Memorandum M-506

THE MOISTURE ABSORPTION OF ARALL COMPARED TO CARBON AND ARAMID REINFORCED COMPOSITES

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CONTENTS

1. Introduction 1
2. Theoretical aspects 1-3
3. Results and discussion 4
4. Conclusions 4
4. References 4
Tables 5
Figures 6-15
1. INTRODUCTION

ARALL (Aramid Reinforced Aluminium Laminate) is a new, highly fatigue insensitive material developed at the Delft University of Technology. It is built up as laminated sheet material with:
- thin sheets of an aluminium alloy (7075-T6 or 2024-T3)
- strong, unidirectional aramid fibres
- epoxy metal adhesive system.

The moisture absorption of ARALL is examined in ref. 2.

In this paper, this absorption behaviour is compared with the one of CFRP (Carbon Fibre Reinforced Plastic) and AFRP (Aramid Fibre Reinforced Plastic).

The calculations are based on diffusion coefficients obtained in ref. 1 and are emphasized on the role of the fibres (aramid or carbon), material thickness and diffusion barriers (aluminium sheets in ARALL configuration) in the general absorption mechanism.

2. THEORETICAL ASPECTS

Fick's general differential equation for moisture absorption can be described as:

$$\frac{\delta c}{\delta t} = D_x \frac{\delta^2 c}{\delta x^2} + D_y \frac{\delta^2 c}{\delta y^2} + D_z \frac{\delta^2 c}{\delta z^2}$$

(1)

In ref. 1 this equation is, with the use of adequate boundary conditions, solved for a one-and two-dimensional case and resulted in:

**1-dimensional**

$$\frac{M - M_0}{M_0} = 1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \cdot e^{- (2n+1)^2 \frac{D_y}{1^2} \cdot t}$$

(2)

**2-dimensional**

$$\frac{M - M_0}{M_0} = 1 - \frac{64}{\pi^4} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \cdot e^{- (2n+1)^2 \frac{D_y}{1^2} + \frac{D_z}{b^2} \cdot t}$$

(3)

Similar to this derivation, the 3-dimensional solution leads towards:

$$\frac{M - M_0}{M_0} = 1 - \frac{512}{\pi^6} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^6} \cdot e^{- (2n+1)^2 \frac{D_y}{1^2} + \frac{D_z}{b^2} + \frac{D_x}{h^2} \cdot t}$$

(4)
where \( M \): moisture content
\( M_0 \): initial moisture content
\( (\text{in this case } M_0 = 0) \)
\( M_s \): equilibrium moisture content
\( t \): time

other variables: see fig. 1

Equation 4 is used to calculate the moisture content at different temperatures, exposure periods and specimen thicknesses. The diffusion coefficients are obtained from ref. 1 and summarized in table 1. The following remarks have to be made concerning the use of equation 4 and table 1 for the calculation of the moisture contents:

1. The three materials have a significantly different absorption mechanism
   - ARLALL has aluminium sheets on the outer parts \((x=0 \text{ and } x=h; \text{ fig. 1})\)
   and therefore \( D_x = 0 \); the aramid fibres in the adhesive absorb moisture
   and therefore we get:
     
     \[
     D_y = D_y^* \\
     D_z = D_z^* \\
     D_x = 0
     \]

   - CFRP: the carbon fibres do not absorb moisture; the absorption process
     is dominated by the resin system:
     
     \[
     D_y = D_y^* \\
     D_z = D_z^* \\
     D_x = D_x^* \\
     \]

   - AFRP: the aramid fibres absorb moisture; the fibres are unidirectionally
     and situated in the Y-direction
     
     \[
     D_y = D_y^* \\
     D_z = D_z^* \\
     D_x = D_x^* \\
     \]
2. The infinite series in equation 4 is strongly dominated by the \( n=0 \) case (with increasing \( n \), the influence on the summation decreases with \( (2n+1)^{-6} \)). An approximation such as equation 5 is therefore permitted:

\[
\frac{M - M_0}{M_S - M_0} = 1 - \frac{512}{\pi^6} \cdot e^{-\pi^2 \left( \frac{D_Y}{b^2} + \frac{D_z}{b^2} + \frac{D_x}{b^2} \right) \cdot t} \tag{5}
\]

3. Theoretically \( M = M_0 \) for \( t=0 \): this is not the fact in equation 5, due to an insufficient but mathematically necessary approximation of the initial boundary condition. In the 1-dimensional case, the difference is small (± 8 %) but in the 3-dimensional case it becomes considerable (\( M = 0.46 \ M_S \) at \( t=0 \)).

This inaccuracy is only present for the initial condition and not in the actual diffusion process. The inaccuracy can therefore be regarded as a kind of initial moisture content with one disadvantage that the total saturation period will be severely underestimated (\( M \) is initially already \( 0.46 \ M_S \)). But the purpose of this paper is primarily to show differences in absorption behaviour more than supplying data for saturation periods. In this context, the inaccuracy is tolerated.

