International Association for Bridge and Structural Engineering

Seismic assessment and strengthening of Dutch heritage churches with masonry vaults

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Arnhem, The Netherlands

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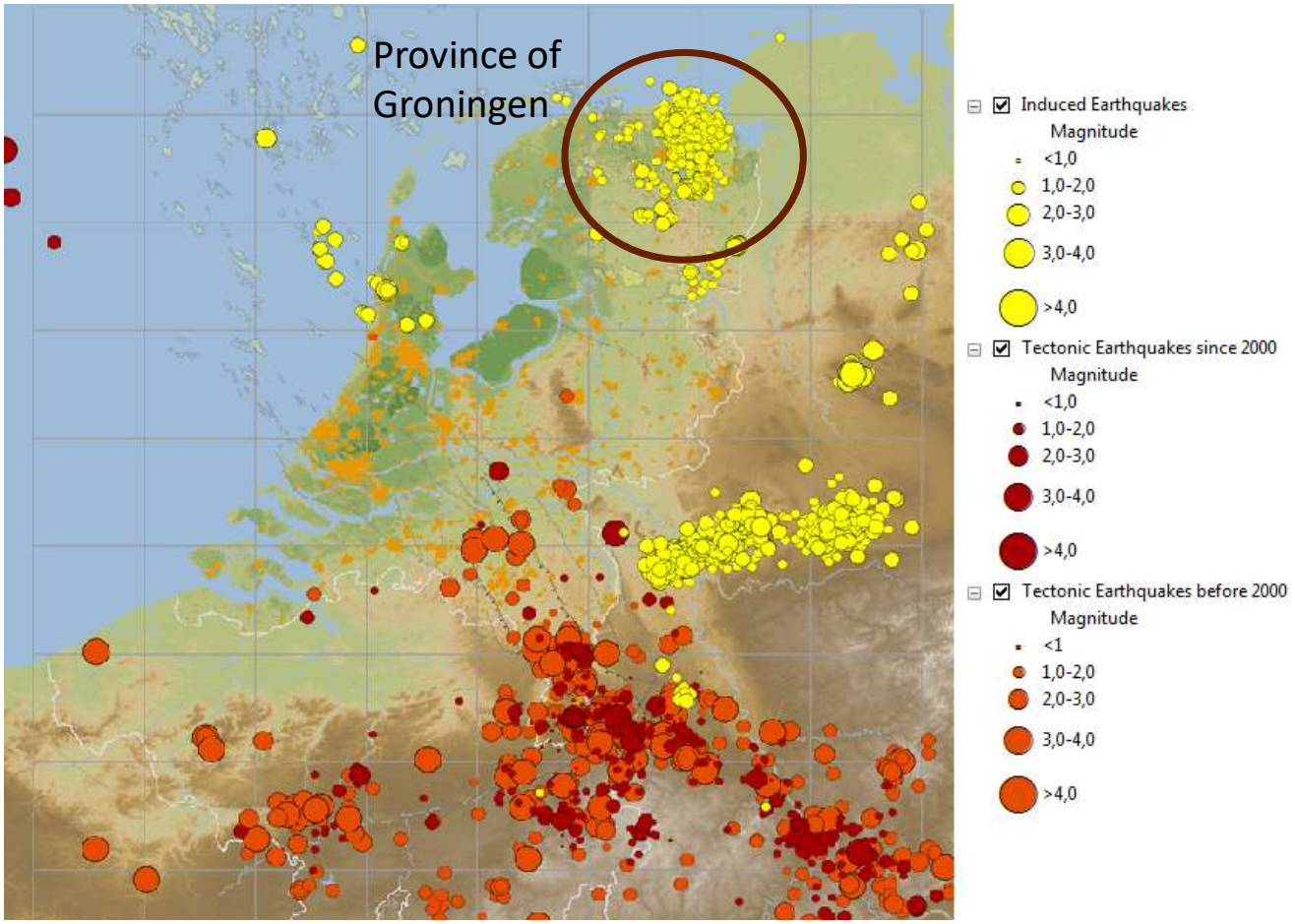
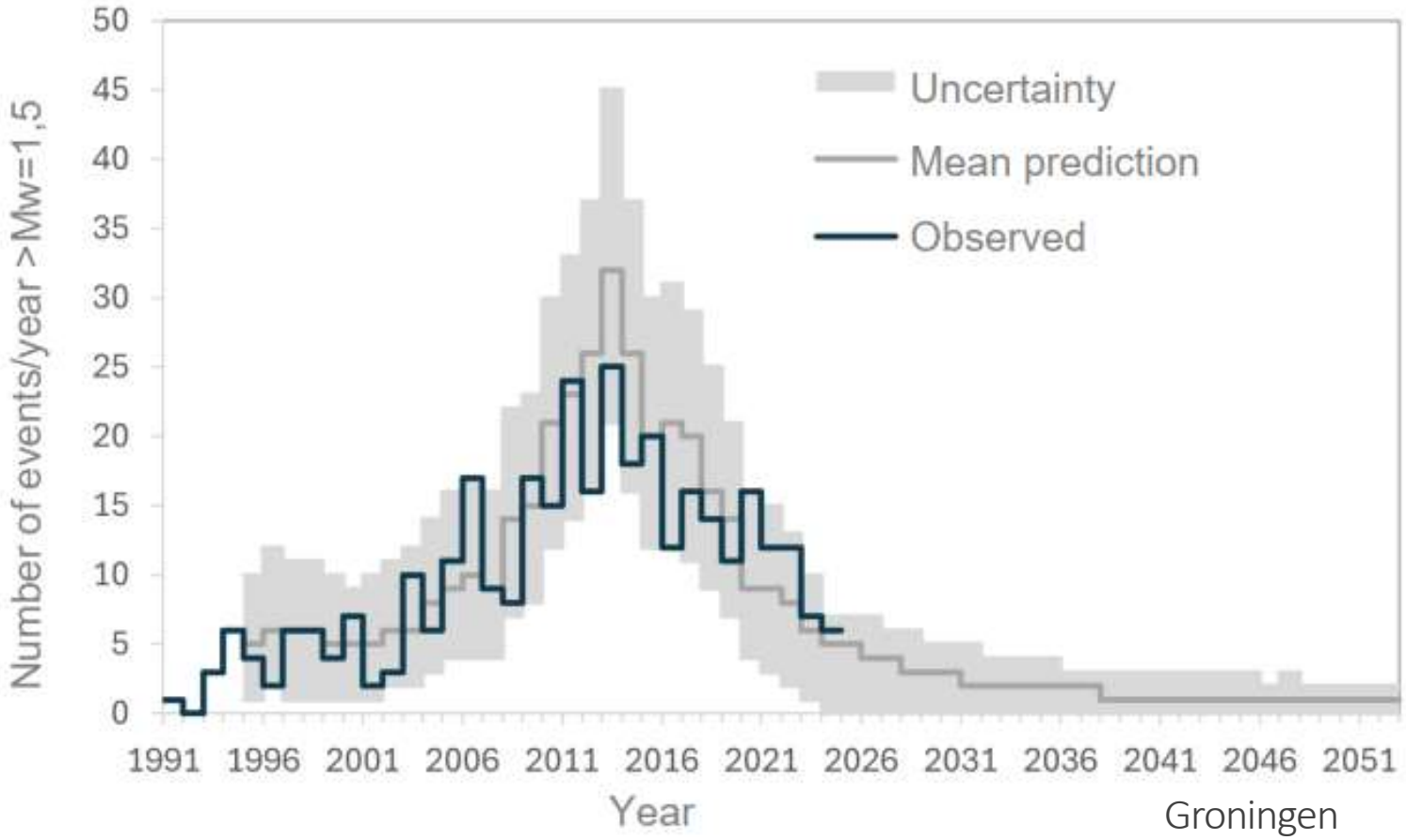
Studio Calvi,

Pavia, Italy

Hazard

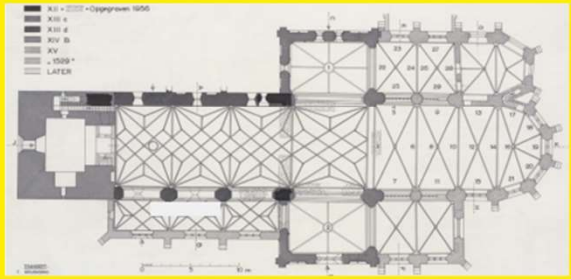

Province of Groningen
Induced Earthquakes
Magnitude
<1,0
1,0-2,0
2,0-3,0
3,0-4,0
>4,0
Tectonic Earthquakes since 2000
Magnitude
<1,0
1,0-2,0
2,0-3,0
3,0-4,0
>4,0
Tectonic Earthquakes before 2000
Magnitude
<1
1,0-2,0
2,0-3,0
3,0-4,0
>4,0

