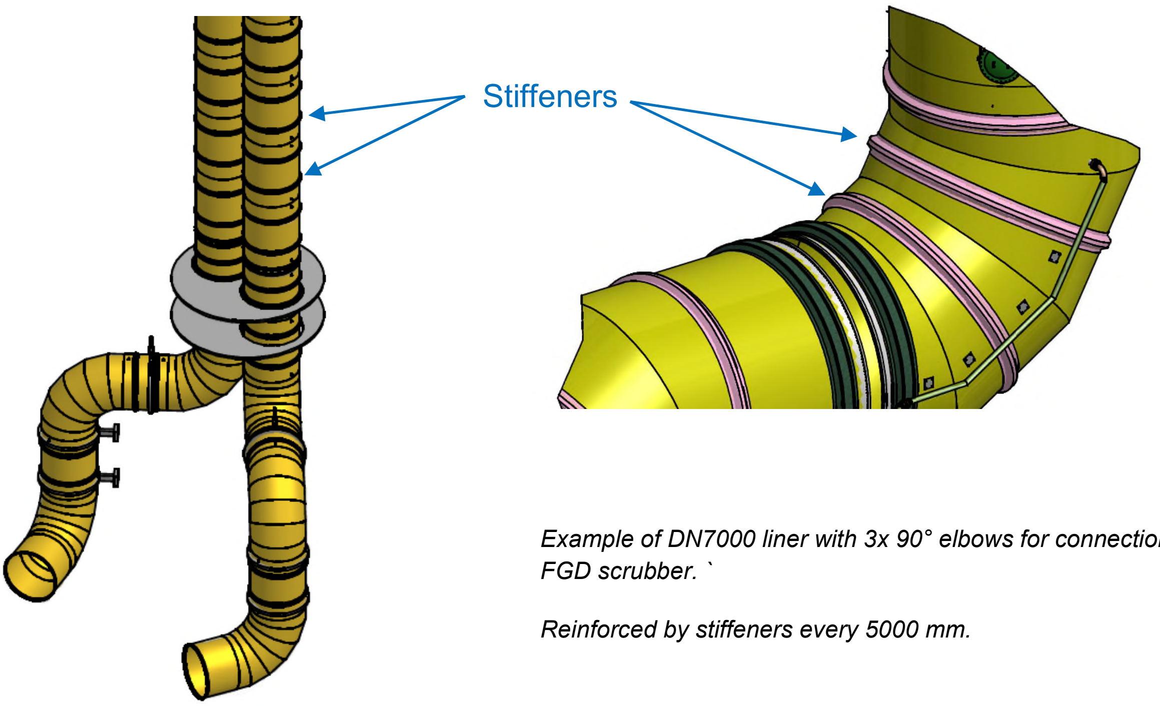
4.5 Stiffeners.

For FRP chimney liners the stiffness of the construction is normative in the design. The most optimal design in such a case is the so-called rib reinforced cylinders where equally spaced stiffener rings are applied around the cylinder. The stiffener itself can either be built-up from massive FRP, rolled steel profiles or hollow FRP profiles.



The optimal type of stiffener, the number of stiffeners, their minimal stiffness (E x I) and the optimal distance between 2 stiffeners is determined by the stress and stability calculation.

Stiffeners can either be integrated into the wall (FRP) or separately installed (Steel).



Example of DN7000 liner with 3x 90° elbows for connection to the FGD scrubber. `

Reinforced by stiffeners every 5000 mm.

4.6 Calculation methods

Design of a chimney liner is always done by setting up a FEA model. The model assesses the outcome by comparing with the allowable values determined from the code. To set up a proper FEA model, the following should be known:

- Geometry → Based on General Arrangement (GA)drawings and the preliminary FRP design by Plasticon.
- Properties → Plasticon laminate properties based on historical test data.
- Loads → Loads from process, dead weight and factors from the EN 1990/CICIND specifications.
- FEA model → Define e.g. the minimum mesh and other boundary constrains.

To assess the outcome of the FEA analyses a design code should be chosen. In Europe, the EN13121-3 is mostly used to assess the outcome of the FEA analyses. In the US, the assessment is mostly done by using the ASTM D5364 as a starting point.

For both Europe as the US also design parameters from CICIND (International Committee for Industrial Chimneys) are used.

