The Cost of Neglect

A State-Dependent Framework for Quantifying the Flood Risk of Historic Masonry Buildings

MSc Thesis, A4

[Bart Koppejan, TU Delft, 24-06-2026]

flood risk = hazard x exposure x vulnerability

[1]

Hazard return period & intensity

x

[2]

Exposed assets

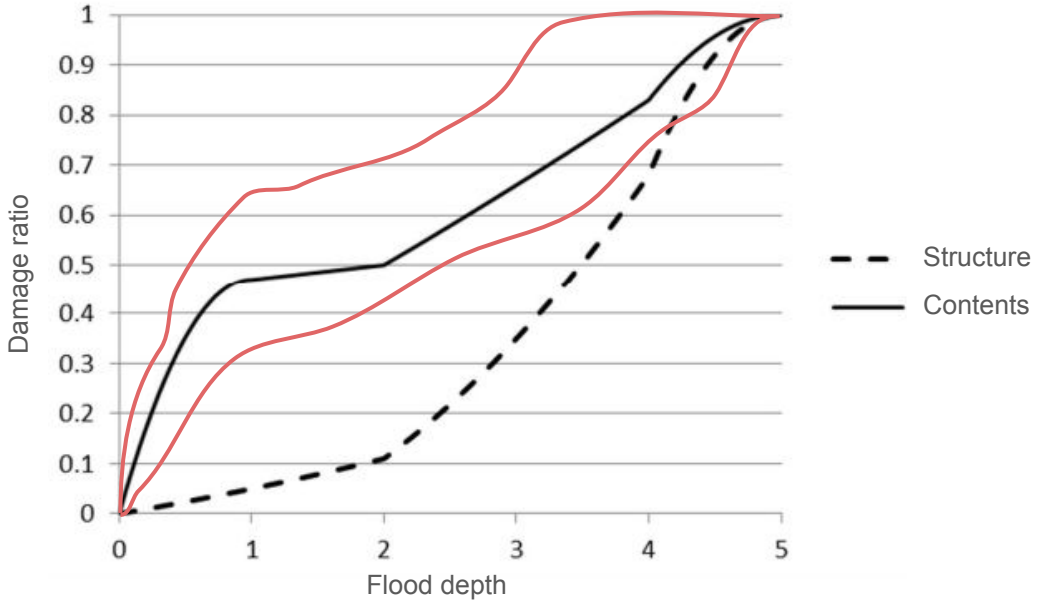
x

[3]

Vulnerability of assets

Vulnerability Curve

Vulnerability curve for single-family dwellings in the Netherlands

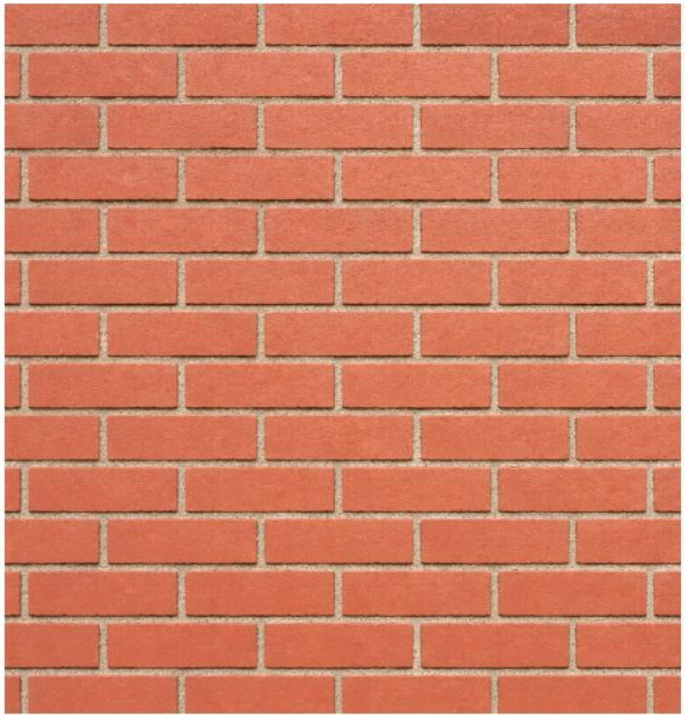


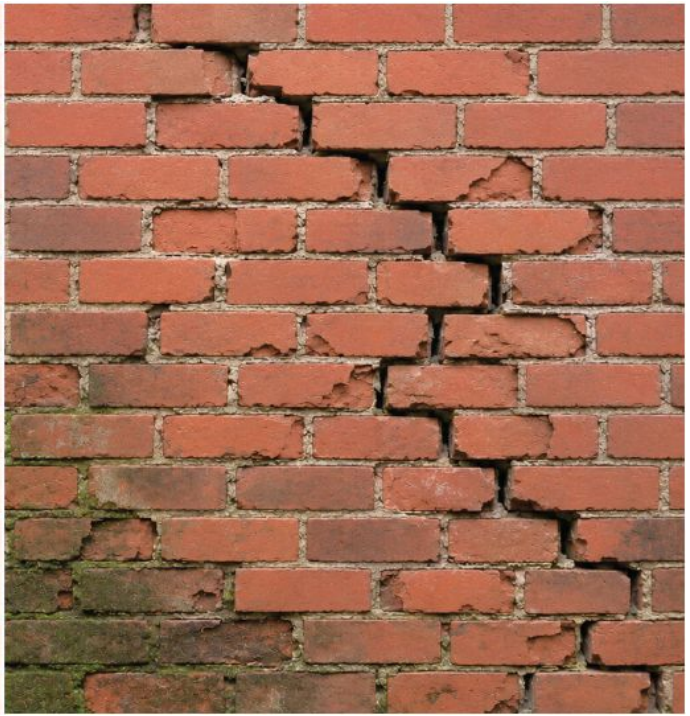
Slager, K., & Wagenaar, D. (2017). *Standaardmethode 2017 Schade en slachtoffers als gevolg van overstromingen* (Nos 11200580–4; pp. 1–27). Deltares.

Research Question

To what extent does the integration of pre-flood conservation states alter the quantification of building-specific vulnerability within probabilistic flood risk assessment?

Research Question



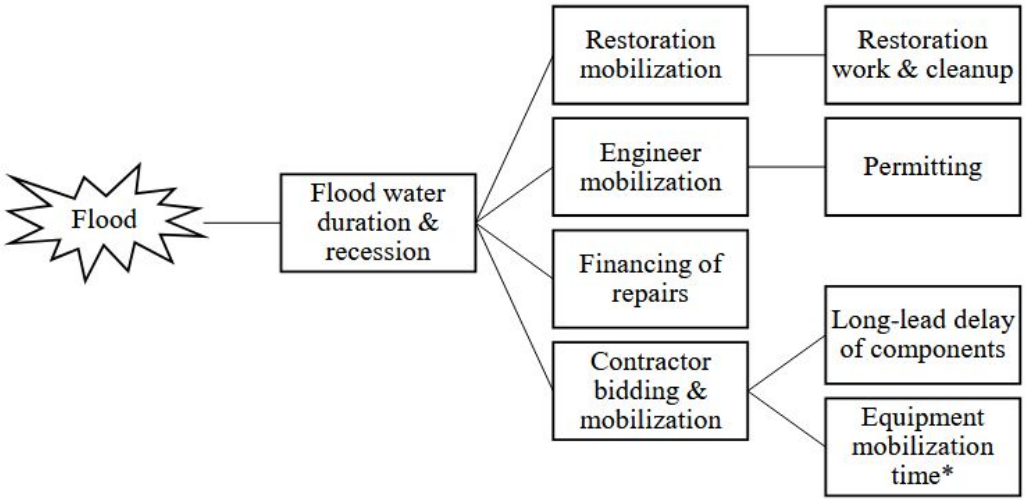


flood risk = **hazard** x **exposure** x **vulnerability**

flood risk = hazard x exposure x vulnerability

Re-Occupancy Downtime

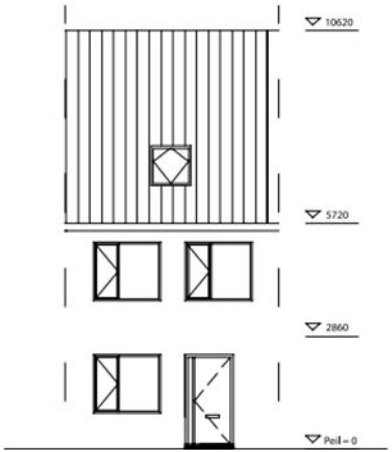
REDi flood recovery impeding delay sequences:



Hogan, J., Almufti, I., & Ackerson, M. (2023). *REDi: Resilience-Based Design Guidelines for Floods* [Technical report].