4. All calculations are performed with a standard adhesive system (AF 163-2) which facilitates the comparison of the different materials. Because the results are purely theoretical (except for the diffusion coefficients in table 1) no attention is paid to the properties of composites consisting of carbon or aramid fibres and the adhesive system. Some adhesion experiments however showed excellent results using this adhesive system in combination with both carbon and aramid fibres. In practice it will probably not be used because of price aspects (the adhesive is more expensive than common resin systems).

5. For the calculations, the following specimen geometry is introduced:

\[
\begin{align*}
1 &= 50 \text{mm} \\
b &= 50 \text{ mm} \\
h &= \text{variable}.
\end{align*}
\]
3. RESULTS AND DISCUSSION

The increase of $M/M_s$ with submergion period is for the three materials shown in fig. 2 - 10 as a function of temperature and material thickness.

- For thin skins ($h << b$; $h << l$; see fig. 2-4), the absorption rate of ARALL is for all temperatures, negligible compared to CFRP and AFRP. Especially at higher temperatures saturation of the composites is reached within a limited period (50 days at 60°C) whereby no mutual differences are observed between the two composites (curves are overlapping each other). More than 3 years of exposure do not result in a saturation of an ARALL sheet, even at higher temperatures. It is obvious that for thin skins the absorption process is totally dominated by the large areas in Y-Z direction which are protected for diffusion in the case of ARALL. The absorption properties of the fibres are for these thicknesses of no importance.

- For thicker specimens ($h = 10$ mm; fig. 5-7 and $h = 20$ mm; fig 8-10), it is obvious that absorption in X-Z and Y-Z direction becomes considerable. This results in a difference in absorption rate between AFRP and CFRP (aramid fibres absorb moisture in contradiction with carbon fibres) and a smaller advantage of the diffusion barrier function of the aluminium sheets in the case of ARALL. But, as could be expected, ARALL has for all temperature still the lowest moisture absorption rate.

4. CONCLUSIONS

- For thin skins ($h << l$; $h << b$), ARALL has a negligible moisture absorption rate compared to composites and no difference in absorption rate is present between CFRP and AFRP. The absorption process is resin dominated.

- For larger thicknesses, the fibres have a serious contribution in the absorption behaviour of the material (AFRP higher absorption rate than CFRP) and the advantage of ARALL compared to composites is decreasing.

5. REFERENCES

(1) Verbruggen, M.L.C.E. Determination of the moisture absorption of ARALL, Report Delft University of Technology, Dept. of Aerospace Engineering
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<thead>
<tr>
<th>temperature °C</th>
<th>diffusion coefficient in fibre direction (aramid fibre)</th>
<th>diffusion coefficient perpendicular to the fibre direction</th>
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<tr>
<td></td>
<td>$D^*_Y$</td>
<td>$D^*_Z$</td>
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<tr>
<td></td>
<td>mm$^2$/s</td>
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**Table 1:** Diffusion coefficients in and perpendicular to the fibre direction for different temperatures (ref. 1)

Data obtained from a 2-dimensional approach followed by weight gain tests
Fig. 1: Specimen configuration
temperature: 20°C
distilled water
l=50mm; b=50mm; h=1mm

Fig. 2: Moisture absorption rate of ARALL compared to CFRP and AFRP
temperature: 20 ºC
thickness: 1mm
temperature: 60 °C
distilled water
1=50mm; b=50mm; h=1mm

Fig. 3: Moisture absorption rate of ARALL compared to CFRP and AFRP
temperature: 60 °C
thickness: 1mm
temperature: 100°C
distilled water
l=50mm; b=50mm; h=1mm

Fig 4: Moisture absorption rate of ARALL compared to CFRP and AFRP
temperature: 100 °C
thickness: 1mm
Fig. 5: Moisture absorption rate of ARALL compared to CFRP and AFRP.

Temperature: 20°C
Distilled water
L=50mm; b=50mm; h=10mm
Fig. 6: Moisture absorption rate of ARALL compared to CFRP and AFRP

- Temperature: 60°C
- Distilled water
- l=50mm; b=50mm; h=10mm

- **AFRP**
- **CFRP**
- **ARALL**

Time (days)
Fig. 7: Moisture absorption rate of ARALL compared to CFRP and AFRP
temperature: 100°C
thickness: 10mm

temperature: 100°C
distilled water
l=50mm; b=50mm; h=10mm
Fig. 8: Moisture absorption rate of ARALL compared to CFRP and AFRP

temperature: 20°C
thickness: 20mm
Fig. 9: Moisture absorption rate of ARALL compared to CFRP and AFRP

- Temperature: 60°C
- Distilled water
- L=50mm; b=50mm; h=20mm

Logistic curves for material absorption rates over time (days)
**Fig. 10:** Moisture absorption rate of ARALL compared to CFRP and AFRP

- **Temperature:** 100°C
- **Distilled water**
- **l=50mm; b=50mm; h=20mm**

![Graph showing moisture absorption rate](image-url)