Hazard



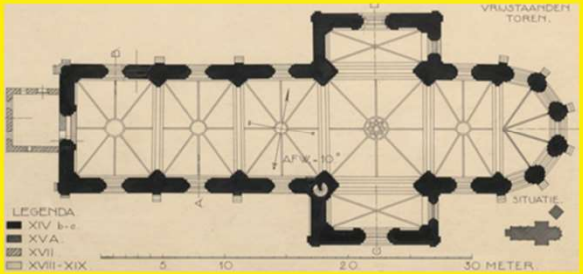
Groningen

Scope



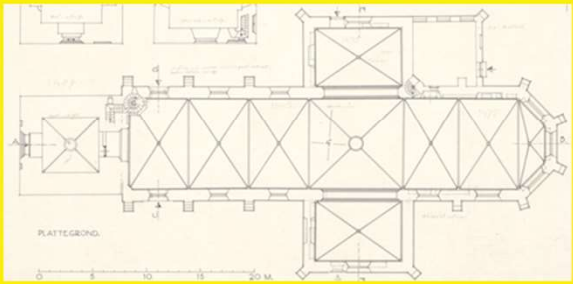
Loppersum

Scope



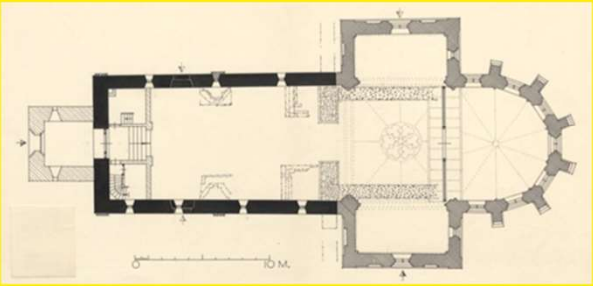
Zeerijp

Scope



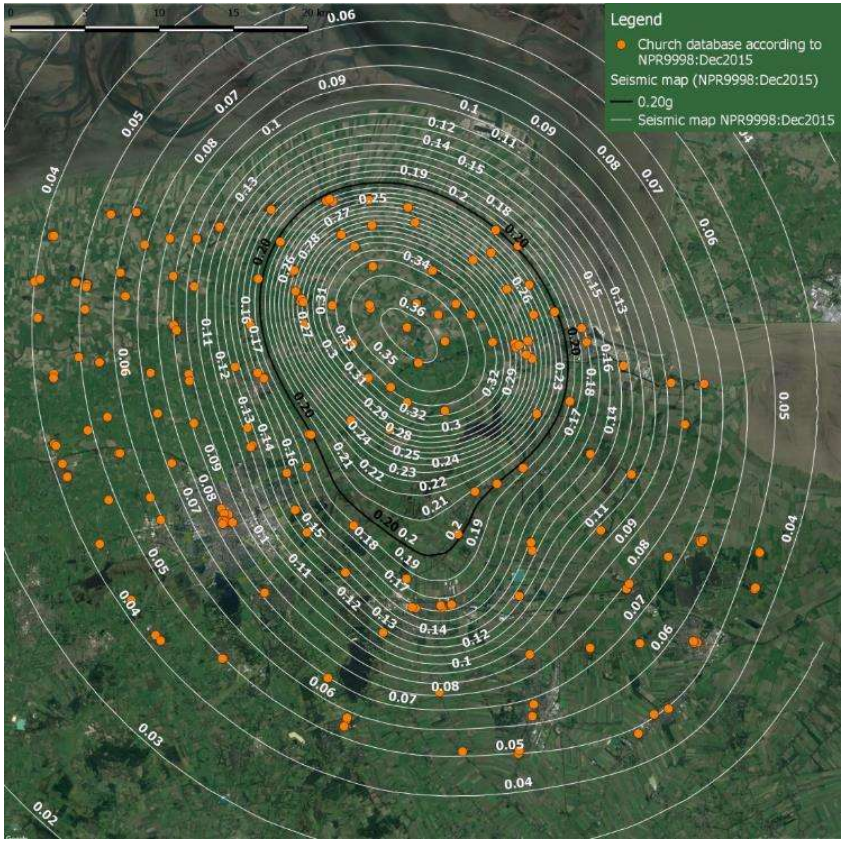
Middelstum

Scope

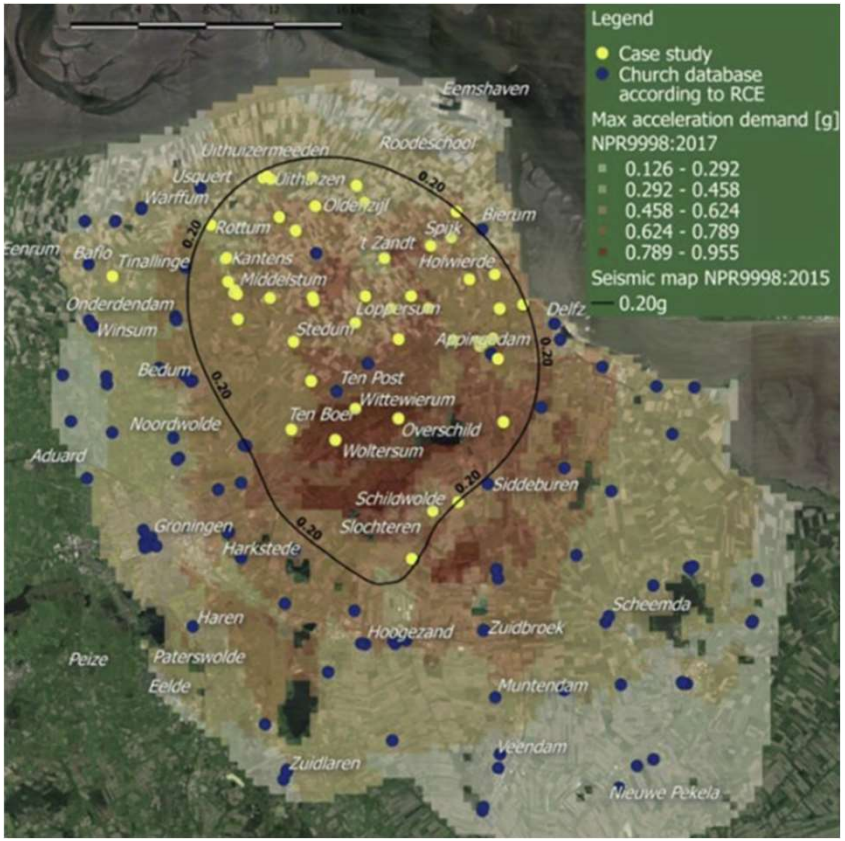


Holwierde

Scope

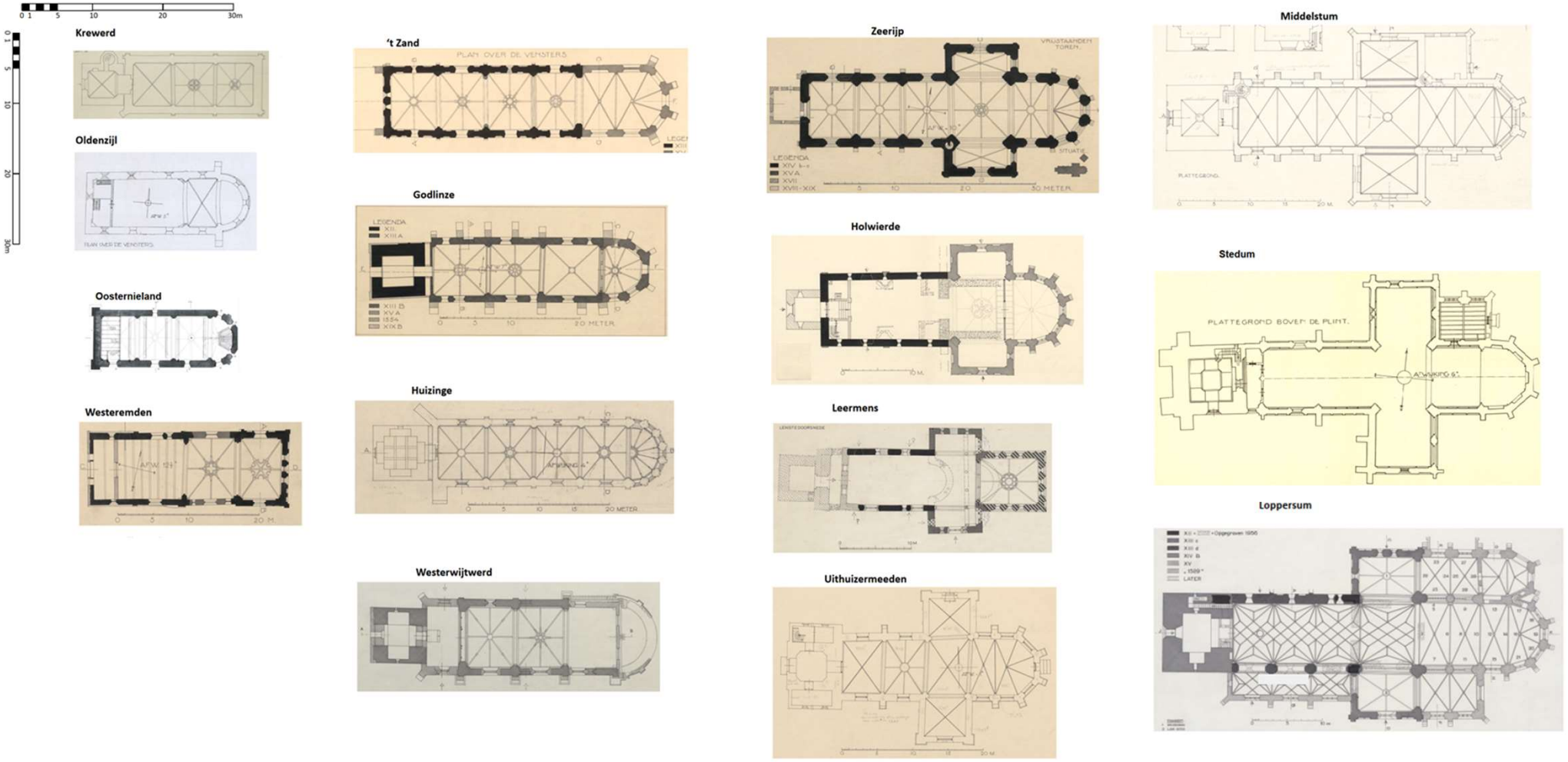


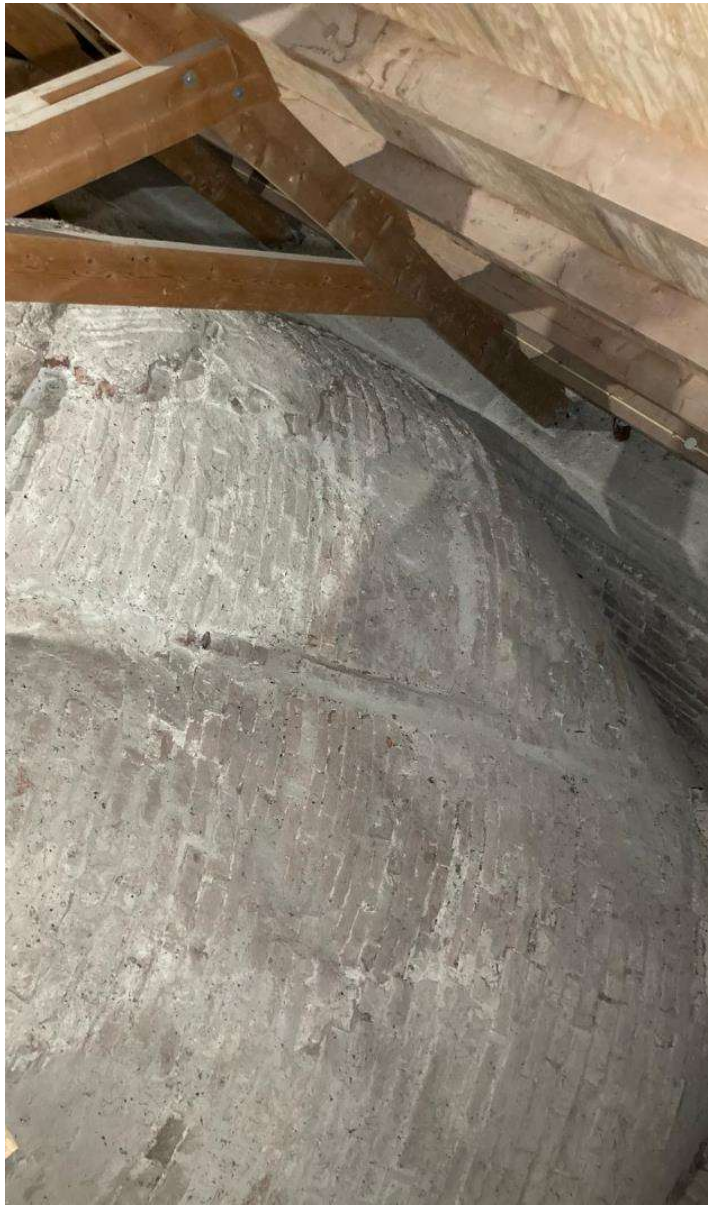