The approach of the different design codes is different but the outcome less or more comparable. In this report the EN 1990 / EN13121 are taken as starting points.

5 Assessment of a FRP design

5.1 Introduction in use of design factors

As mentioned before the process temperature is an important aspect in the design of a FRP liner. From a process point of view there are 3 different operating scenarios

1. Operating conditions ≈ 60°, over ≤ 50 years.
2. By-Pass conditions ≤ 150°C, over ≤ 10 years within the FGD's life time.
3. Excursion ≤ 300°C, once per FGD's life time, ≤ 30 minutes.

Per load scenario the so-called design factor should be determined. Some loads have significant impact but because their duration is very short the overall impact is not normative.

Other loads are relatively low but occur during the complete 50 years of lifetime. Therefore, the impact is rather high.

Design factors will be determined for either strength (stress) or stability (buckling factor). To assess the impact on the construction per load scenario the overall design factor for strength and stability is determined per load scenario.

The design factors according the EN 13121-3:2016 code are built-up from several partial material and load factors each covering a degradation aspect of the FRP, the time factor (duration of a load) and covering normal variances in production, materials and loads.

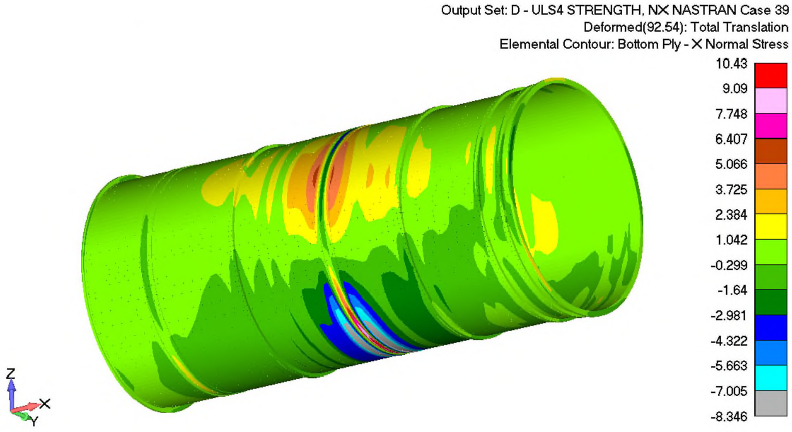
Below a summary of the (partial)design factor for the scenarios mentioned above.

Factor	Description	Operating conditions	By-Pass conditions	Exceptional situation	Remark
A1	*Material properties based on historical test data or theory*	*1.20*	*1.20*	*1.20*	*Plasticon has test data available from different laboratory tested for the last decades*
A2	*Resistance of resins against process environment (corrosion)*	*1.20*	*1.20*	*1.20*	*For resins recommended by the resin manufacture factor 1.2*
A3	*Influence of temperature*	*1.10*	*1.30*	*1.37*	*See 6.1*
A4	*Load cycles (fatigue)*	*1.00*	*1.00*	*1.00*	*Not applicable for FGD*
A5	*Duration of a load scenario (resulting in creep)*	*1.70 / 1.40*	*1.60 / 1.30*	*1.00 / 1.00*	*Axial / Circumferential creep factors are based on historical test data. Shorter duration means lower factor*
γm	*Material variation coefficient*	*1.40*	*1.40*	*1.40*	*Standard factor for FRP according the EN 1990 code*
γf	*Load variation coefficient*	*1.50*	*1.50*	*1.00*	*Standard factor for FRP according the EN 1990 code*
Overall factor for strength $A1 * A2 * A3 * A4 * A5 * \gamma m * \gamma f$	***K=***	***6.0***	***6.3***	***2.8***	- -
Overall factor for stability $A1 * A2 * A3 * A4 * \sqrt{A5} * \gamma m * \gamma f$	***F=***	***3.9***	***4.5***	***2.8***	- -

In this example the combination of load duration (A5) and temperature (A3) during By-Pass condition is normative for the design.

