Fibre Orientation Visualization with AvizoFire®

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Abstract
The application of fibre orientation visualization, fibre orientation simplification, and its evaluation that will be described in this paper, were applied on a so called Ultra High Performance Fibre Reinforced Concrete (UHPFRC) being used for the on-site repair of bridges in Slovenia. The image processing, fibre separation, orientation calculation, and visualization has been done by using AvizoFire® which provides an extensive framework and toolbox from 3D imaging to analysis and material characterization. While orientation fields could be computed from undifferentiated fibres image, in this case for highlighting distribution details, individualizing fibres via advanced segmentation and separation techniques have been applied.

Keywords: Fibre Analysis, 3D, Visualization, Quantification

1 Introduction
Fibre orientation calculation has been a topic since decades and the past provided most sophisticated methods bringing this challenge to a successful solution. These methods ranged from image acquisition like computed tomography, image processing, to morphological operations like erosion and dilation or more advanced methods, up to the final calculation of the spatial information in fibre composed material. The actual fibre detection and separation is not in the scope of this document. The intention of this paper is the visualization and enhanced presentation of the results of such efforts. The characteristics like stiffness, robustness, etc. of fibre reinforced materials are essential in the design of such materials in order to achieve the desired specifications. In order to better understand the inner structure in those samples, this paper has its focus on the quantification, visualization and therefore better interpretation of those characteristics.

All applications in this paper will be processed as an example on an Ultra High Performance Fibre Reinforced Concrete (UHPFRC) courtesy provided by Dr. Alenka Mauko and Dr. Aljosa Sajna from the Slovenian National Building And Civil Engineering Institute (ZAG), Ljubljana, SLOVENIA.
This concrete is used for the on-site repair of Log Čezsoški bridge, Slovenia, FP6 project ARCHES http://arches.fehrl.org/.
The data has been acquired with a microXCT400 (XRadia). The objective that was used was a 0.39 x macro objective. The size of the sample was 5cm in diameter at a resolution of 30 μm.

The material is composed as follows:

<table>
<thead>
<tr>
<th>Component</th>
<th>Fibres[%]</th>
<th>P [kg/m³]</th>
<th>Mass [kg/m³]</th>
<th>Volume [l/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powders</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cement (C)</td>
<td></td>
<td>3110</td>
<td>758,7</td>
<td>244,0</td>
</tr>
<tr>
<td>Limestone filler (LF)</td>
<td></td>
<td>2660</td>
<td>758,7</td>
<td>285,2</td>
</tr>
<tr>
<td>Microsilicia (SF)</td>
<td></td>
<td>2200</td>
<td>151,7</td>
<td>69,0</td>
</tr>
<tr>
<td>Added water</td>
<td></td>
<td>1000</td>
<td>222,5</td>
<td>222,5</td>
</tr>
<tr>
<td>Steelwool¹</td>
<td></td>
<td>7850</td>
<td>706,5</td>
<td>90,0</td>
</tr>
<tr>
<td>Steelfibres 10mm</td>
<td></td>
<td>7850</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Admixture</td>
<td></td>
<td>1100</td>
<td>554,6</td>
<td>49,7</td>
</tr>
<tr>
<td>Superplasticiser (SP)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total water (W)</td>
<td></td>
<td>1000</td>
<td>258,0</td>
<td>258,0</td>
</tr>
<tr>
<td>Sika Extender (SE)</td>
<td></td>
<td>980</td>
<td>4,6</td>
<td>4,6</td>
</tr>
<tr>
<td>Air</td>
<td></td>
<td></td>
<td></td>
<td>35,0</td>
</tr>
<tr>
<td>Total</td>
<td>9</td>
<td>2658,0</td>
<td>1000,0</td>
<td></td>
</tr>
</tbody>
</table>

¹The detailed composition of the fibrous mix is patent protected and is available upon request with a license of exploitation

Note: The concept of development of new UHPFRC matrices with Limestone filler developed in this example is in the process of being patented. A patent application was filed in July 2009 by Dr. E. Denarié and Dr. Y.Houst from EPFL
2 Using AvizoFire for fibre visualization

With AvizoFire an arbitrary number of fibres can be individually identified and visualized. The individualization is achieved by running a so called labelling command on the complete fibre volume. By running this command, all individual fibres are enumerated and receive a unique id. Through this id each fibre can be identified and selected in further processing. Furthermore this enumeration makes it easy to colorize each fibre separately. The fibres in the next image are rendered by using a volume rendering technique and they are colorized with the use of a so called looping colour lookup table (or colormap):

![Image of fibres with color lookup table](image)

By using this kind of looping colour lookup table it is almost guaranteed that neighbouring fibres are not colorized with the same colour.