Dec 2015 → 224 monumental churches

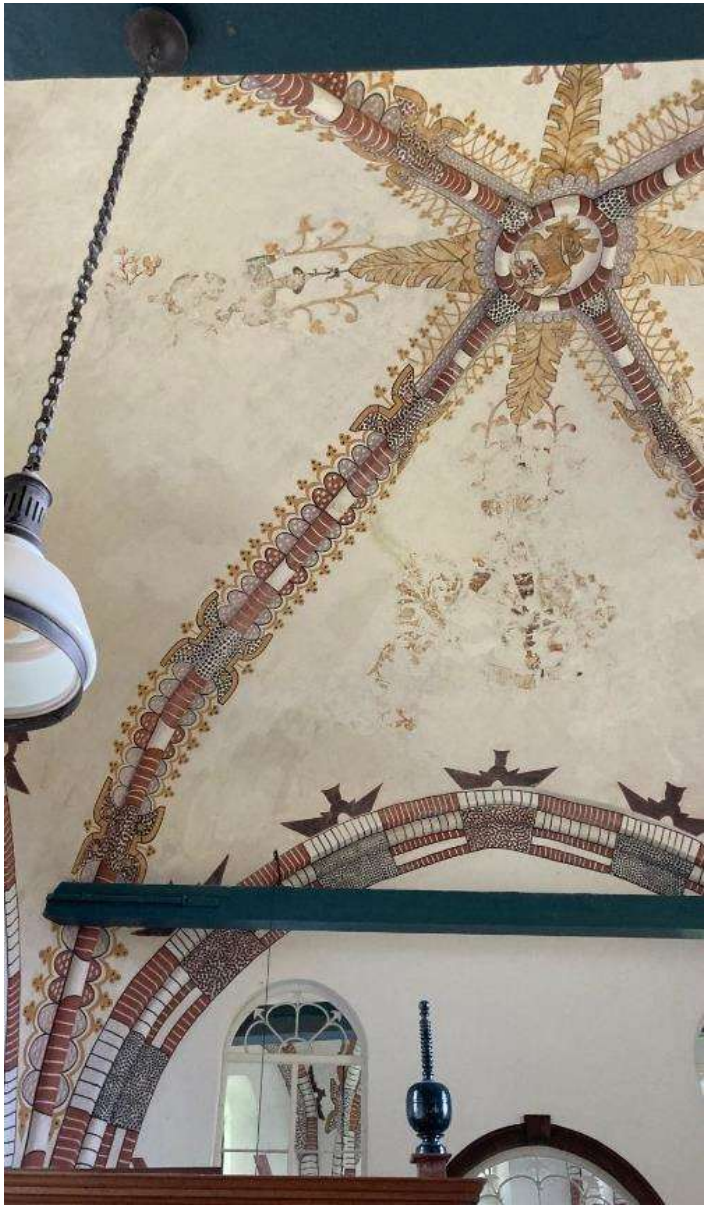


Now → 54 monumental churches have been assessed
- 18 churches strengthened
- 15 **masonry vaults**

Scope


Krewerd
Oldenzijl
Oosternieland
Westeremden
't Zand
Godlinze
Huizinge
Westerwijtwerd
Zeerijp
Holwierde
Leermens
Uithuizermeeden
Middelstum
Stedum
PLATTEGROND BOVEN DE PLINT.
Loppersum

