A collaborative work on the digital-physical anastylosis of the nave arch

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Workshop Web3D technologies for the Notre-Dame de Paris by Violette Abergel and Livio de Luca (online)
The case study: the collapsed arch F29-30 in the nave

Collapsed arch (GT Pierre – Bruno Phalip)
Juxtapositions of 3D Data in Aïoli

Point cloud
Tallon 2010
before fire

Point cloud surveys post fire: vaults and nef (cleaning operations)
The physical anastylosis test

Physical anastylosis by LRMH and Stone working group (Leroux Lise, LRMH)
Digital and physical reconstruction

Digital:
2010 Tallon point cloud

Physical:
Tarpaulin printed at scale 1 (shapes and dimensions of the voussoir slots)

Virtual anastylosis:
Volumes & shapes reconstruction

Isometry on the digital model of the fallen F29-30 arch, fitted closest to the Tallon point cloud (Antoine Gros, 2020)

Physical anastylosis:
- Initial reconstruction hypothesis
- Archaeological predicates for the reconstruction (=reconstruction criteria)
Digital and physical reconstruction

Input of the physical anastylosis results in the parametric model

Visualization of the physical anastylosis in the virtual environment

Lapidary mark in situ
The anatomy of a voussoir

Notches on voussoirs (GT Pierre – Elise Baillieul & Arnaud Ybert)

- Cross lapidary mark
- Moulding features
  - "tore" (fr.), "throat moulding" (en.)
- Polychromy
### Vousoir N1B: graphical documentation and lapidary study inventory

**Structure:** doubleau entre les travées 1 et 2 de la nef

**N° d'inventaire:** N 1b

**Geologie & Site possible:**
- Nummulites
- Étrusque
- Miliolites
- Orbites
- Cérithes
- Algéralines

**Nature:**
- Calcaire
- Grès
- Granit
- Schiste
- Marbre
- Autre: Glacis (cicatrisé) larg.: 18

**Finition:**
- Laiter
- Breture
- Gradine
- Grain d'orge
- Boucharde
- Ripe

**Fossiles visibles:**
- Silex
- Galets

**Équarissage:**
- Chasse
- Pic
- Této
- Polka

**Dégrossissage:**
- Pic
- Brosse
- Cloaque (cicatrisé)

**Traces de taille:**
- Oblique
- Croisée
- Chevron
- Gerbe
desordonnée
- Parallèle

**Longueur:** 47 cm

**Liane associé:**
- Mortier
- Ciment
- Joint sec
- Autre:

**Rendu initial:**
- Sable
- Chaux
- Galet
- Terre cuite
- Incl. métalliques

**Décors sculptés:**
- Feuille d'acanthe
- Grotesque
- Crochet
- Scène historiée
- Héraldique

**Remplissage:**
- Non

**Observations:**
- Décor rubané rouge ajouté lors de restaurations le long de l'extrados et dans les gorges entre les tores et le meplat central.
- Surface visible traitée à la gradine et breture en frappe perpendiculaire; surface enfouie dans la maçonnerie traitée à la breture.
- Réalisation de la croix à la breture. Une branche a été mal réalisée, les coups d'outils n'étant pas alignés.

Date de rédaction: 17 septembre 2020

Rédacteur(s): Cédric Moulis, Bruno Phalip
User experience tests

- nomenclature
- angle measurement
- observation/annotation tests
Lapidary study of the voussoir collection

Digital:
+ No accessibility obstacle
+ Digital surrogate

- Need for digital tool appropriation

-> Adjusting digital protocols and tools as close as possible of archaeological research

Physical:
+ Direct observation
+ Traditional workflow for archaeologists and other specialists

- Accessibility obstacles (work authorization, safety protocols, disperse teams, storage location)
- Handling problems (heavy, pallets)
How to replicate archaeologists or heritage specialists’ work using the 3D models of voussoirs?

Method:

- questionnaire
- interview & work session with archaeologists from the Stone working group
- feedback to 3DHop team
Voussoirs in the remains of the nave

Trajectory of a voussoir after its collapse

Cleaning operations by unmanned machines
Remains sorting, temporary storage on pallets

Trajectory of a voussoir after its collapse

Inventory number attribution & initial inventory

SRA Archaeologists and LRMH: bucket unloading and sorting

Pallet temporary storage
Cleaning operations dataset:

Trajectory of a voussoir after its collapse

Photo sorting/indexing, metadata extraction

Olivier Malavergne, LRMH
Trajectory of a voussoir after its collapse

Decontamination

Voussoir digitization

Eloi Gattet. Mercurio, Feb. 2021
Aïoli for tracking and identifying voussoirs

Use of Aïoli for the spatio-temporal tracking of the voussoirs (De Luca, 2021)
Fall position of voussoirs in the nave
Identification of the voussoir fall location
The collapsed arch reconstruction as an optimization problem

Linear Programming: minimisation of the objective function to be framed by a set of constraints gathered in a system of inequalities

1. **Problem statement + Problem modelling**
2. Import of libraries
3. Declaration of the solver
4. Creation of variables (constants and decision vars.)
5. Definition of the objective function
6. Definition of constraints
7. Invocation of the solver
8. Display and analysis of the solution(s)

(Gros Antoine, Duvocelle Benoit, 2022)
The collapsed arch reconstruction as an optimization problem

<table>
<thead>
<tr>
<th>solution type</th>
<th>Width</th>
<th>Fall Location</th>
<th>Keystone</th>
<th>Crosses</th>
<th>Notches</th>
<th>Notches Location</th>
<th>PA Clusters</th>
<th>total number of replaced voussoirs</th>
<th>violations</th>
<th>average model confidence</th>
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<tbody>
<tr>
<td>Physical Anastylosis</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>36 (50%)</td>
<td>4</td>
<td>na</td>
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<tr>
<td>Digital ‘gl’</td>
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<td></td>
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<td></td>
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<td>71 (100%)</td>
<td>2</td>
<td>19.46%</td>
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<tr>
<td>Digital ‘glec’</td>
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<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>x</td>
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<td>x</td>
<td>71 (100%)</td>
<td>0</td>
<td>73.55%</td>
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</table>

**Table 1.** Detailing of the milestone models for reconstruction hypothesis with their performance and uncertainty. With gl: gaussian distribution of width; ec: notches and crosses; r: matching fall location with slot location; t: notches locations; hybrid hypothesis: full LP model with pairs from the physical anastylosis input.
The collapsed arch reconstruction as an optimization problem

Visualization in the 3D viewer of the reconstruction hypothesis (Gros, Abergel, 2022)
Reconstruction hypothesis tests, communication about different hypothesis, general audience dissemination
(Journée du Patrimoine, 2021)
FSP-REPERAGE Project and Notre-Dame Working Groups

REPERAGE Project team:
Livio de Luca (MAP), Dorothée Chaoui-Derieux (SRA), Antoine Gros (MAP), Anaïs Guillem (FSP), Lise Leroux (LRMH), Olivier Malavergne (LRMH), Thierry Zimmer (LRMH).

Stone Working Group: especially Élise Bailleul (UMR 8529-IRHiS), Cédric Moulis (EA1132- Hiscant-MA), Bruno Phalip (Université Clermont-Auvergne)

The whole team of the Digital Data Working Group