5.2 Assessment of an FRP construction.

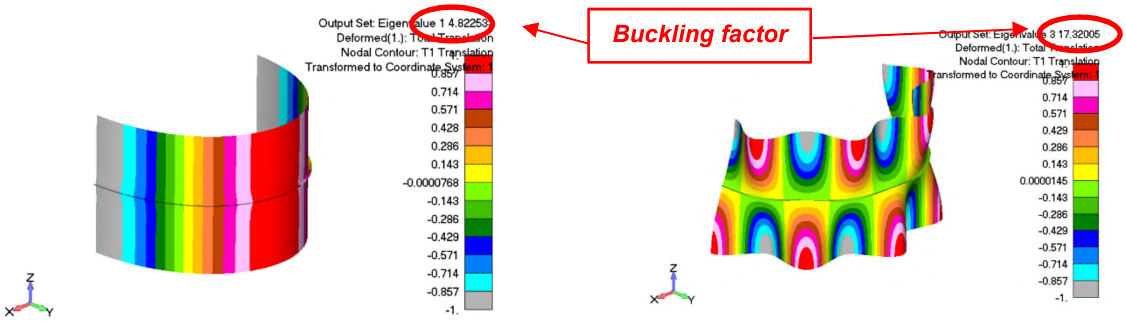
Below two examples how to verify a design by comparing the minimum design-factor K (strength) and F (stability) according the EN 13121-3 code with the available factors from the FEA analyses per load case.



Above the stress load in a DN8000 horizontal gas duct. In the x-direction the maximum tensile stress is 10.43 Mpa.

The ultimate stress at rupture for this duct is 180 Mpa. The K-factor for this project was determined 6.22. The realized K-factor is 180 Mpa/10.43 Mpa = 17.25.

Because 17.25 > 6.22 the assessment shows that the construction fulfills the requirements according EN13121-3.



For stability (overall and local) an identical approach is followed. Above an example of a cylinder with stiffeners loaded by external pressure (vacuum).

The overall and local buckling factors are determined and compared to the minimum F-factor as per EN 13121-3 design. The buckling factor achieved should be higher than the - for that load case required - F-factor.

6 Operating at higher temperatures

6.1 HDT of a resin

One of the important characteristics of a resin is the HDT or Heat Distortion Temperature. The HDT is the maximum temperature a resin (and therefore laminate) can handle before it loses most of its strength properties. The HDT is depending on the chemical backbone of the resin. In general, vinylesters have the highest HDT of commercially available resins. A higher HDT value means thermal stability up to higher temperatures. For flue gas liners affected by high temperatures, Derakane 470 HT- 400 or equivalent is often used due to its excellent thermal stability. For this resin a HDT of 180°C is specified by Ashland.

DERAKANE® 470 HT-400 Epoxy Vinyl Ester Resin

Property[1] of clear casting[6] at 25°C (77°F)	Value (SI)	Method	Value (US)	Method
Tensile Strength	80 MPa	ISO 527	12,000 psi	ASTM D638
Tensile Modulus	3500 MPa	ISO 527	510 kpsi	ASTM D638
Tensile Elongation at Yield	3%	ISO 527	3%	ASTM D638
Flexural Strength	150 MPa	ISO 178	22,000 psi	ASTM D790
Flexural Modulus	3500 MPa	ISO 178	510 kpsi	ASTM D790
Heat Distortion Temperature[7]	180°C	ISO 75	360°F	ASTM D648
Glass Transition Temperature, Tg[2]	195°C	ISO 11359-2	380°F	ASTM D3419
Volume Shrinkage	8.3%		8.3%	

According the EN 13121-3 the maximum temperature of the load carrying structural layer should be at least 20°C below the HDT of the chosen resin. If this is not the case a different resin should be chosen.

6.2 Impact of temperature

The maximum applied temperature of the SL is an important aspect during the design of a FRP liner. Laminate properties determined at 20°C should be divided by the partial load factor A3 to have the properties at a temperature “x”

To determine the A3 factor the following equation according EN13121-3 should be used.