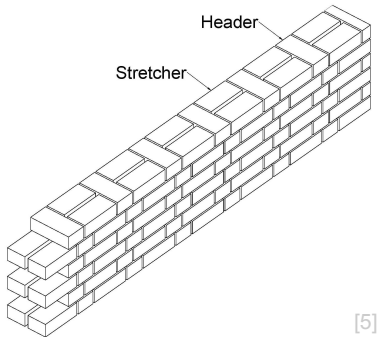
flood risk = hazard x exposure x vulnerability

Archetype



[4]

	Case Study
Building year	<1964
Total floor area (m2)	100.8
Total height (m)	9.00
Ground floor area (m2)	46.64
Closed facade (m2)	43.45
Window area (m2)	20.78
Door area (m2)	4.15
Sloped roof (m2)	49.29
Width (m)	5.1
Depth (m)	9.1



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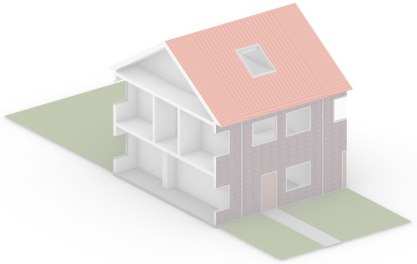
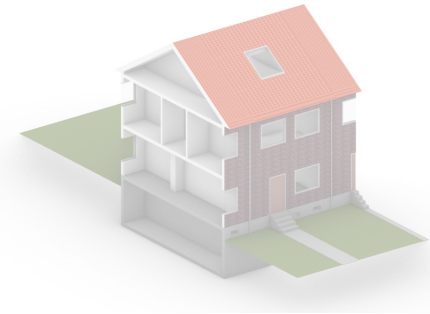
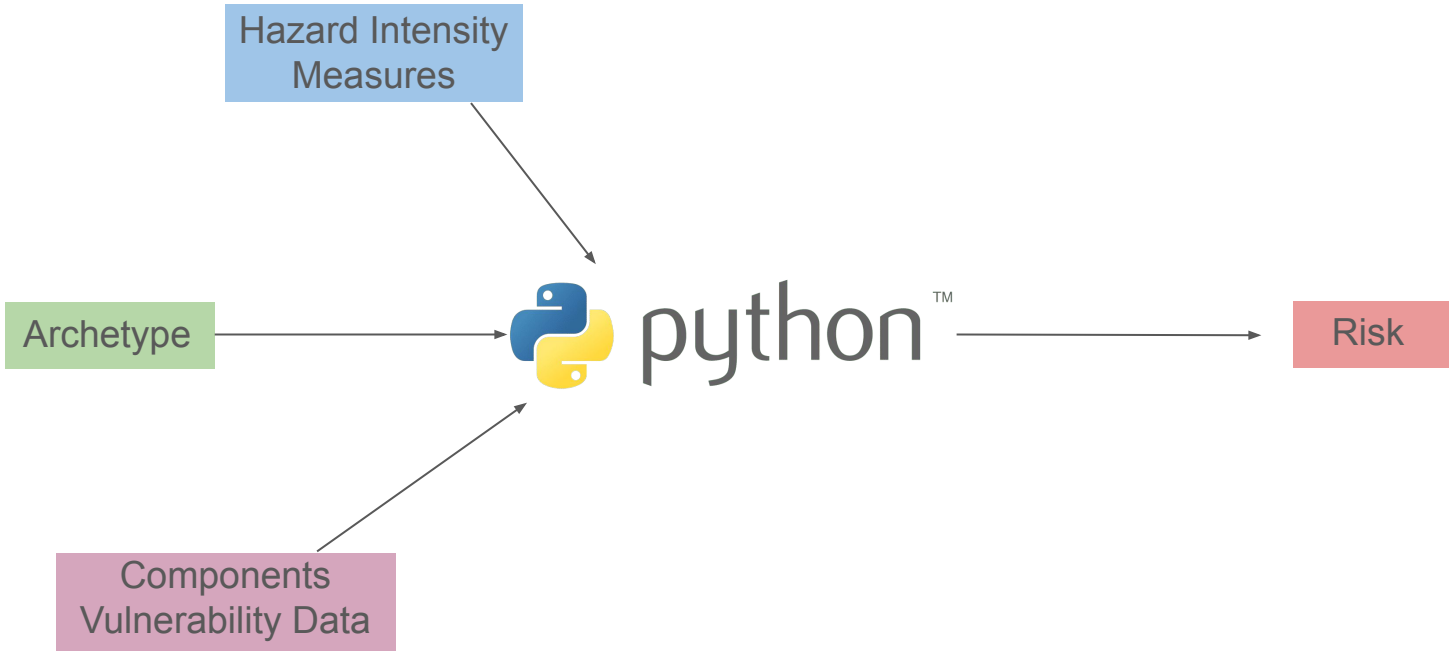


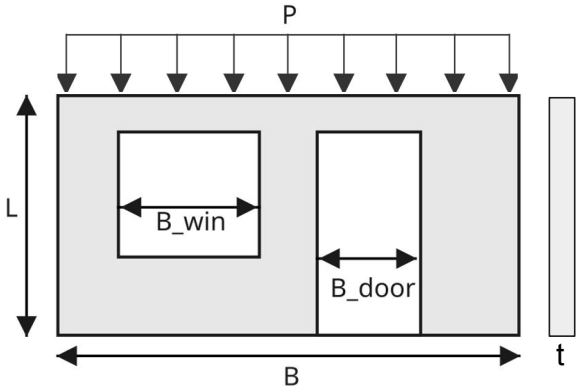


flood risk = hazard x exposure x vulnerability



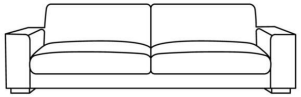
Component Vulnerability

Structure
force-driven



Flood resistance: Structural capacity based on geometry and conservation state

Contents
depth-driven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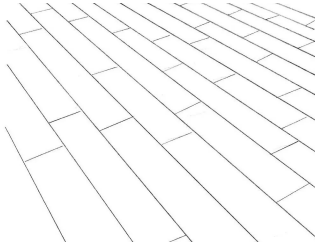
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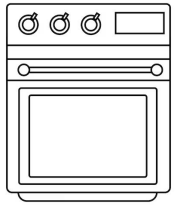
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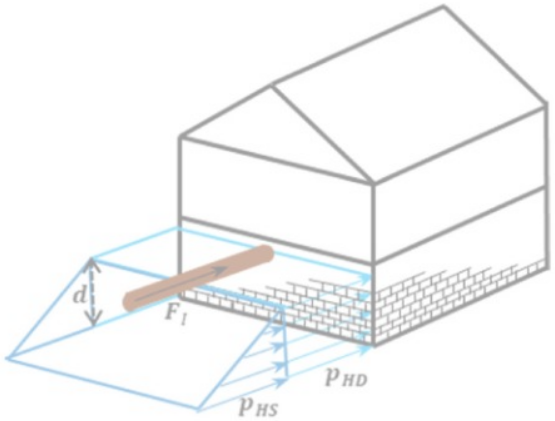
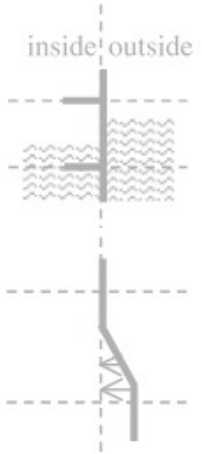
Flood resistance: Based on inundation depth in respect to the location within the building

Hazard Intensity Measures

Phase I: Force-driven



p_{HS} = hydrostatic pressure
p_{HD} = hydrodynamic pressure
F_i = debris impact force
d = flood depth

