Inspection guidelines and determination of reasons for failure of flue gas ducts and stacks of fibre-reinforced plastics

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KIMAB
Swerea KIMAB is one of the oldest Swedish research institute, founded 1921 and it is a merge between the Swedish corrosion institute and the institute for metal research.

Gunnar Bergman started the polymer group in 1981.
Polymeric materials

Karin Jacobson
Group leader

Daniel Ejdeholm
Research leader

Nina Pendergraph
Researcher

Klas Esbo
Researcher

Love Pallon
Researcher

Martina Källrot Janståhl
Researcher

Dinko Lukes
Researcher

Johanna Josefsson
Trainee
Our expertise – Need driven industrial research

- Member program: Polymeric Materials in Corrosive Environments
- Approximately 30 members
- From producers to end users
- Main focus areas are chlorine production, sulphuric acid, flue gas cleaning and pulp and paper production
- We are also active in a number of research projects and do contract work, material recommendations, ageing studies and exposures in harsh environments (H₂SO₄, HF, ClO₂, spent acid, chlorine….)
Agenda

• Damage modes of FRP – a Handbook

• Inspections

• Investigation of flue gas stacks

• KIMAB’s “in-house flue gas stack”
Damage modes of FRP

- Diffusion
- Blisters
- Stress corrosion cracking
- Discoloration
- Delaminations
- Cracks
  - Surface cracks
  - Drying cracks
  - Structural cracks
Diffusion

• FRPs are permeable

• Diffusion of the corrosive media into the corrosion barrier is okay, but never into the structural layer

• Microscopy analysis of a polished cut-out can be an efficient tool to determine the diffusion
Blisters

- A combination of diffusion and an osmotic pressure
- In general they are superficial and situated close to the surface
Delamination

- Often due to thermal stress
- In general more severe than blisters
- Can often be repaired
Stress corrosion cracking

- A combination of chemical attack and stress on fibers
- Rapid and dangerous raptures
- Impact damage can be a starting point for failure
Inspections
Destructive testing

Composition

Mechanical strength

Thermal history by differential scanning calorimetry (DSC)

Chemical composition by Fourier Transform Infrared Spectroscopy (FTIR)

Microscope

Structural laminate

Corrosion barrier
Non-destructive testing

- Visual inspection
- Ultrasound
- X-ray
- Acoustic emission
- Barcol Hardness
Investigation of flue gas stacks
Fitness for service

• What are the limiting factors when the chemical conditions are mild?

• How will the mechanical properties change during the service life?
45 year old flue gas stack

- The stack was originally 40 m high
- Elongated (1985) to 68 m
- The diameter is approx. 3.6 m.

Severely attacked
45 year old flue gas stack
- Mechanical properties

Only a slight decrease in modulus!

(The deviations between 30 and 45 years could be due to misalignment in fiber direction for the sample cut-out)
Investigation

• 8 flue gas stacks were investigated according to their reduction in the elastic modulus (E-modulus)

• The reduction was determined by comparison of destructive tensile test and the optimal theoretical E-modulus, which was calculated by classical lamination theory

• The damage modes of the stacks were predominantly surface cracks and deeper cracks

• The stacks were probably designed with a safety factor of 10
Method

How to measure the reduction?

KIMAB’s approach:

- Destructive tensile tests
- Burn out + Calculations

Current E modulus
Theoretical E modulus

\[ \text{PDS} \]

(Percent of design strength)
Calculations

Based on classic lamination theory, the theoretical E-modulus can be determined from a burn out at 600 °C for 4h.

<table>
<thead>
<tr>
<th>Density</th>
<th>$\rho$, 1140.0 kg/m^2</th>
<th>densitet resin</th>
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</table>

<table>
<thead>
<tr>
<th>The samples dimensions</th>
<th>Notes</th>
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<tbody>
<tr>
<td>Length 25.72 mm</td>
<td>Average</td>
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<tr>
<td>Thickness 21.69 mm</td>
<td>Average</td>
</tr>
<tr>
<td>Height 7.39 mm</td>
<td>Average</td>
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<table>
<thead>
<tr>
<th>The glass fibres dimensions</th>
<th>Nr</th>
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<tbody>
<tr>
<td>Thickness of CSM 0.3 mm</td>
<td>5</td>
</tr>
<tr>
<td>Thickness of WR 0.65 mm</td>
<td>1</td>
</tr>
<tr>
<td>Thickness of R 1.2 mm</td>
<td>2</td>
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</table>

<table>
<thead>
<tr>
<th>The samples weight</th>
<th>Notes</th>
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<tbody>
<tr>
<td>Weight of melting pot 25.2 g + the sample 31.8 g After the burn out 28.2 g</td>
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</table>