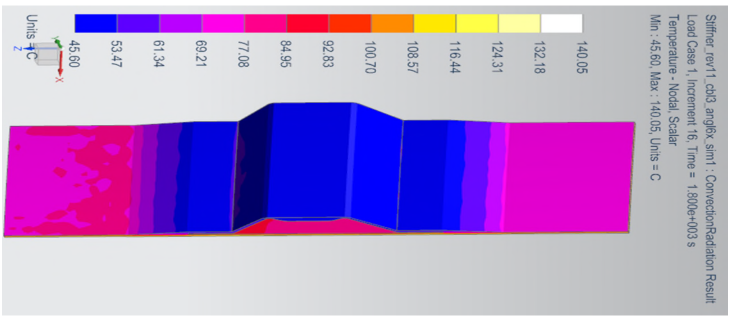
$$\boxed{A_3 = 1{,}0 + 0{,}4\,\frac{TS - 20}{HDT - 30}}$$

Where TS is the laminate temperature in °C and HDT a resin specific value in °C. The A3 factor should not exceed a value of 1.4. If this is the case another resin (with a higher HDT) should be used.

6.3 Laminate temperature

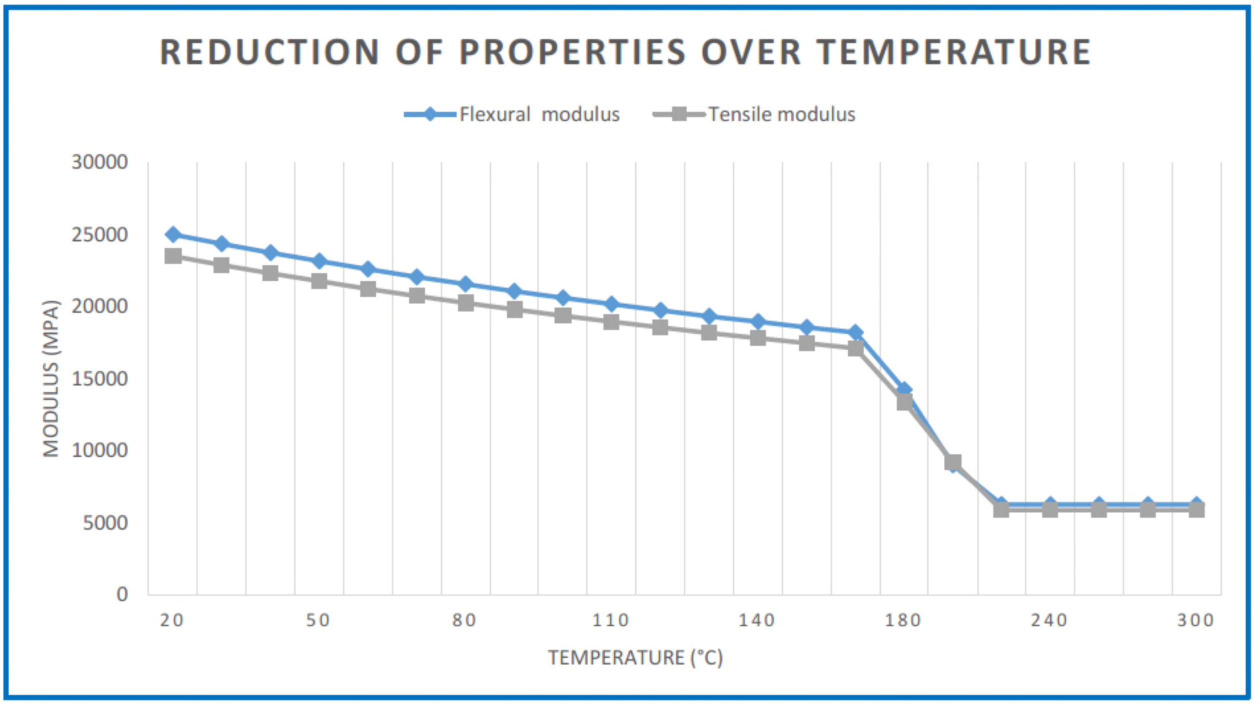
The temperature of the SL can be calculated by knowing the flue gas temperature, gas velocity inside and air velocity outside the liner, the wall thicknesses and the heat transfer coefficients per CICIND code – chapter 7.

An example of a CFD calculation is given below where a flue gas temperature of 150°C results in a SL temperature of less than 100°C.



6.4 Degradation of mechanical properties.

Taking a filament winded laminate as an example (glass content 65% wt. and made of Derakane 470 HT-400) the reduction of properties 20°C to 300°C would look like:



Based on the EN 13121-3 a laminate can absorb and transfer loads up to 20°C below its HDT value. In this case for Derakane 470-HT 400, up to a temperature of 160°C.