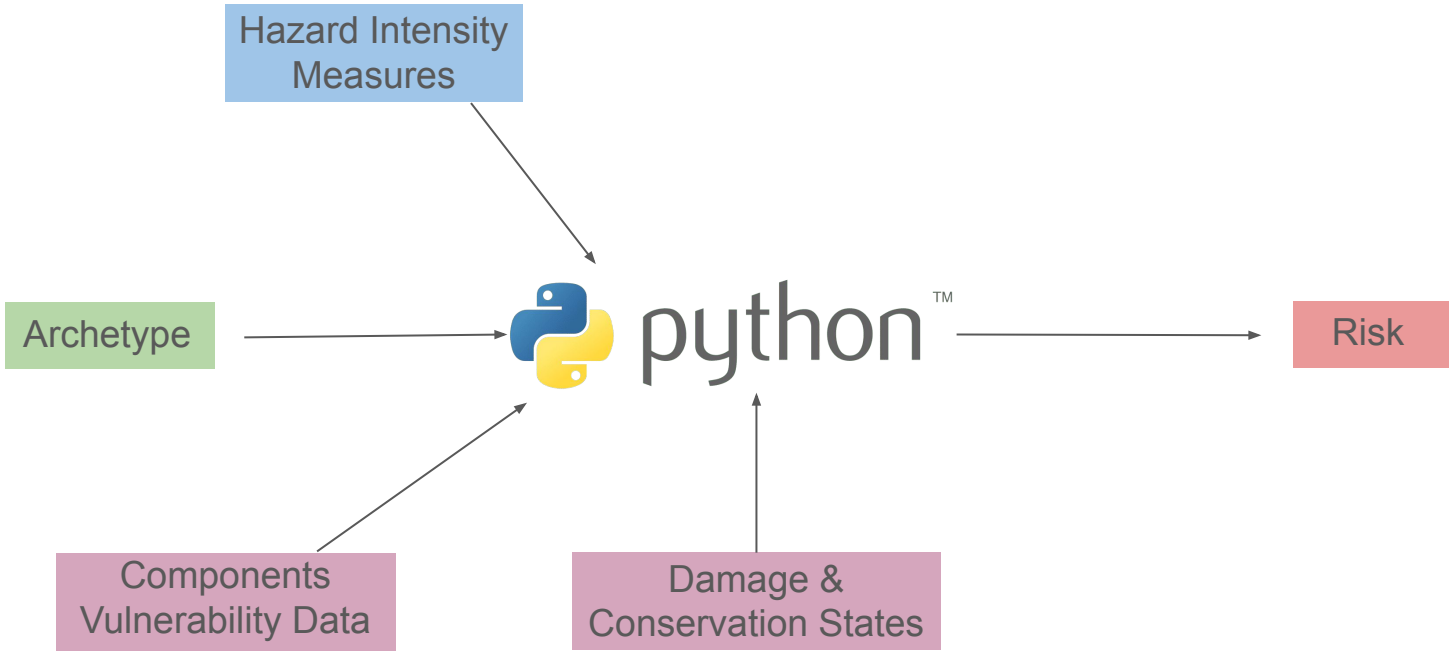


p_{HS} schematics

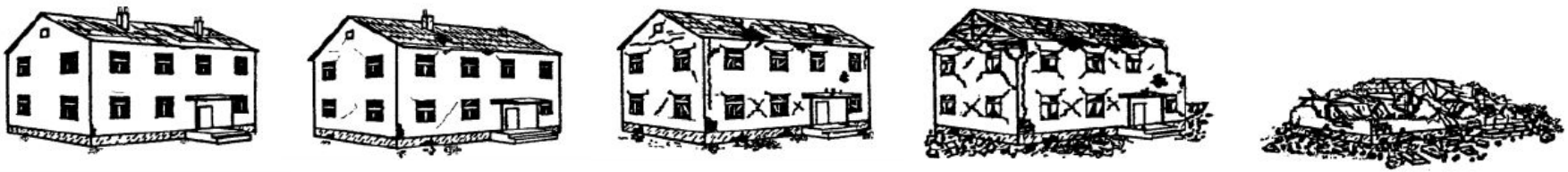
Phase II: Depth-driven

Moaiyedfar, Y., & Deniz, D. (2025). Collapse fragility models for unreinforced masonry buildings under flood and flow-type landslide actions. *Journal of Building Engineering, 101*, 111895. https://doi.org/10.1016/j.jobe.2025.111895
Kelman, I., & Spence, R. (2004). An overview of flood actions on buildings. *Engineering Geology, 73*(3–4), 297–309. https://doi.org/10.1016/j.enggeo.2004.01.010

flood risk = hazard x exposure x vulnerability



Damage Progression



Grünthal, G., R.M.W. Musson, J. Schwarz, & M. Stucchi (Eds). (1998). *European Macroseismic Scale 1998*. Centre Europèen de Géodynamique et de Séismologie.

Damage & Conservation State

Crack width

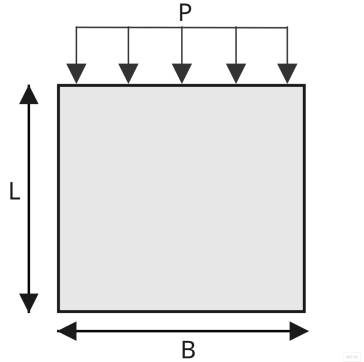
Damage State	C_w	Recovery Actions				
		Drying	Cleaning	Repointing	Crack repair	Rebuild
DS0	-					
DS1	< 1 mm	x	x			
DS2	1-5 mm	x	x	x		
DS3	5-25 mm	x	x	x	x	
DS4	> 25 mm					x

Structural capacity reduction factor

CS	λ
0	1
1	1
2	0.8
3	0.6

Table: Damage scale based on crack width and recovery actions

Modelling



P = 100 kPa

L = 2700 mm

B = 2700 mm

t = 100 mm

Damage State	Depth
DS2 (Cracks 1-5 mm)	90 cm
DS4 (Collapse)	100 cm

Complex computer model

Developed Methodology

For simulation i:

Threshold demand for damage state DS, given conservation state CS

Reference threshold demand for damage state DS

Configuration scalar

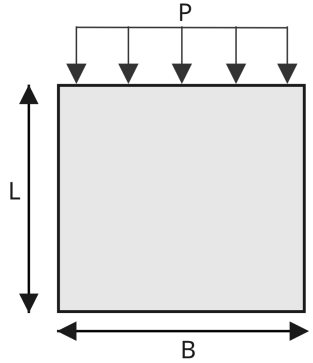
$$q_{DS,i}(CS) = q_{ref,DS} \cdot \left(\frac{t_i}{t_{ref}}\right)^2 \cdot \left(\frac{L_{ref}}{L_i}\right)^2 \cdot \left(\frac{P_i}{P_{ref}}\right) \cdot \lambda_{CS} \cdot \varepsilon_{mat,i} \cdot \varepsilon_{model,i}(CS)$$