<table>
<thead>
<tr>
<th>The glass fibres weight</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of CSM 0.68 g</td>
<td></td>
</tr>
<tr>
<td>Weight of WR 0.35 g</td>
<td></td>
</tr>
<tr>
<td>Weight of R 1.94 g</td>
<td></td>
</tr>
<tr>
<td>Tot 2.37 g</td>
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</table>
Calculations

**Area**
- Average area: 557,877 mm²

**Weights**
- Weight of the sample: 6,618 g
- Weight of the glass: 3,0 g
- Glass content: 44,9 wt%
- Resin content: 55,1 wt%
- Check: 0.002 Should be close to zero

**Density**
- \( \rho_r = 1109,7 \text{ kg/m}^2 \) density resin

**CSM, WR, Roving**

<table>
<thead>
<tr>
<th>CSM</th>
<th>WR</th>
<th>Roving</th>
<th>Unit</th>
<th>Notes</th>
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<tr>
<td>m_r</td>
<td>0,245</td>
<td>0,625</td>
<td>1,739</td>
<td>kg/m²</td>
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<tr>
<td>t_r</td>
<td>2,000</td>
<td>200</td>
<td>20</td>
<td>mm</td>
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</tbody>
</table>

**Thickness**
- Calculated thickness: 0,31, 0,61, 1,19 mm
- Measured thickness: 0,3, 0,65, 1,2

**Ultimate tensile unit strength for the laminate**
- \( U_{lam,k} = 2140 \text{ (N/mm)} \)

**Ultimate modulus for the laminate**
- \( X_{lam,k} = 124519 \text{ (N/mm)} \)

**Thickness of the glass**
- \( t = 4,55 \text{ (mm)} \)

**Strengths**
- \( S = 470 \text{ (MPa)} \) Strength
- \( E = 31343 \text{ (MPa)} \) E-modulus
Example

Resin Atlac 382-05

120-140°C, \( \text{SO}_3, \text{SO}_2, \text{HCl} \)

Flue gas from soda recovery boiler

Flue gas stack

Ca 65°C

(PDS=Percent of design strength)

Top part

\( \text{PDS}_{\text{top}} = 0.79 \)

Intermediate part

\( \text{PDS}_{\text{int.med.}} = 0.65 \)

Bottom part

\( \text{PDS}_{\text{bottom}} = 0.68 \)

Cut-outs

Figure 59: Surface cracking in non-repaired laminate (at a manhole), i.e. 30-year-old laminate, from the bottom part of the scrubber.
Observations
- KIMAB’s approach correlates well with the observations from the microscope analysis, and thereby enables remaining service life determinations

- As long as no severe damage modes can be seen, the reduction in E-modulus is limited
New project, In-house “flue gas stack”

- What about other losses in material properties?
- Delaminations, a reason for concern
- Can we provoke delaminations by rapid heating?
- Need for deeper understanding of the mechanisms behind delamination
- Previous experiments with unrestricted test piece failed to provoke delamination
Continuation – New project, in-house ”flue gas stack”

- Test pieces with restricted expansion
- Industrially produced laminates
- Downsizing
  - Diameter ≈ 0.4 m
  - Height ≈ 1.5 m
- Simulated by-pass operation
  - 60 °C and 98% RH
  - 200 °C
- 20 kW heating, 20→200 °C in 8 s
  - Thermal chock – to stimulate stresses
- High convection of air, 10 m/s in the stack
- Longtime cyclic exposure
Continuation – New project, in-house "flue gas stack"

- Possibility to evaluated materials before full scale construction
- To understand the mechanism behind delamination
- Online monitoring with sensors possible
Calculations on downsizing

Temperature gradient

- Corrosion layer – 3.5 mm, mechanical laminate – 6.5 mm
- At a diameter of 300 mm hoop stress starts to deviate from real conditions
- Possible to retain wall thickness of an original stack

Hoop stress

4% difference

*Calculations made by Erik Marklund, Swerea SICOMP
New possibilities

• Screening of materials
• Effect of insulation
• Online monitoring with coupled sensors
  • Acoustic emission
  • Infrared camera
  • Lamb waves

• Your suggestions on FRP build-up and monitoring techniques to be tested are most welcome!
Thanks to our members!

<table>
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<th>Company Name</th>
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<tr>
<td>Accoat A/S</td>
<td>INOVYN/Solvay Specialty Polymers SpA</td>
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<tr>
<td>AGRU Kunststofftechnik GmbH</td>
<td>Kemira Kemi</td>
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<tr>
<td>Akzo Nobel Industrial Chemicals B.V.</td>
<td>Lubrizol Deutschland GmbH</td>
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<td>Akzo Nobel Pulp and Performance Chemicals AB</td>
<td>Lyma Kemiteknik</td>
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<td>Aliancys Nederland B.V.</td>
<td>Nordpipe Composite Engineering Oy</td>
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<td>Ashland Technologies GmbH</td>
<td>Plasticon Germany GMBH</td>
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