From laboratory tests, it is known that heating up the laminate above 160°C will not affect the integrity and chemical resistance but the mechanical properties will be on impacted. Tests showed that in the range 220°C -300°C the properties remain stable at ± 25% of the original properties at 20°C.

After cooling down, laminates have been checked on delamination's or other irreversible changes. None of those have been found.

Ashland has several well documented cases of chimneys built-up out of Derakane 470 HT-400 and used for decades. These chimneys are operated in a temperature range far above the HDT of the resin.

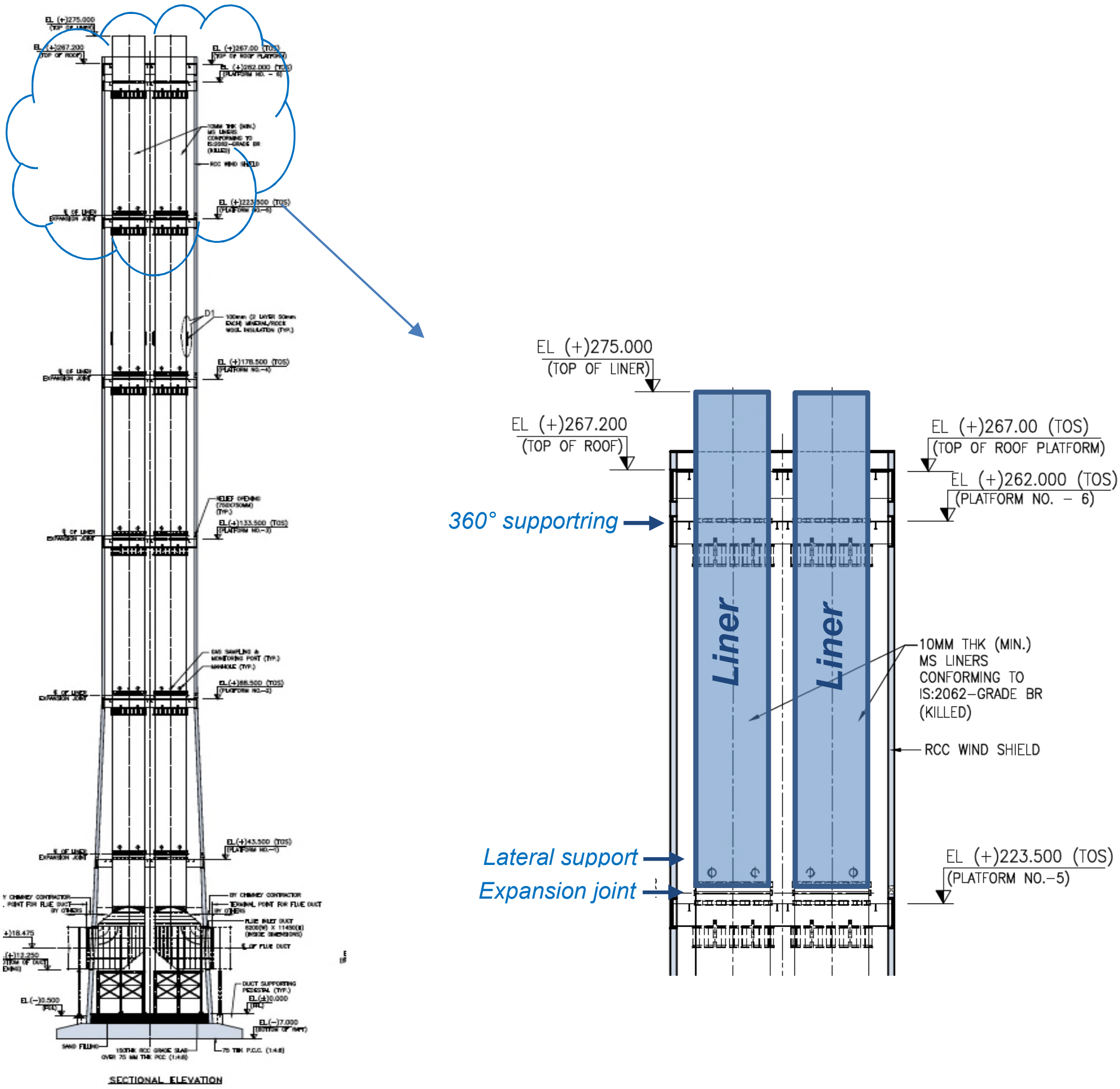
The outcome of case histories is that if the structural design considers the high temperatures in a proper way no problem will occur during the lifetime of the chimney.