Structural capacity reduction factor

Material uncertainty factor

Model uncertainty factor

Developed Methodology



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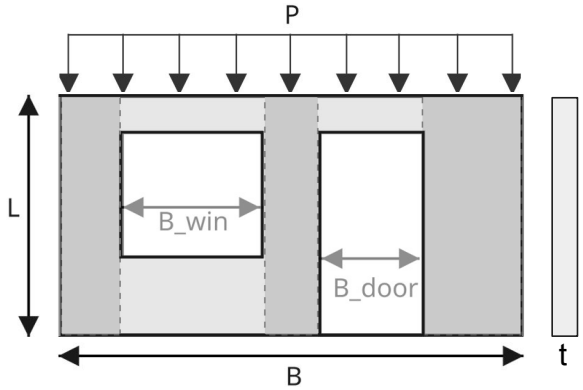
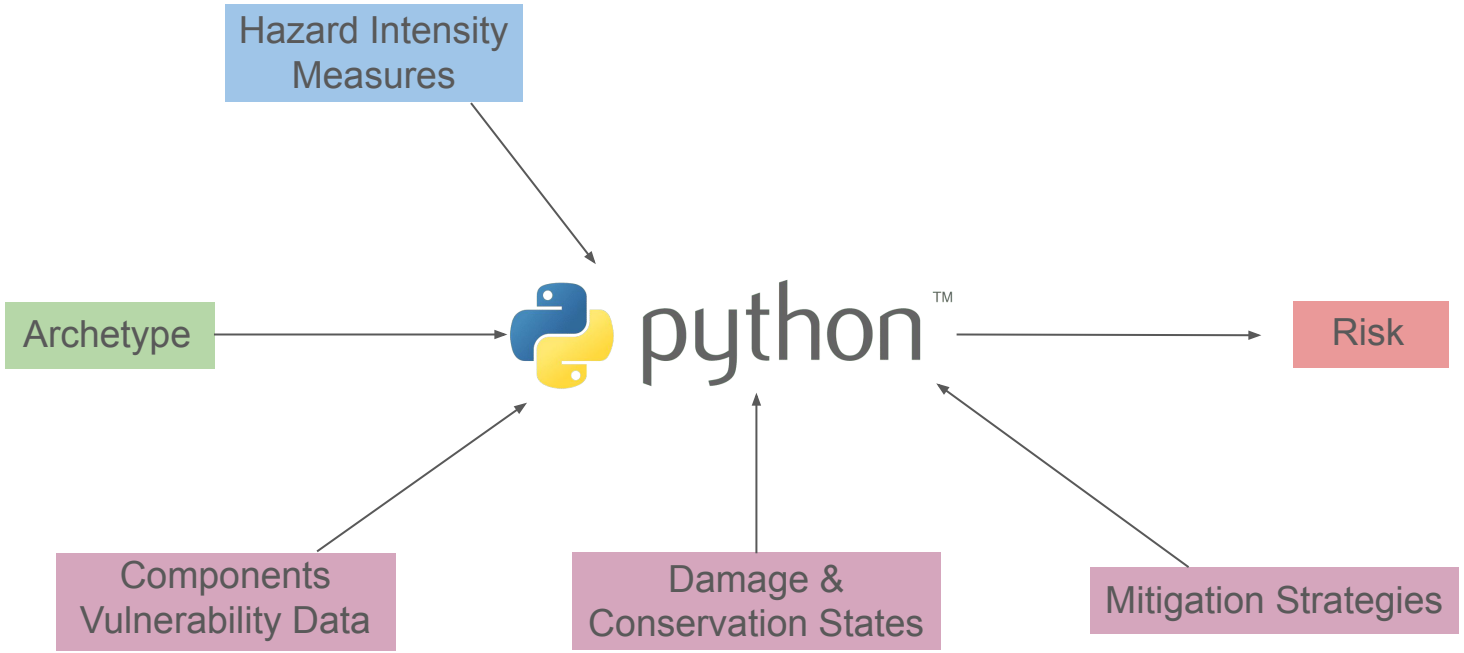


Slow and heavy

Fast and light

flood risk = hazard x exposure x vulnerability



Mitigation Strategies

Structural

Masonry repair

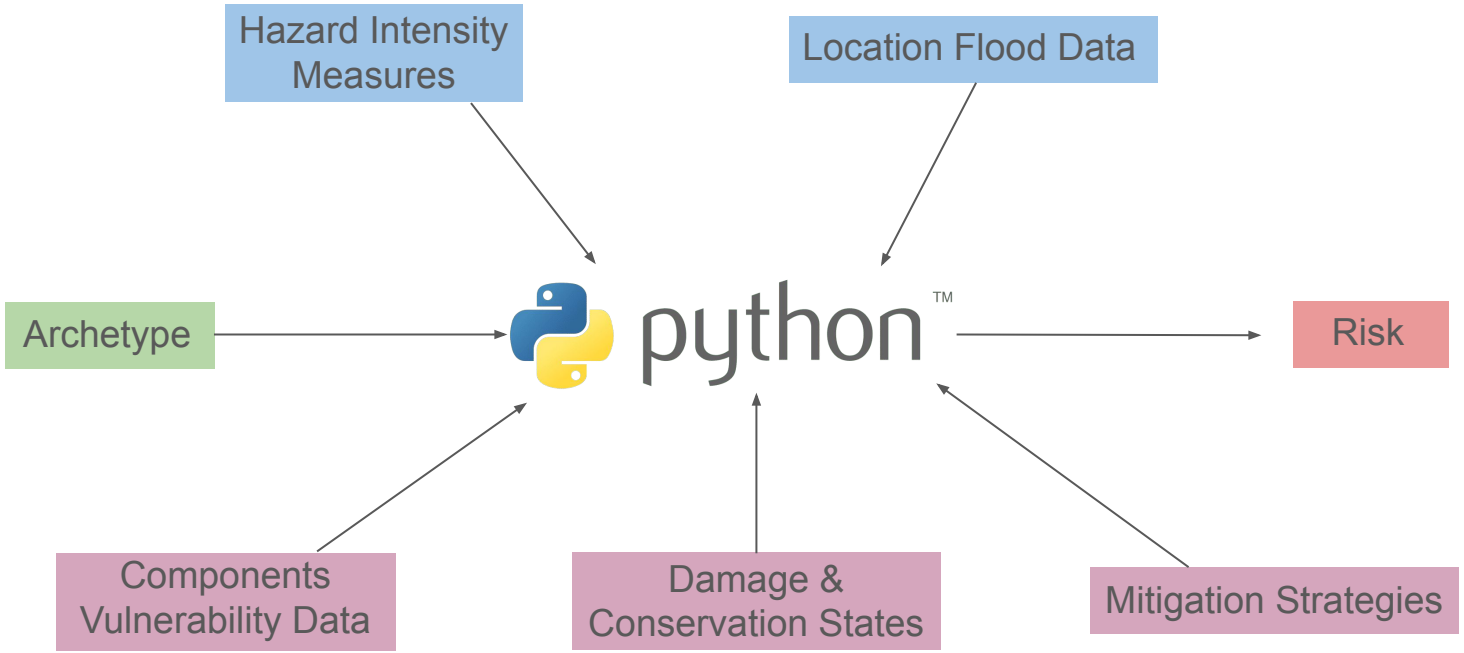
Contents

Increase elevation

Replace with water proof component

Combined strategy

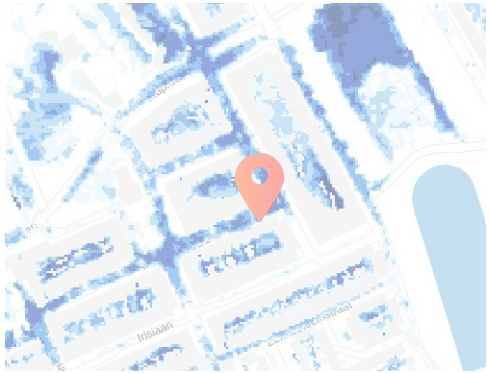
flood risk = hazard x exposure x vulnerability



Location Flood Data

LIWO: Dutch National Information System for Water and Flooding

Pluvial - Low inundation, 1/100 years



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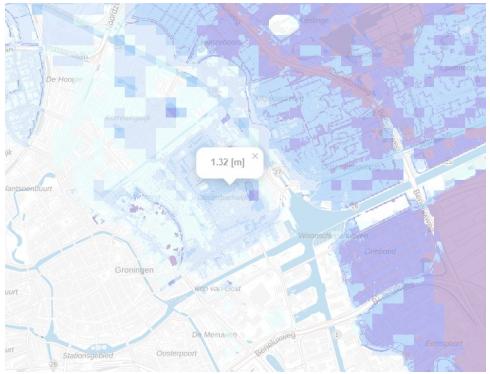