As one can see, this rendering technique does not provide good enough precision to really understand the spatial composition of the fibres. Therefore each individual fibre is evaluated by AvizoFire's quantification tools.

In this case following measures are calculated:

- BaryCenter in x,y,& z coordinates to determine the fibres’ gravity centres
- Length3d to determine the fibres’ most elongation in 3d space.
- OrientationTheta (θ) and OrientationPhi (Φ)

The goal of this evaluation is to be able to approximate or even better, replace each fibre that is inside the volume by a geometric primitive like a cylinder in this case. This is achieved by processing the results of the above computation in the following way:

For each entry in the result list, each fibre respectively, the gravity centre is taken and transformed into a translation that transports the cylinder to the correct spatial location. The length3D measure is used to calculate the so called scale factor that scales the cylinder to the correct size. From the two orientation measures θ and Φ finally the appropriate rotation information is determined. All of this information compose the so called transformation matrix for each individual cylinder that finally will approximate the accompanying fibre.
The following image shows the same fibre volume like above but approximated by cylinders:

As one can see clearly, the spatial position, order in depth, and orientation is much clearer with this kind of rendering.

3 Fibre orientation distribution visualization

The images rendered in either way, volume or geometry based rendering, do not provide any information about the distribution of fibre orientations. But, as already mentioned in the introduction, it is essential in the design process of fibre reinforced materials to measure and understand the structure for achieving the desired characteristics.

In order to better understand the fibre orientation distribution, further processing of the previous fibre evaluation result is needed. The goal of this approach is to give each fibre (or approximating geometry) a colour that reflects its spatial orientation. This approach will use so called colour classing:

For a rather coarse colour classing approach the top half of a sphere is taken and divided vertically into four sections. The sectioned half sphere is then horizontally cut into 2 sections. This results in 8 sections (4 upper and 4 lower sections). Each of the section gets a unique id that can then be used for composing a colour.

Now, when processing the fibre orientation evaluation result again, each fibre can be colorized according to its section id. The section id can be calculated by evaluating following formula for all fibres:

$$\text{sec ID} = \left\lfloor \frac{\theta + 180}{90} \right\rfloor + \left\lfloor \frac{90 - \phi}{45} \right\rfloor \times 4$$

\(\theta\) in \([-180..180]\), \(\phi\) in \([0..90]\), secID in \([1..8]\)
Following picture shows the same fibre volume like already show above but after colour classing processing:

![Fibre Volume](image)

Note: When looking at previous image, the spectator may notice that fibres that are colorized in light blue and in red seem to have the same orientation, but they are colorized differently. Same orientation is true in means of $\theta$, but $\Phi$ is taking care that the fibres receive a complementary section id. Therefore also the colouring must be complementary.

For obtaining classes with arbitrary higher resolution, the above formula is put into a more general composition:

$$\text{secID} = \left\lfloor \theta + \frac{180}{360} \right\rfloor + \left\lfloor \frac{90 - \phi}{90} \right\rfloor \times n_{c\theta}$$

$\theta$ in [-180,180], $\Phi$ in [0,90],

$n_{c\theta}$ = number of classes $\theta$,

$n_{c\Phi}$ = number of classes $\Phi$,

secID in [1.. $n_{c\theta} \times n_{c\Phi}$]

### 4 Fibre orientation distribution visualization simplification

All the methods introduced above already enhance fibre orientation visualization by order of magnitude. But what if the fibre orientation distribution shall be shown in one single representation?

In a final step the evaluation results for $\theta$ and $\Phi$ are processed again:

A one dimensional grid is composed with a size of $360 \times 90$ cells (360 cells in horizontal direction are able to hold the evaluation results from OrientationTheta and 90 cells in vertical directions are suitable to hold the evaluation results from OrientationPhi).

All fibres are processed in a way that the cell with index $[\theta, \Phi]$ is increased by 1. This results in an image like this:
It can be clearly seen that for this sample the fibres seem to have a tendency to be more horizontally oriented than vertically. Furthermore those horizontally oriented fibres tend to like orientation at ~50° and ~220° which is almost in line. Note: This was already seen when the fibres were coloured according to their orientation above (horizontal fibres pointing almost in identical directions but having complementary colours).

In a next step this grid is visualized with an Avizo module called *Bar Chart Slice*. The Bar Chart Slice module offers another method for the visualization of scalar data fields defined on regular grids. The slice is represented as a set of bars, one for each value. The height of each bar is determined by the data value and a tuneable scale parameter.

Finally the Bar Chart Slice is spherically projected. This results in a *fibre orientation hedgehog* which is a spatially correct representation of all accumulated fibre directions:

Note: All images in this paper have been created using the AvizoFire package from VSG. The fibre processing tool is a custom module that has been created by using the Avizo XPand extension. This module is not part of the standard packaging but can be made available upon request.