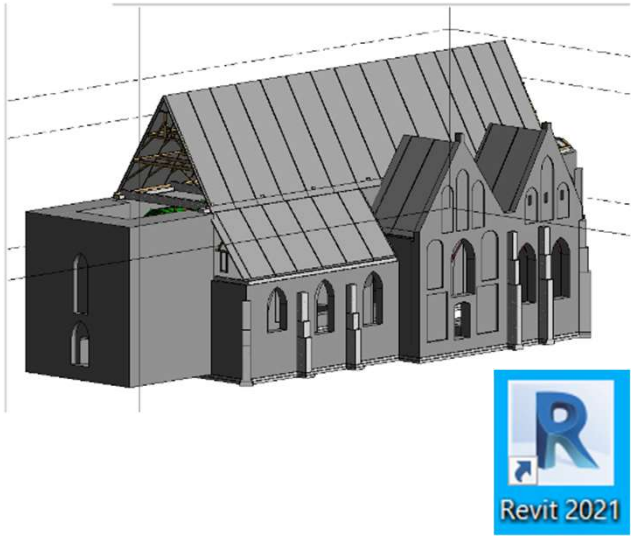


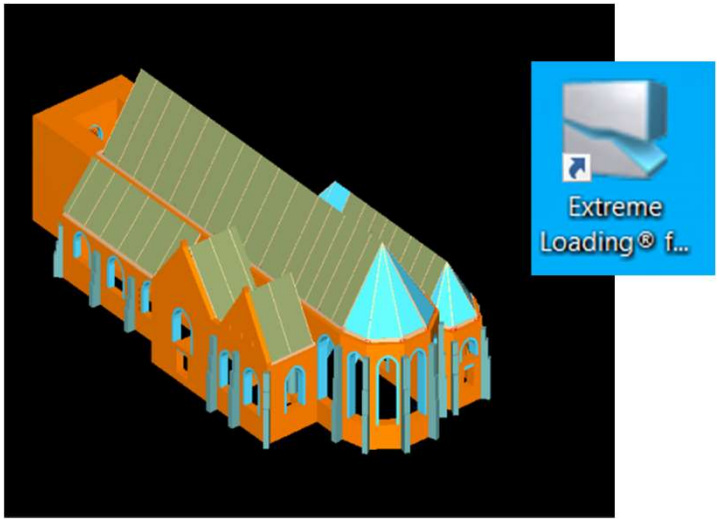



19/07/2017

Assessment

Point Cloud → Revit Model → Structural model

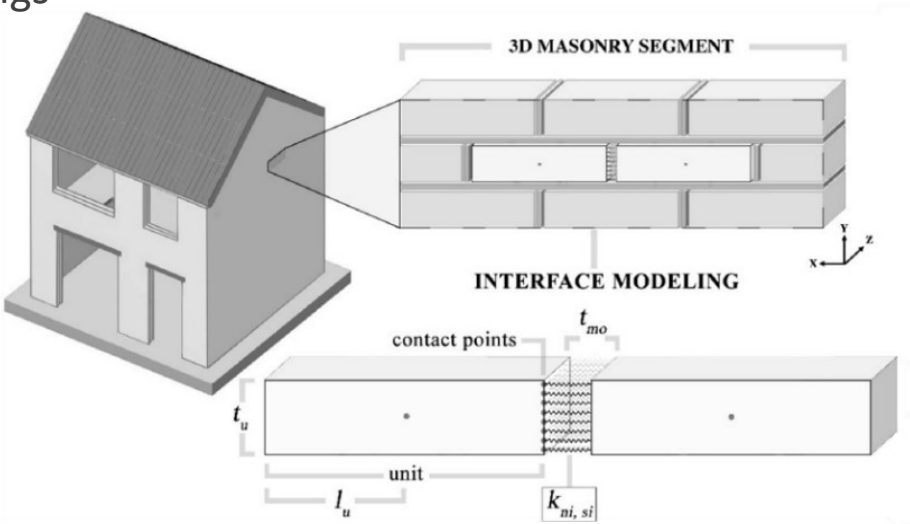




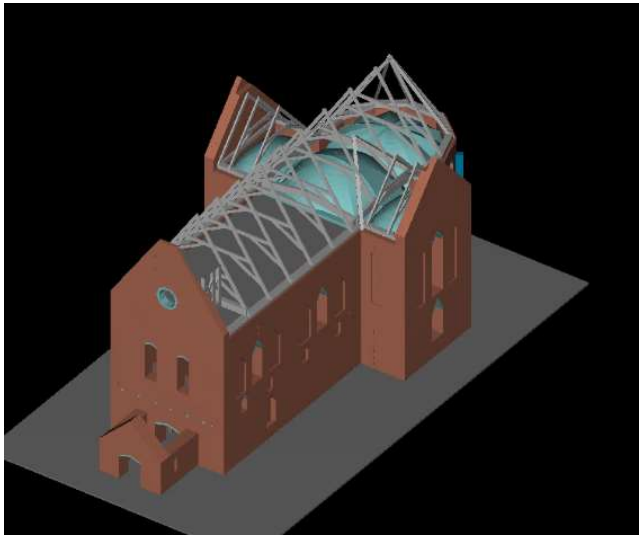
Assessment

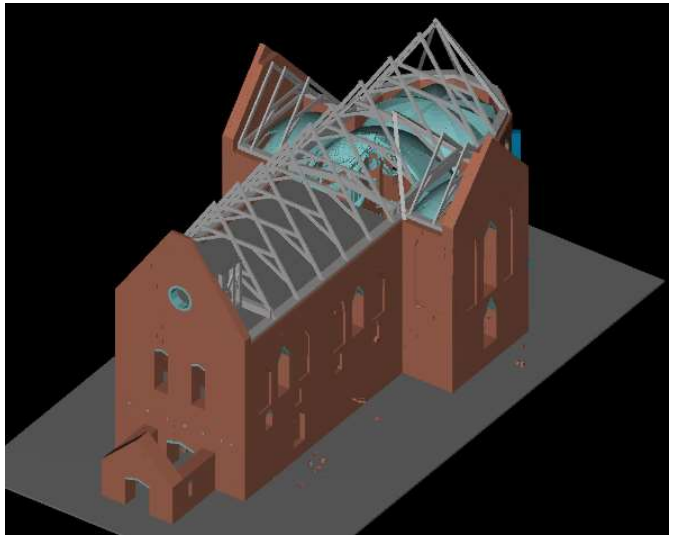
The chosen software for detailed NLTH (Non-Linear Time History) analysis is Extreme Loading for Structures based on the Applied Element Method (AEM):

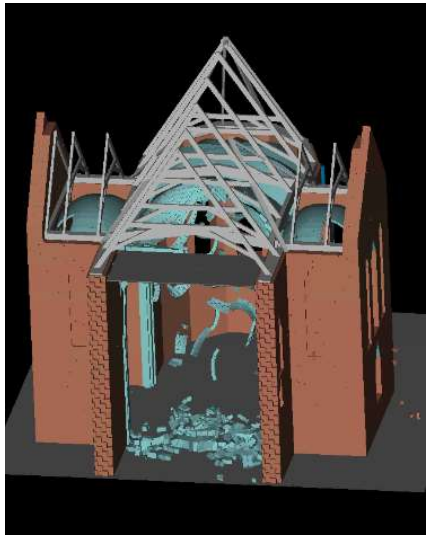
- Rigid body and spring model (discrete element family)
- Each brick/mesh element modeled separately and fully rigid
- System deformability lumped in zero-thickness interface springs