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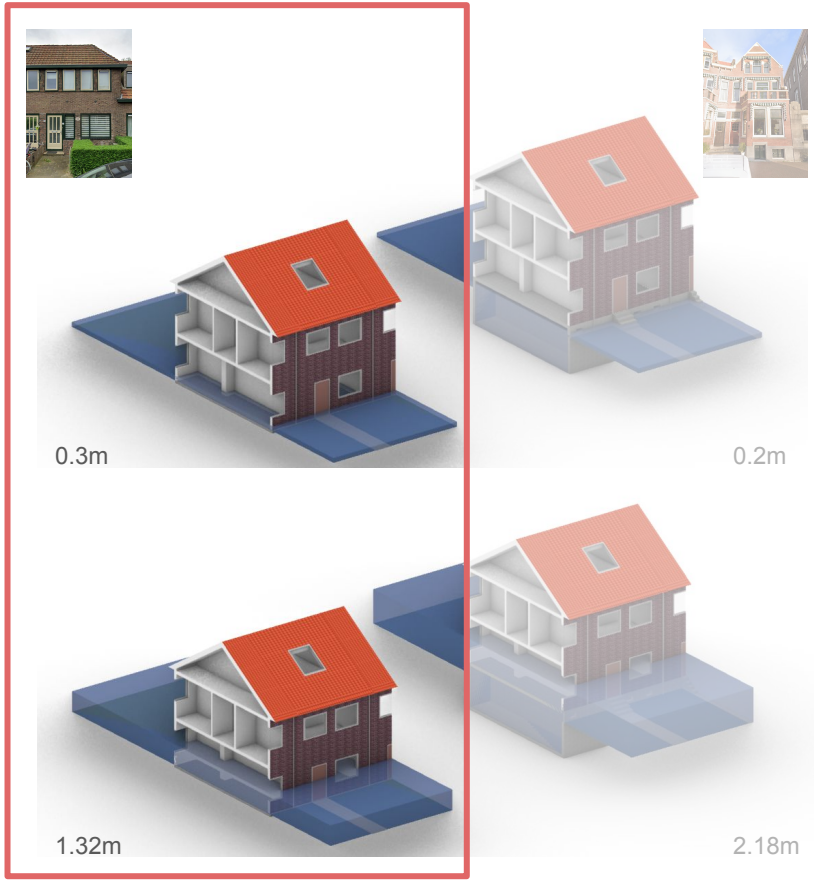


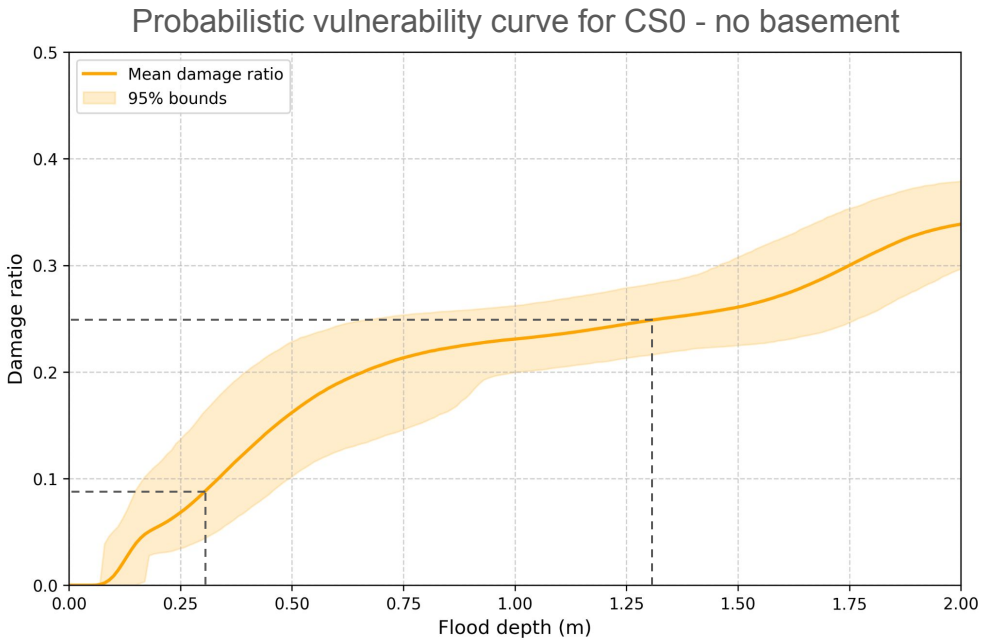
Fluvial / Coastal - High inundation, 1/10 000 years