7 Using FRP liners for the Sangaji FGD project

7.1 Design base

For the Sangaji project Plasticon investigated the potential use of FRP liners for emitting the flue gasses on 275 m height after desulfurization in the FGD. The project exists of 2 liners of DN7200 diameter each installed in a concrete chimney of 267 m height. The top of the FRP liner is at 275 m.

The FRP liners are split-up in parts of 45 m¹ each. Every part is supported by a 360° support ring at the top and laterally guided at the bottom. To absorb expansion caused by temperature, compensators are installed every 45 m.

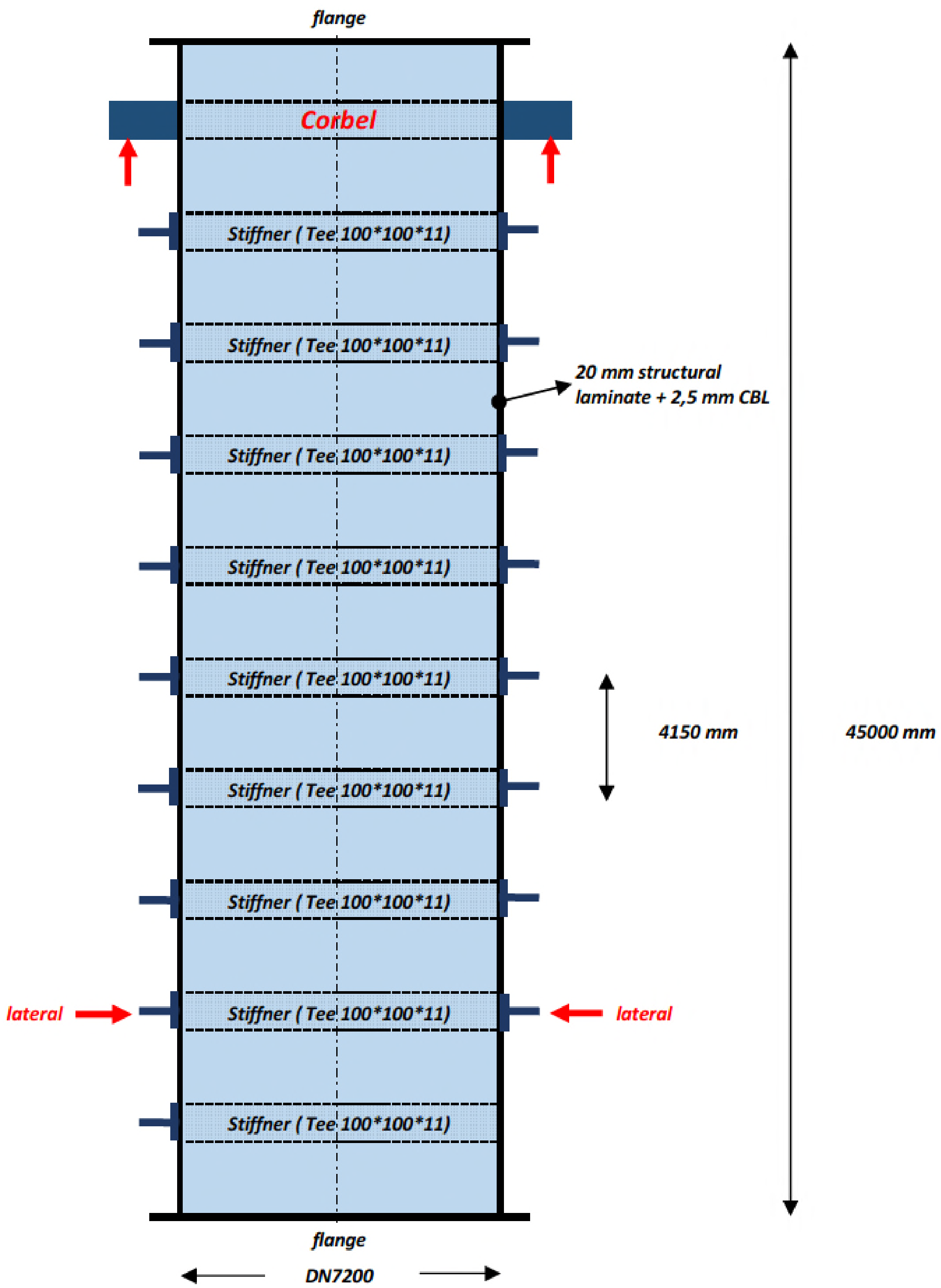


For the feasibility study, we assumed that following loads impact the liner for longer/shorter periods.