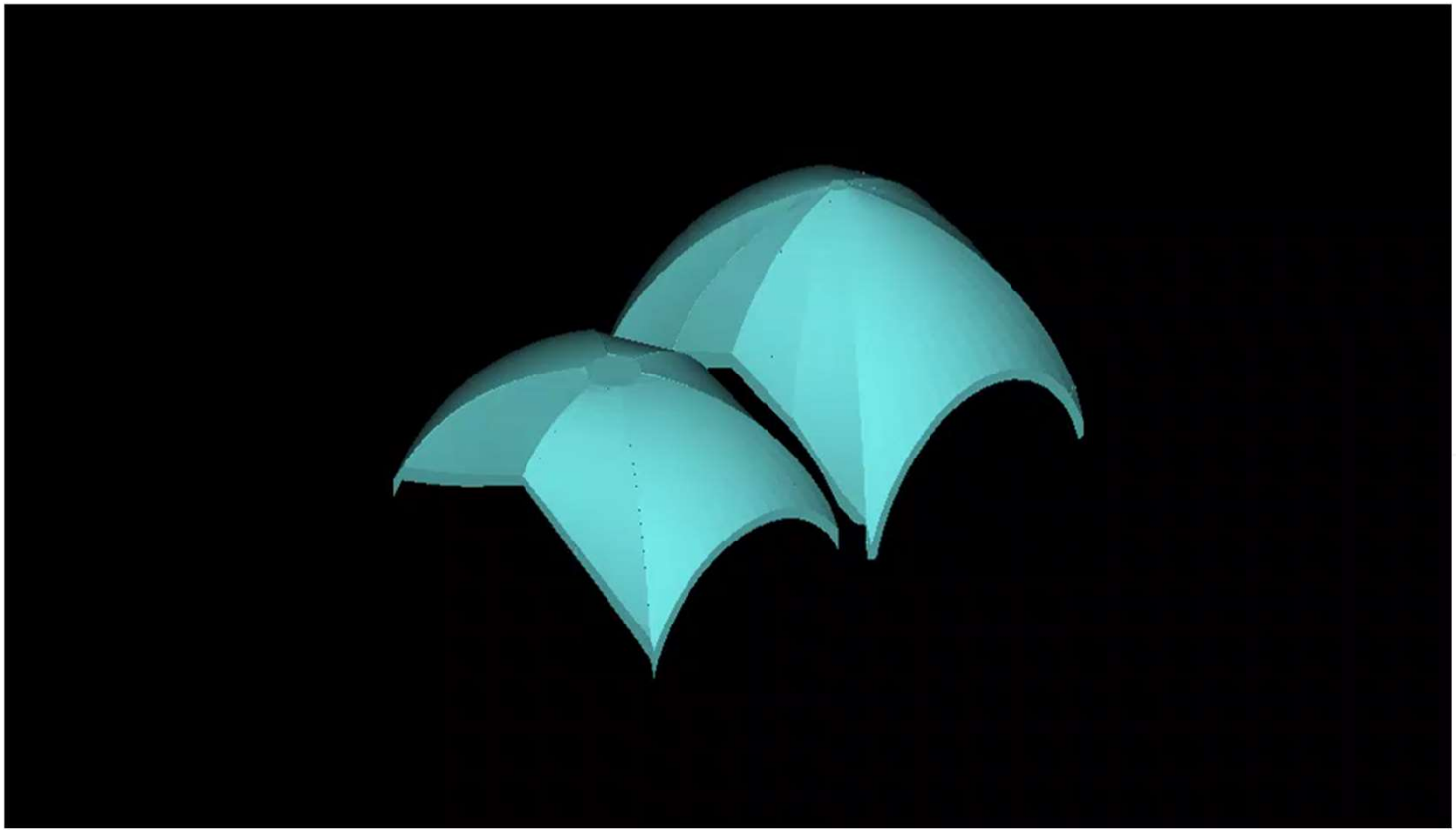
Assessment

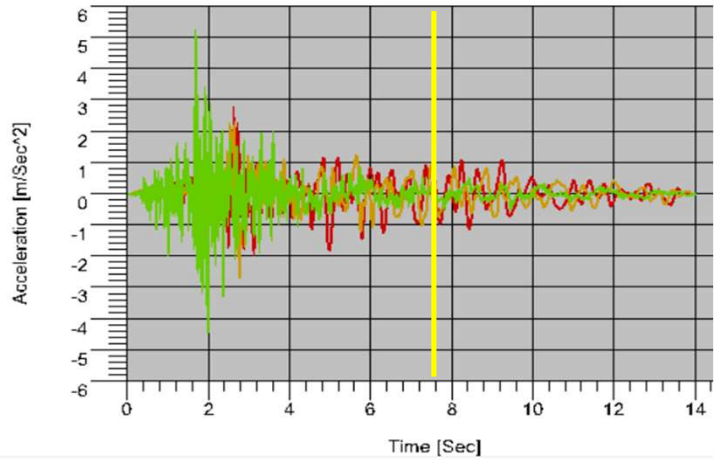






Assessment





Possible retrofitting solutions for vaulted ceiling

Steel diaphragm

Ties at the intrados

FRP/FRCM

Main requirements of the retrofitted solution:

- It must be compliant with the code
- It has to respect the artistic and historic value of the church

Possible retrofitting solutions for vaulted ceiling

Example of application of FRP: ex-monastery in Bergamo (Italy) (project by Studio Calvi)

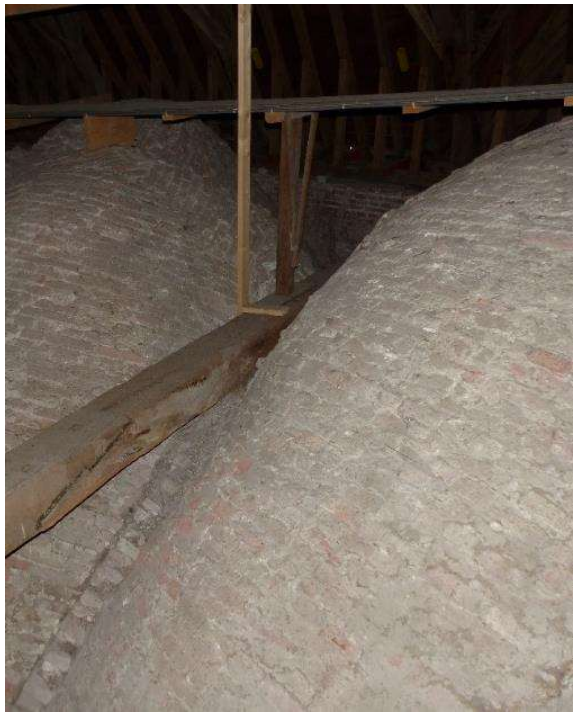
Example of application of FRCM: ex-Church in Cremona (project by Studio Calvi)

FRP system (fiber-reinforced polymer) consists of a sequence of one or more plies of unidirectional fibers embedded in a chemical bonding resin

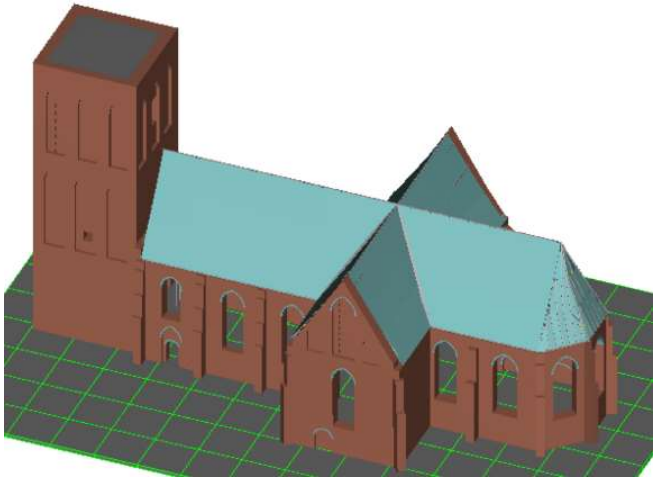
FRCM system (fiber-reinforced cementitious matrix) is a thin structural layer which combines:

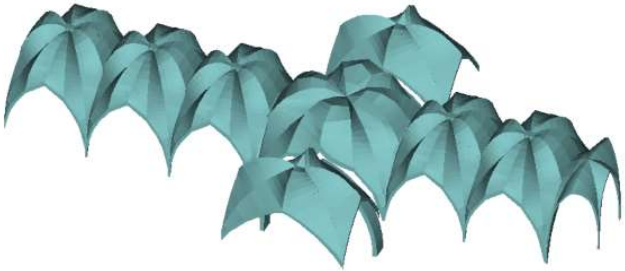
- specially designed mortar (that does not contain synthetic polymers);
- fibers mesh reinforcement (glass, basalt, aramid or galvanized steel).