Probabilistic Vulnerability

Damage ratio as a function of flood depth

Variance shown in light colour

Stepped curve reflecting floor height



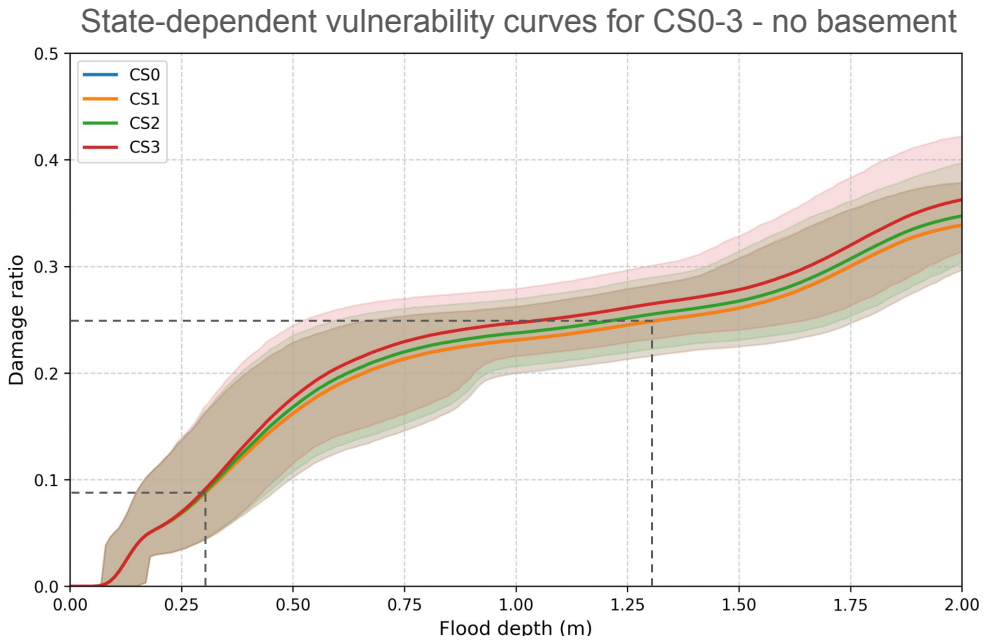
State-Dependent Vulnerability

Split off around 0.3m

Significant overlap of probability variance bounds

CS0 & CS1 overlap

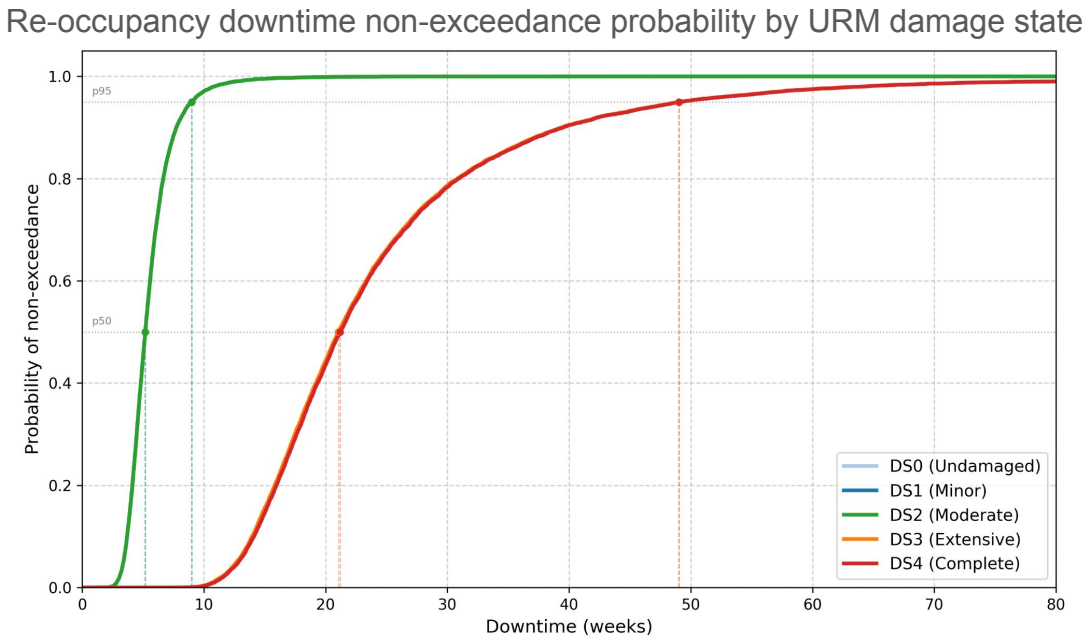
Low increase in costs



Re-Occupancy Downtime Curve

DS0-2 & DS3-4 overlap

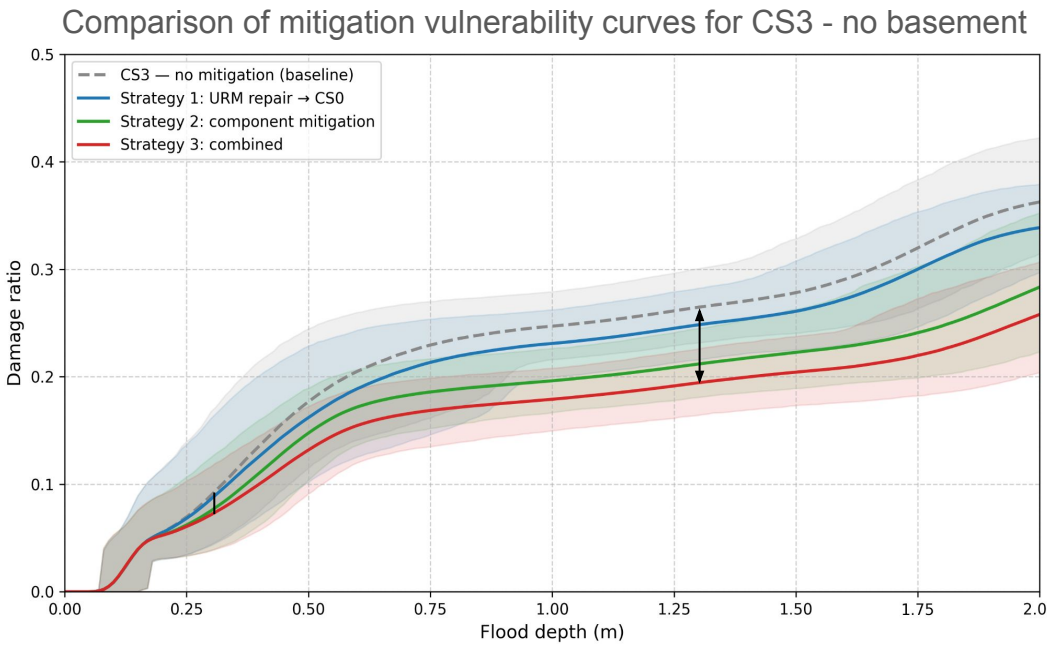
Threatened structural integrity causes long delays



Mitigation Effectiveness

Structural repair has little effect on damage ratio and repair costs

Mitigating contents effective for depths over 0.2 meter



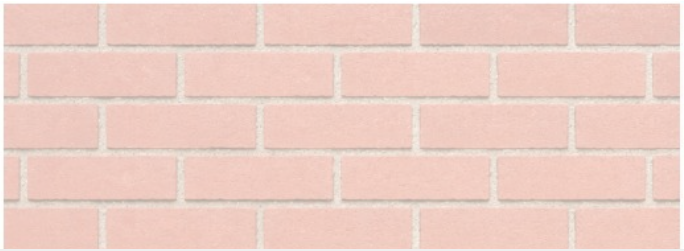
Mitigated Results

Location 1
No basement

Location 2
Basement

Conclusion

To what extent does the integration of pre-flood conservation states alter the quantification of building-specific vulnerability within probabilistic flood risk assessment?




“The Cost of Neglect is not paid for with money, but with displaced families.”


The Cost of Neglect

A State-Dependent Framework for Quantifying the Flood Risk of Historic Masonry Buildings

MSc Thesis, A4

[Bart Koppejan, TU Delft, 24-06-2026]

Extra Information

Applicability

A methodology for state-dependent flood risk assessment

- **Bridging the gap** between regional models and heavy building-specific models
- Allowing for **multi-hazard integrability**
- Quantifying mitigation strategy effectiveness for **targeted interventions**

Limitations

Hazard

- Simplification in flood actions

  e.g. hydrostatic pressure and debris weights

- Up to 3 m/s flow velocity

Vulnerability

- Pre-hazard condition isolated strictly to visible crack widths
- Facade simplified
- Independent failure of components

Future Developments

- More pre-flood damage types
- More archetypes
- More hazards

URM repair costs:

	Lower bound	Upper bound	min_euro/m^2	max_euro/m^2	min_dollar/m^2	max_dollar/m^2	min_dollar/ft^2	max_dollar/ft^2
DS2	20%	80%	20	80	23	93	2	9
Variable	repoint median	repoint median						
DS3	10	25%	46	100	54	116	5	11
Variable	x bricks replacement	rebuild median						
DS4	100%	100%	280	700	326	814	30	76
Variable	rebuild min	rebuild max						

	min (€)	max (€)	median (€)
repoint	60	190	100
replace	50	120	100
rebuild	280	700	400

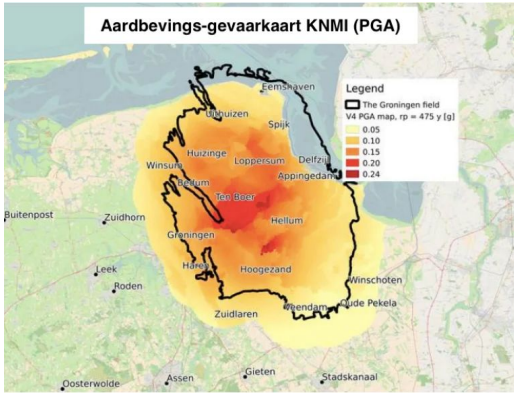
euro to dollar average 2025: 1.1626

m^2 to ft^2: 10.76391042

exterior wall area per floor 21.725 m^2

Location Case Studies

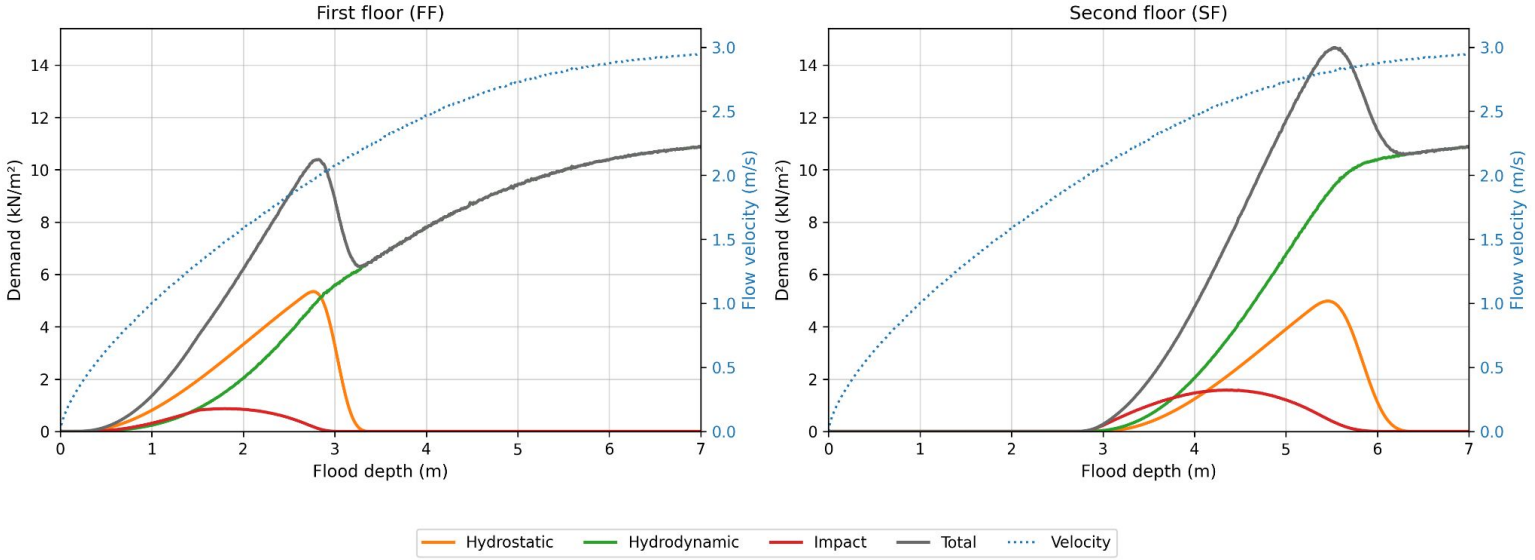
Kamperfoeliestraat 71, Groningen
Building year: 1932
Basement: no
Area: 67 m^2