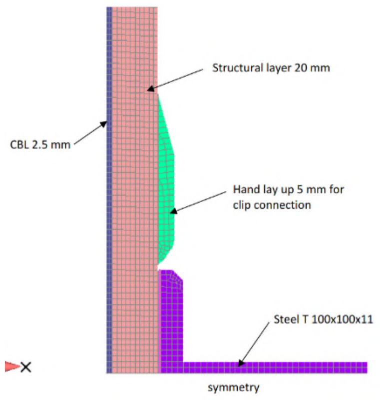
- Pressure : +20 mBar / -20 mBar for 50 years
- Ash & condensate : 20 kg/m² for 50 years
- Temperature : 60°C for 50 years / 150°C for less than 10 years / 300°C for less than 30 minutes

7.2 Laminate and stiffeners

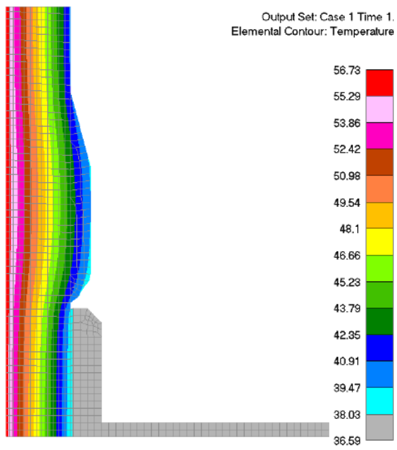
Based on Plasticon's long term experience and by use of EN13121-3 design rules, following draft construction was set-up to be evaluated by use of FEA

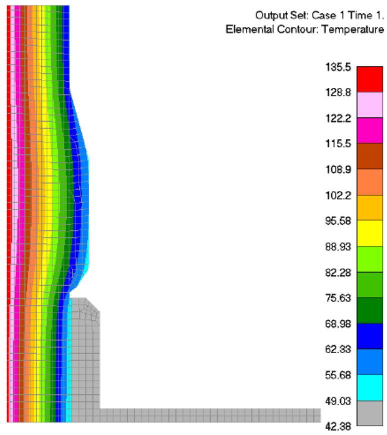


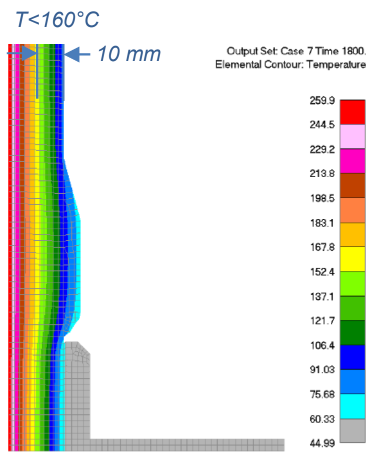
To determine the temperature curve of the cylinder / stiffener construction a thermal model was set up and analyzed by use of FEA



The temperature curve of this cross-section - per load case - is:







T_{gas} = 60°C
t = ∞

T_{gas} = 150°C
t = ∞

T_{gas} = 300°C
t = 30 minutes

From the graphs above following - for the design relevant temperatures - can be determined:

	60°C / ∞ scenario	150°C /∞ scenario	300°C/ 30 min scenario
T_{max} at surface CBL	57°C	136°C	260°C
T_{max} structural laminate	55°C	127°C	232°C
Surface temperature	40°C	57°C	100°C