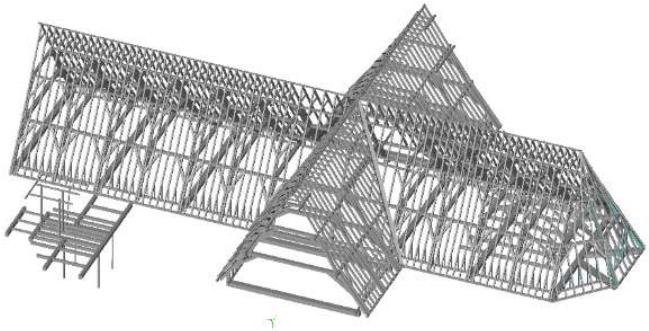
Case study



ELS Model



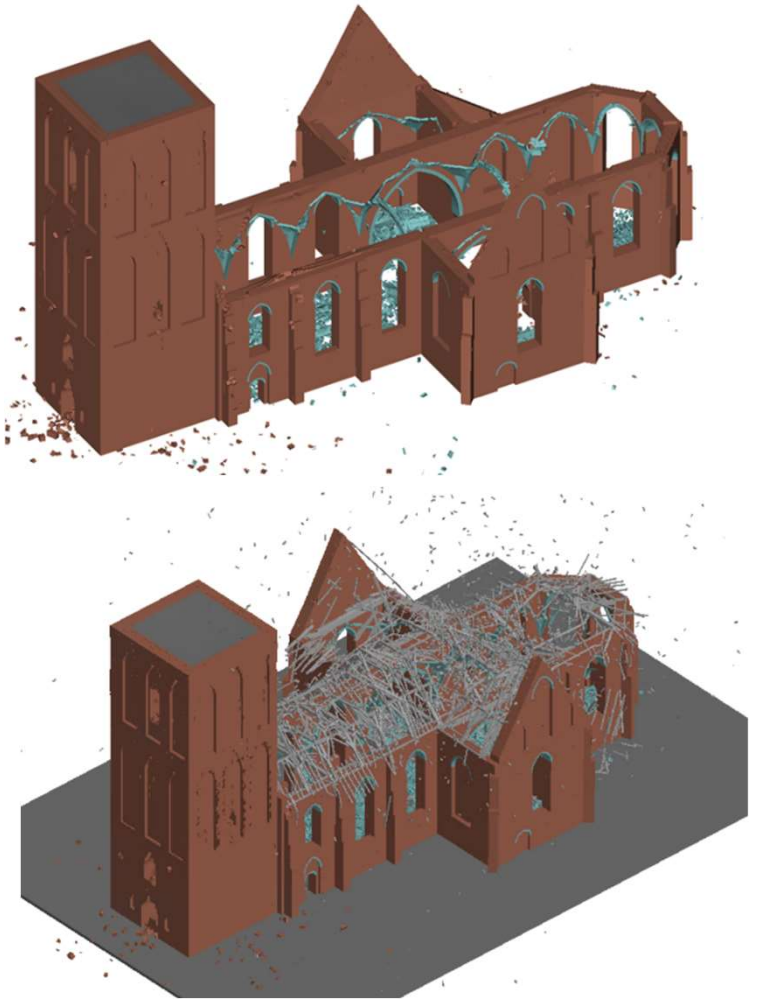




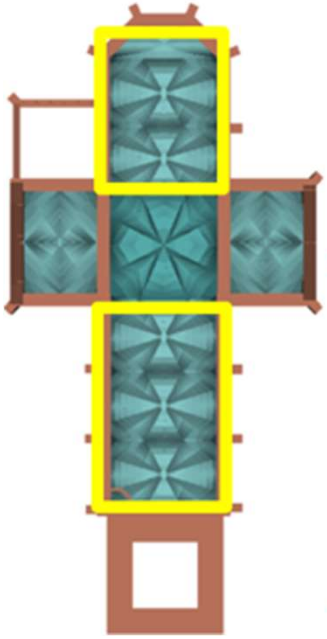
Assessment results

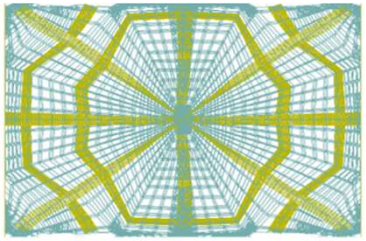
Configuration	Final results
Original	Complete failure of vaults and roof.

Earthquake	Final results
#1	Collapse
#2	Collapse
#3	Collapse
#4	Collapse
#5	Collapse
#6	Collapse
#7	Collapse
#8	Collapse
#9	Collapse
#10	Collapse
#11	Minor failure in the roof

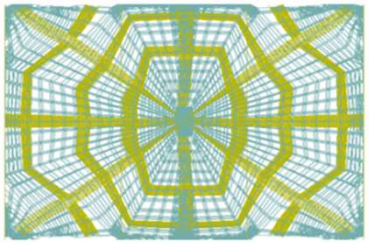


Options for central nave:

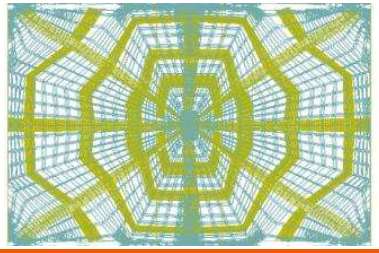


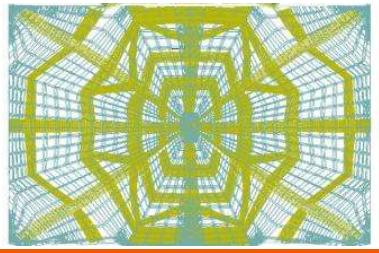


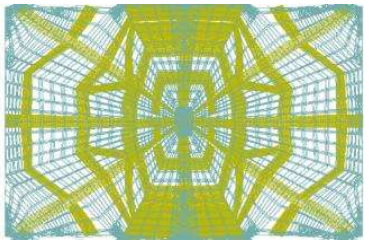
Layout 1
Retrofit layout for indicated vaults



Layout 2
Incremented amount of strips from previous layout

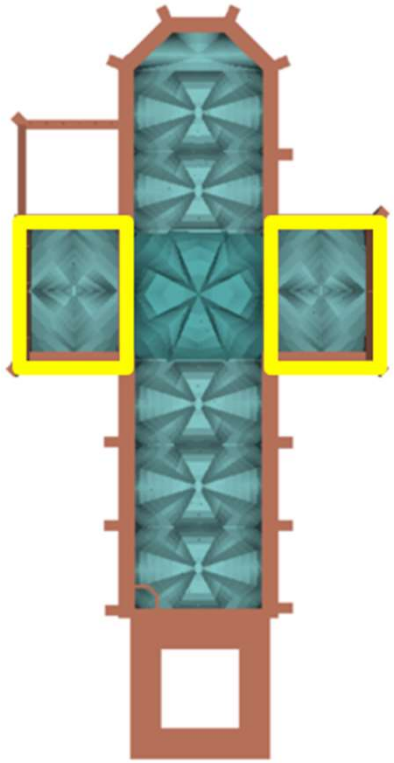






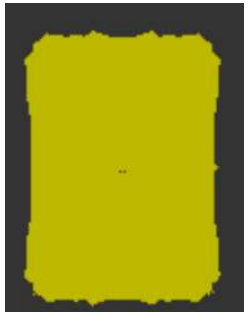
Layout 3-4-5
Incremented amount of strips from previous layout

Options for transept:



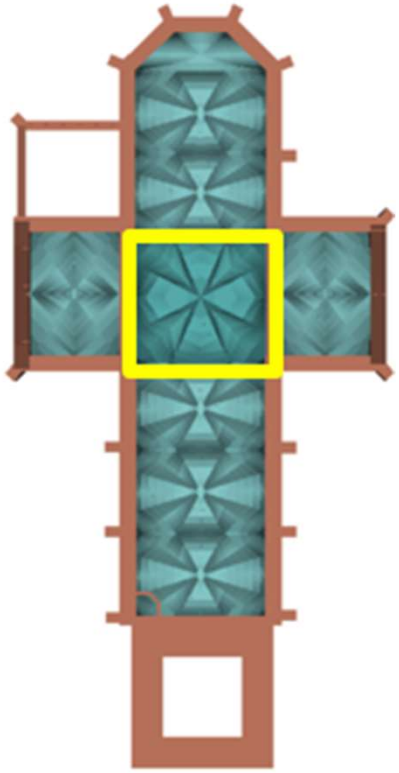
Layout 1*: Retrofit layout for transept vaults

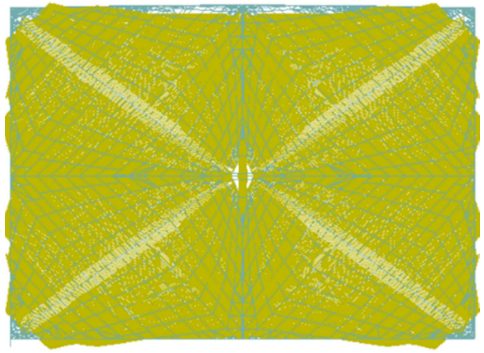
Layout 2*: Incremented amount of strips from previous layout



Layout 3*: total FRCM

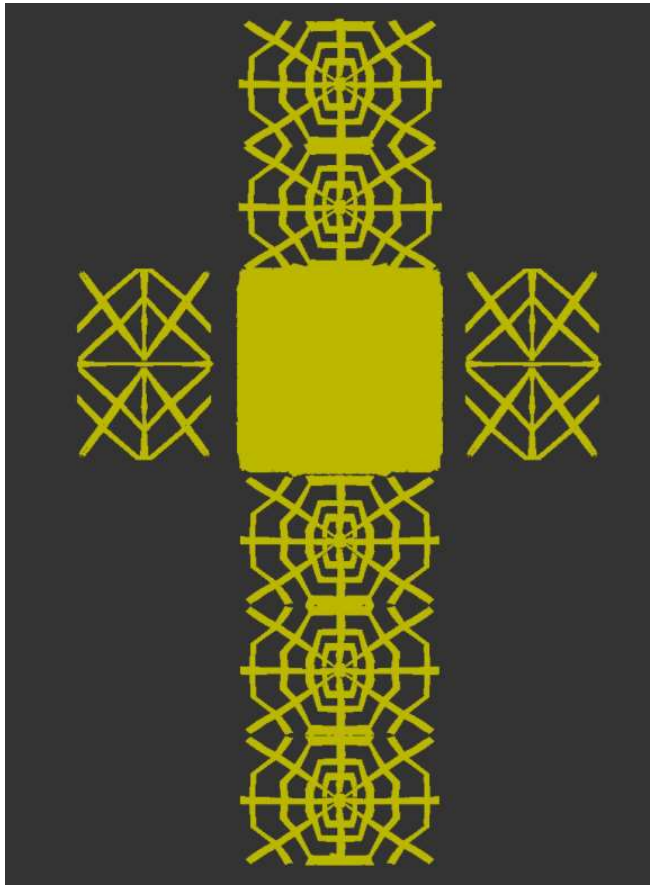
Option for central vault:

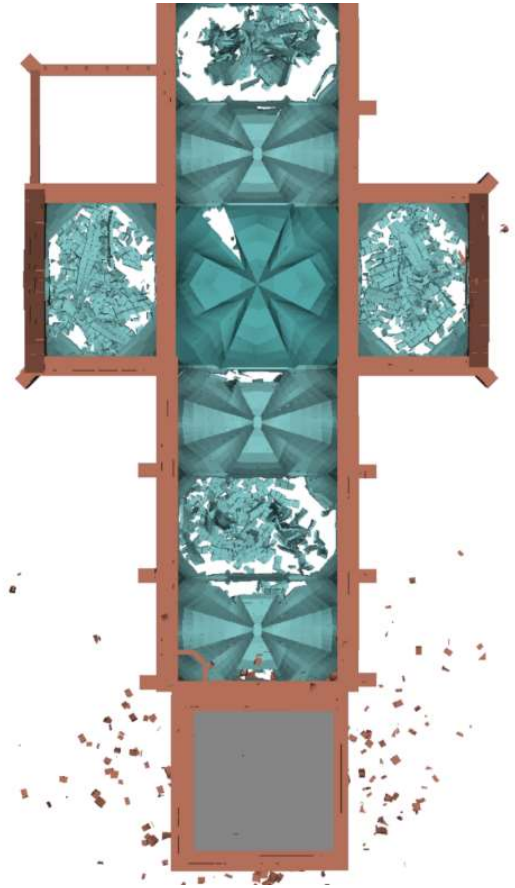




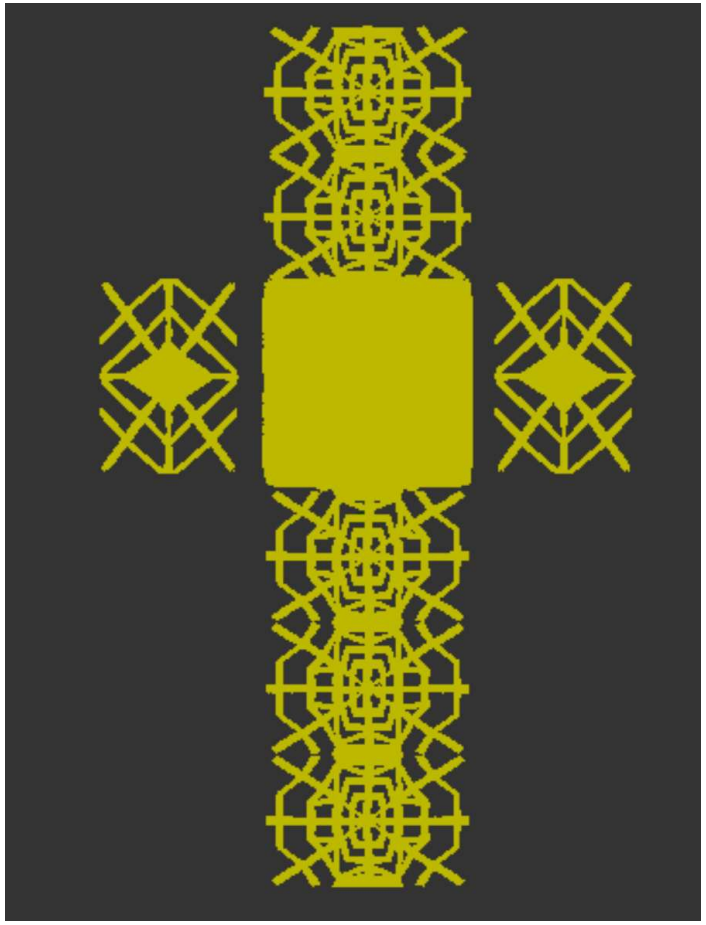
Layout c*: total FRCM

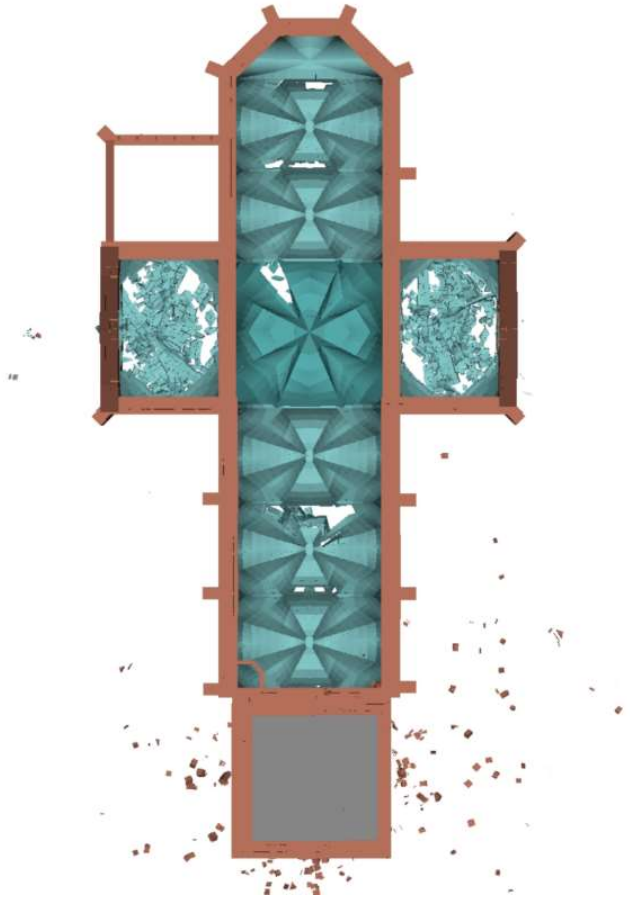
Result of one of the combinations of various layouts