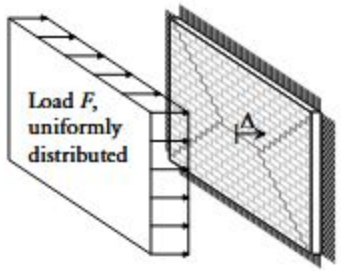
Location Case Studies

‘s Gravendijkwal 56, Rotterdam
Building year: 1912
Basement: yes
Area: 327 m^2

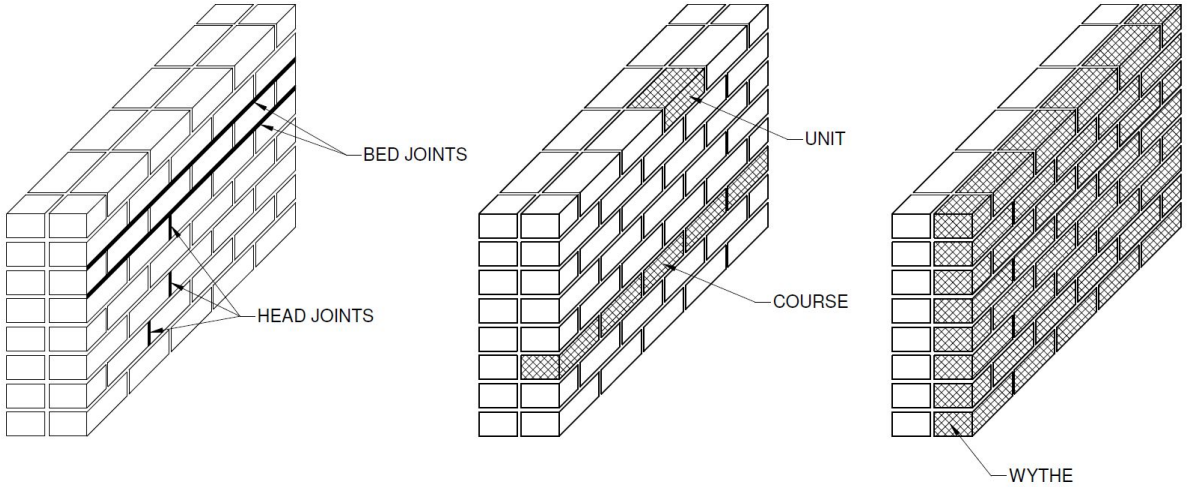
Hazard Demand



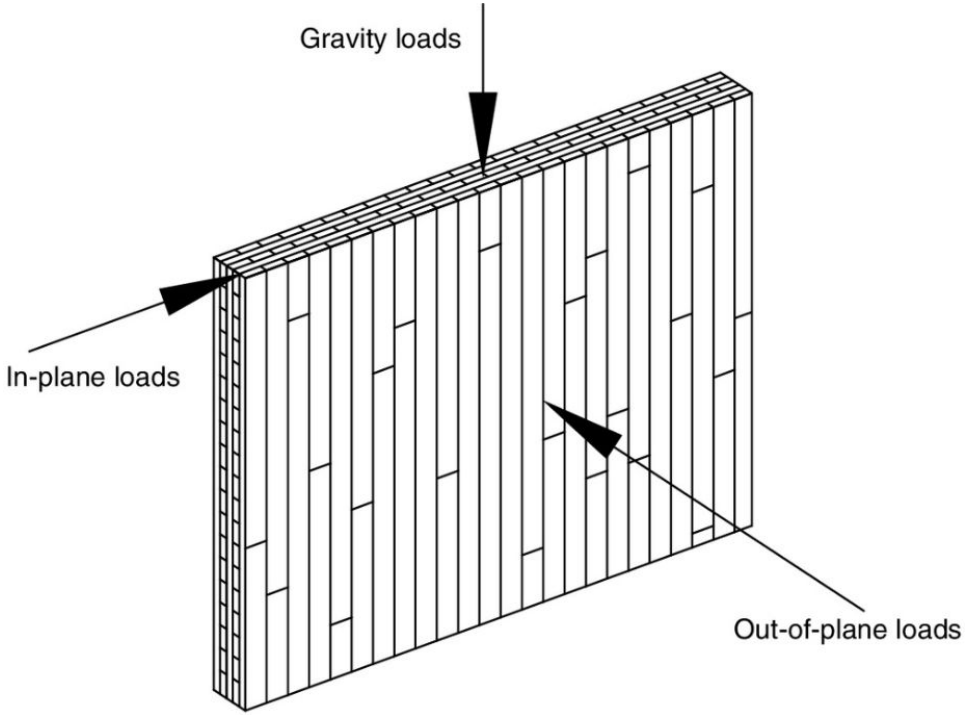
Equivalent Uniform Load



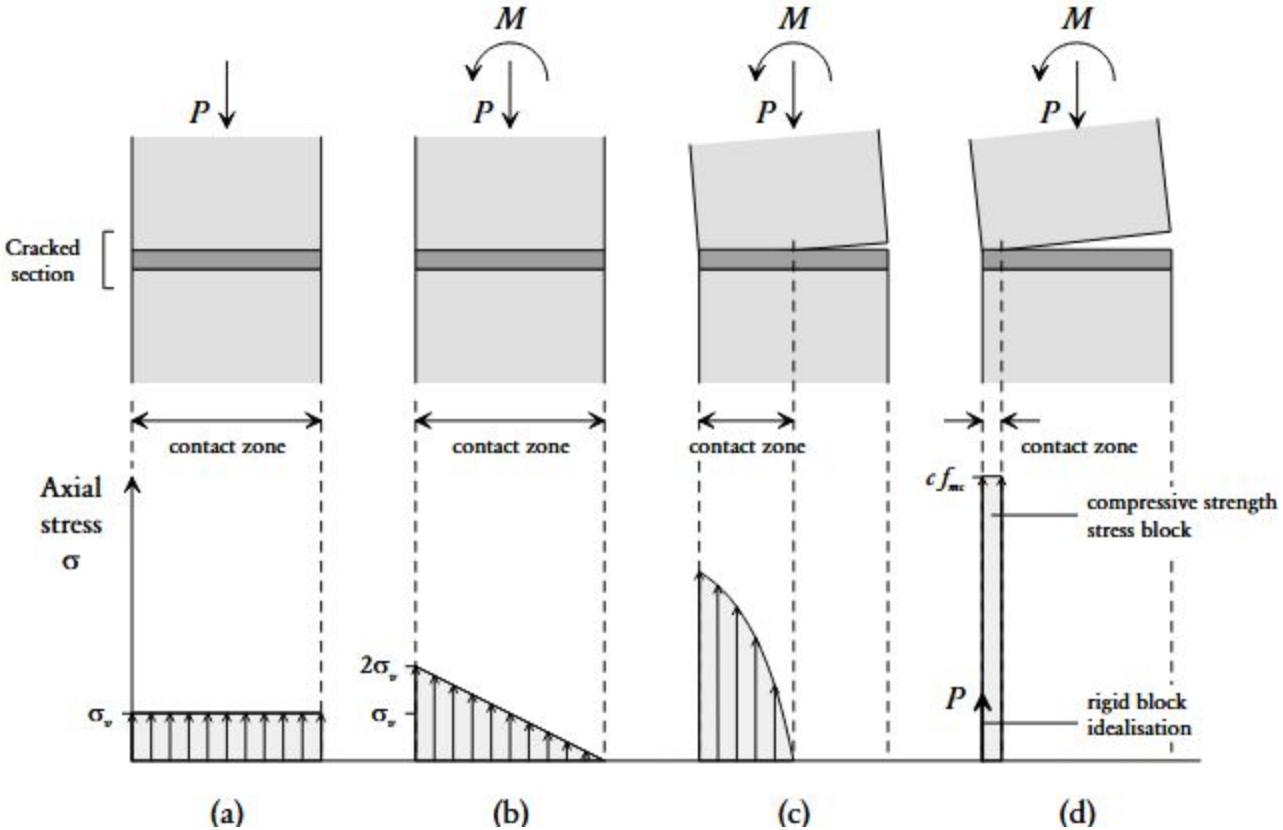
URM Terminology



Loads on URM

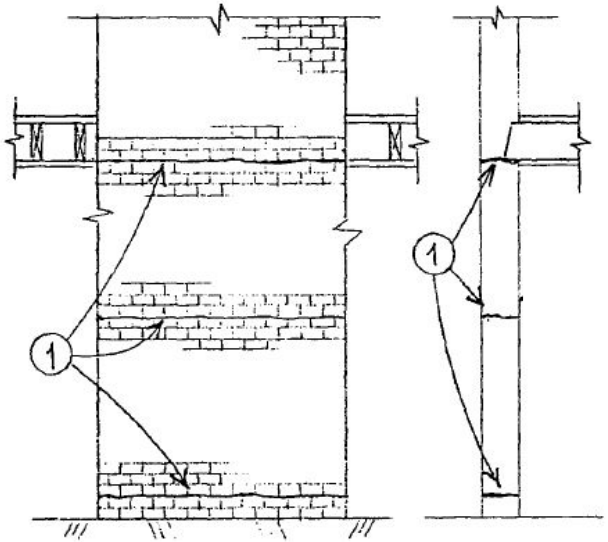


OOP Failure Mechanism

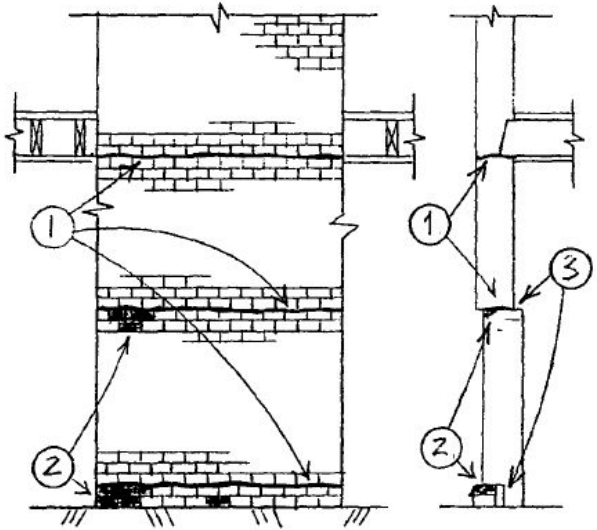


OOP Failure Mechanism

Start

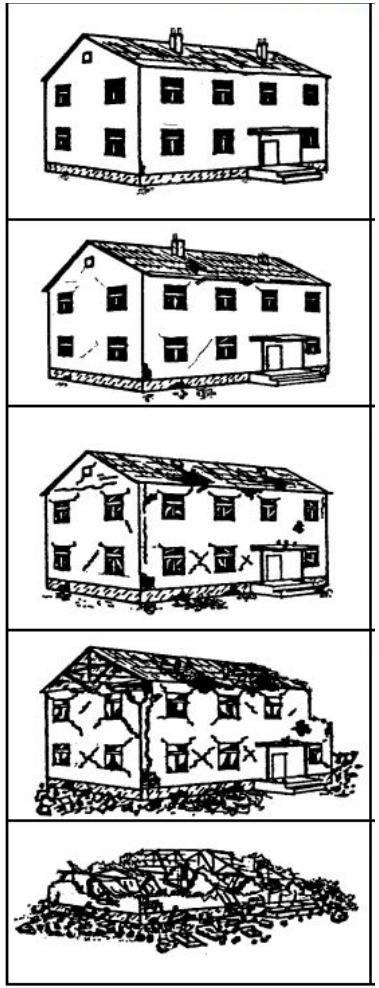