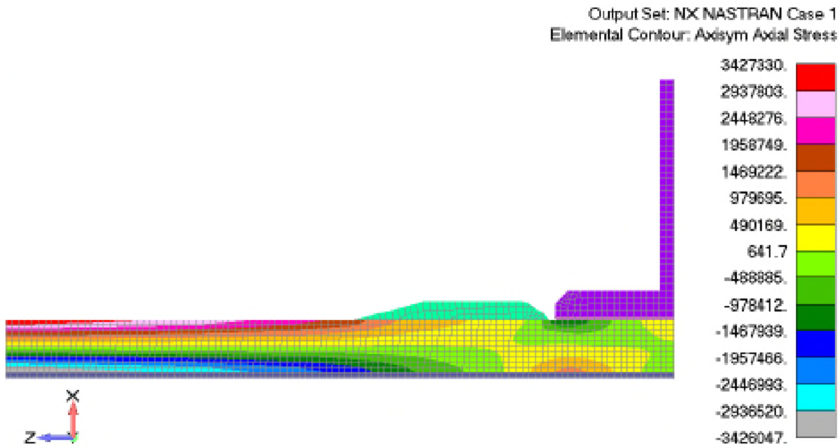
For the exceptional loading of 300°C/30 minutes it would mean that the maximum temperature of the SL is higher than the (HDT -/- 20°C) requirement according EN13121-3. But, the temperature will decrease by moving outwards in the SL. Finally, the temperature will drop to a 100°C at the surface

Some detailed analyses showed that on a point 10 mm below the surface the temperature is <160°C, which means that the outer 10 mm of the SL is still perfectly able to transfer loads and to resist buckling loads.

Of course, the applying stress will be higher and the buckling factor will be lower (due to reduced “load carrying thickness”) but due to the short timeframe in which this situation will occur, the calculated design factors are also significantly lower (see chapter 4.1).

7.3 Check of design / axial stress (dead weight, process & thermal expansion).

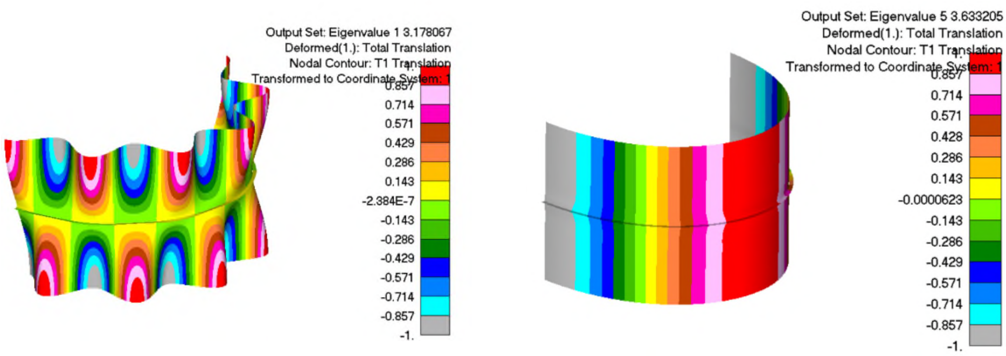
	60°C / ∞ scenario	150°C /∞ scenario	300°C/ 30 min scenario
Required design factor (K) for strength	6.0	6.3	2.8
Achieved design factor for strength	49.2	15.5	10.5
Load carrying thickness of structural laminate	20.0 mm	20.0 mm	10.0 mm
Assessment	Ok	Ok	Ok



Graphical presentation of the thermal axial stress @ 300°C flue gas

7.4 Check of design / buckling factor (from external pressure).

	60°C / ∞ scenario	150°C /∞ scenario	300°C/ 30 min scenario
Required design factor (F) for stability	3.9	4.5	2.8
Achieved design factor for strength	4.8	4.8	3.2
Load carrying thickness of structural laminate	20.0 mm	20.0 mm	10.0 mm
Assessment	Ok	Ok	Ok



Graphical presentation of the local and global buckling of the "10 mm load carrying cylinder"' @ 300°C flue gas

8 Conclusion.

Plasticon Composites is well able to design, produce and install a FRP chimney liner which:

1. has a service life of 50 years
2. can resist flue gas with temperatures of 60/150 °C during decades.
3. can resist a short term (30 minutes) exceptional temperature of 300°C without permanent damaging the laminate structure, shape or corrosion resistance.
4. as proven by comparable case histories, the calculations and the FEA, the up to 300 °C requirement poses no issues for the FRP liners in the Sangaji project.