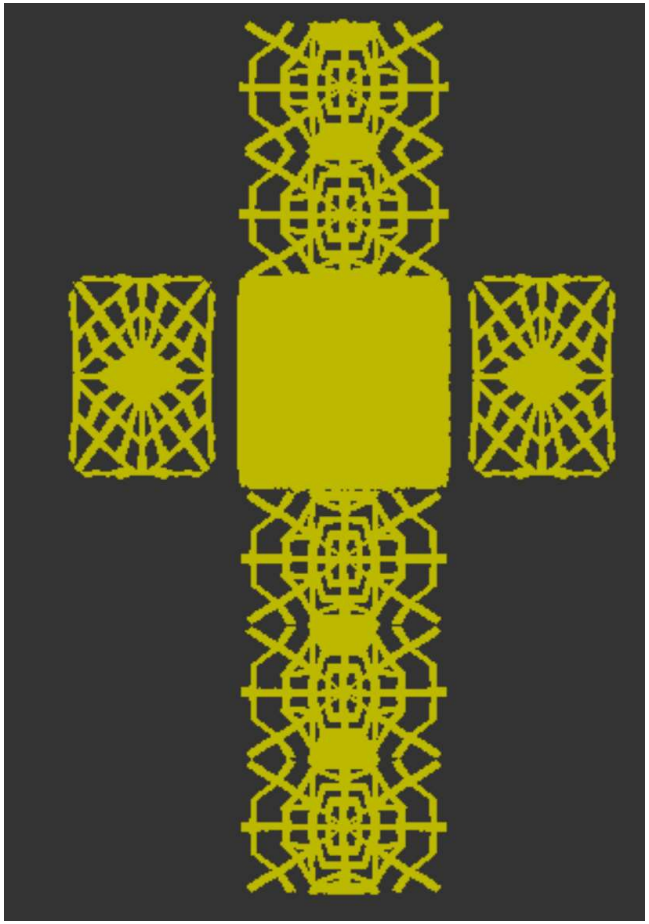


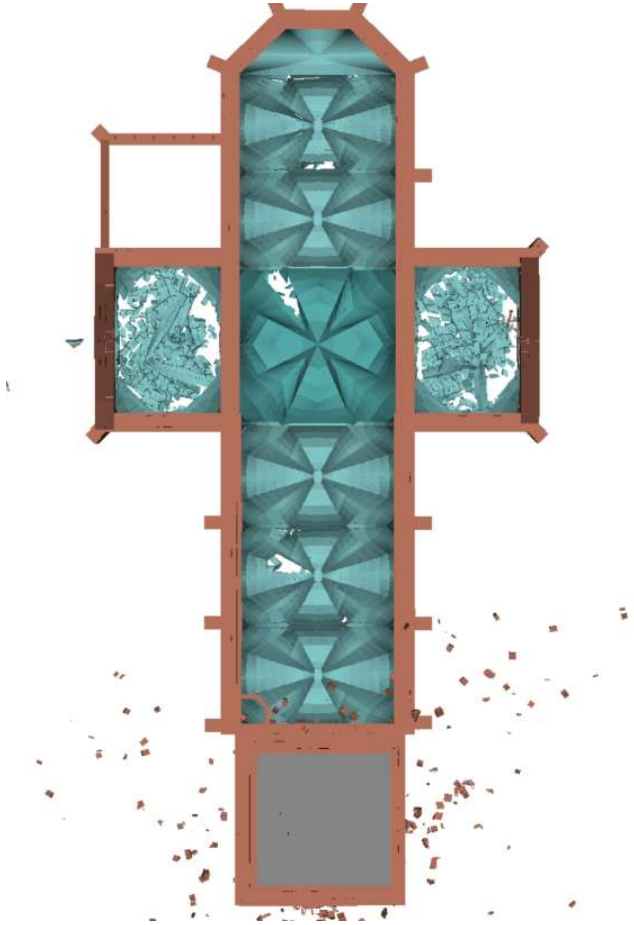
Result of one of the combinations of various layouts



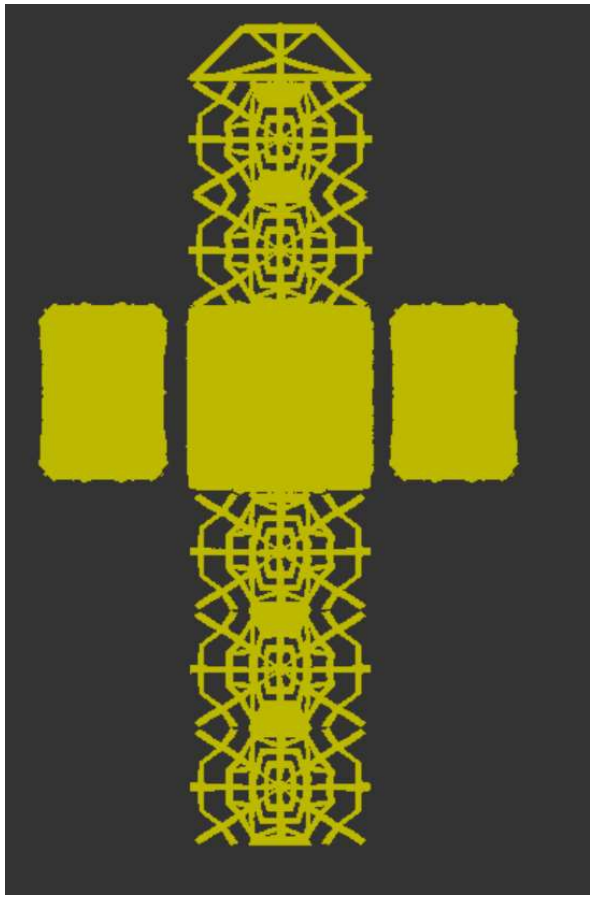


Result of one of the combinations of various layouts

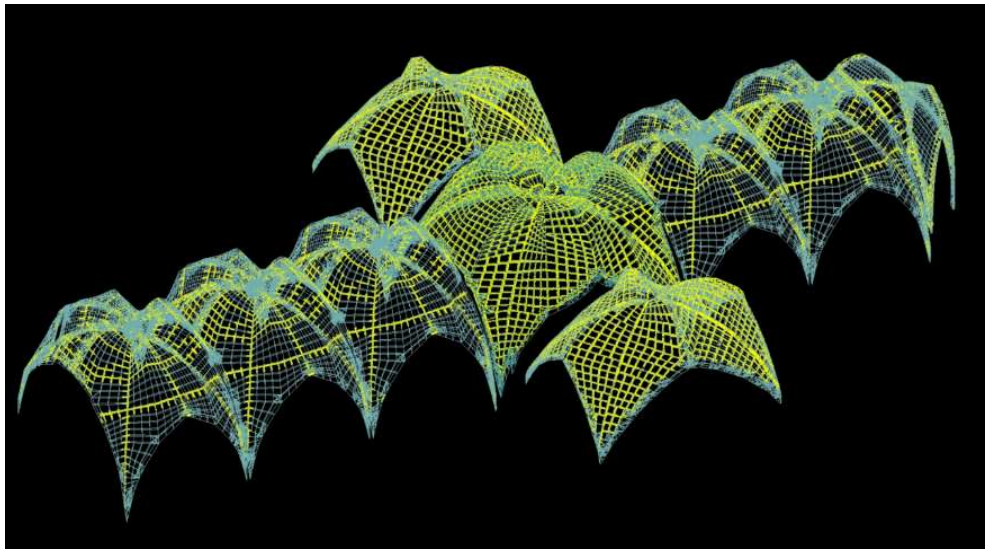




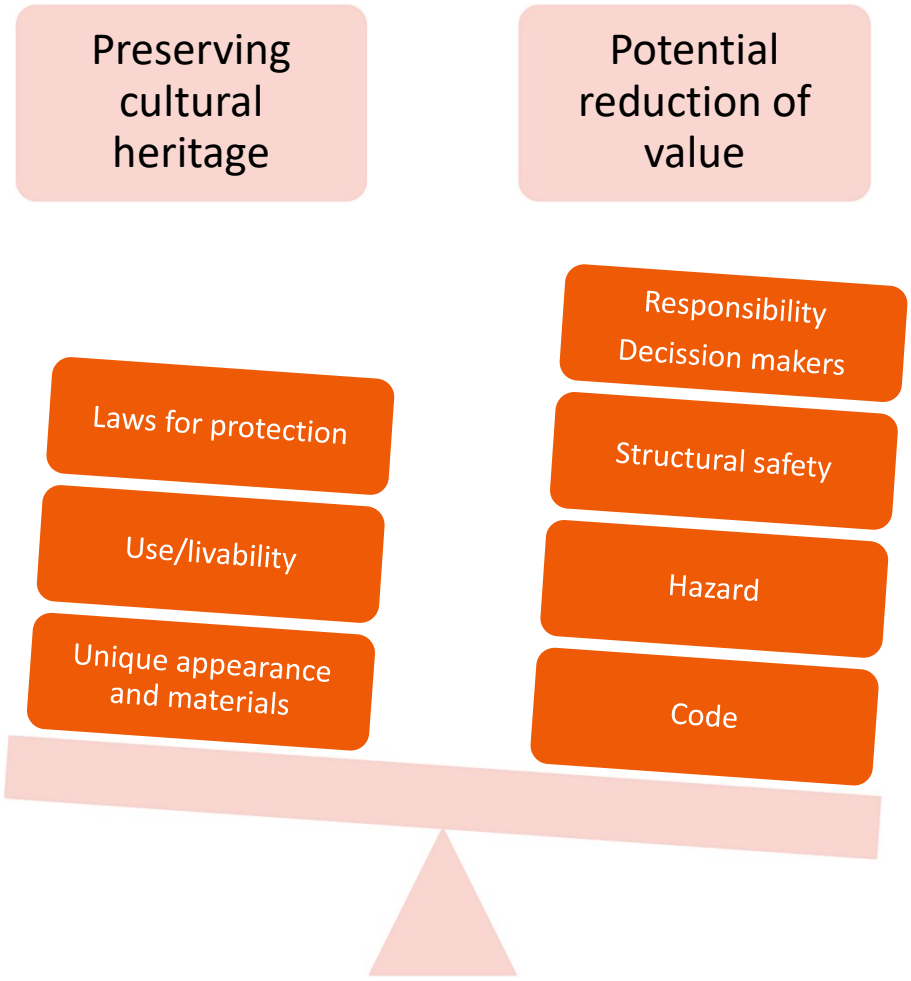
Final layout



Combination of different FRCM configurations for each vault



Discussion


Preserving cultural heritage
Potential reduction of value
Laws for protection
Use/livability
Unique appearance and materials
Responsibility Decission makers
Structural safety
Hazard
Code

abt STUDIO CALV BEAM

IABSE

Questions?