End

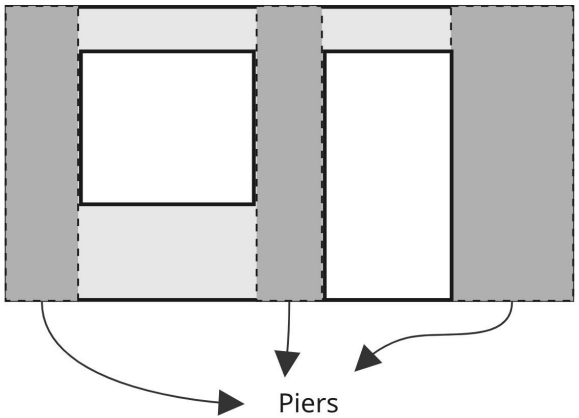


1) Cracks; 2) Spalling; 3) Out-of-plane offsets

Damage States Example

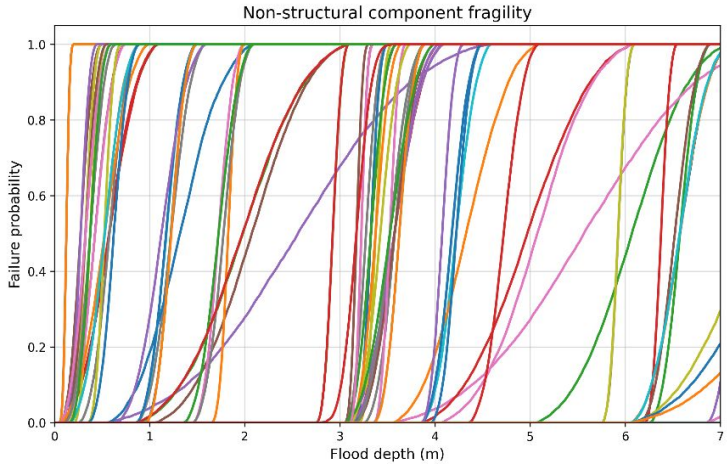


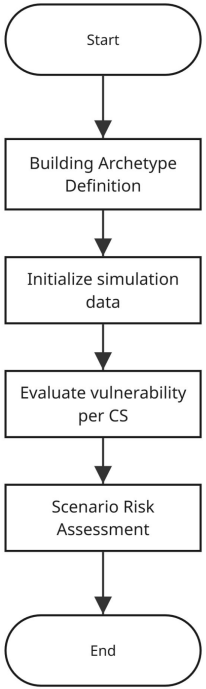
URM Vulnerability

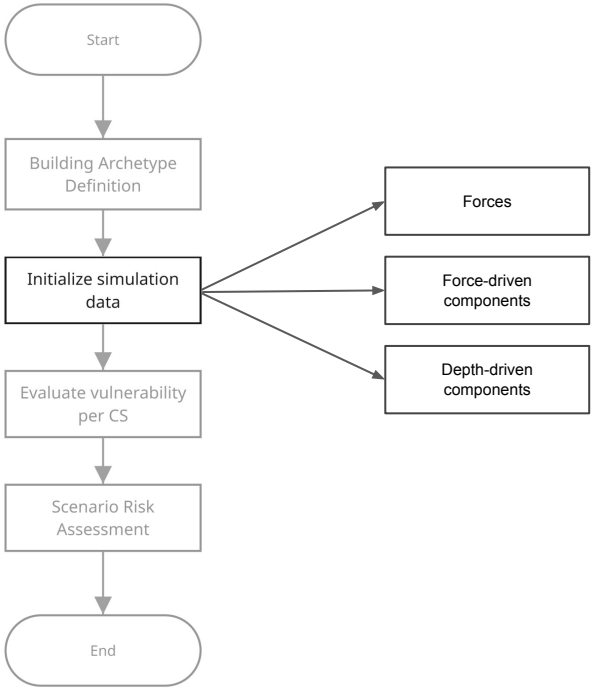


$$q_{DS,i}(CS) = \left(\frac{t_i}{t_{ref}}\right)^2 \cdot \left(\frac{L_{ref}}{L_i}\right)^2 \cdot \left(\frac{P_i}{P_{ref}}\right) \cdot \lambda_{CS} \cdot q_{ref,DS} \cdot \varepsilon_{mat,i} \cdot \varepsilon_{model,i}(CS)$$

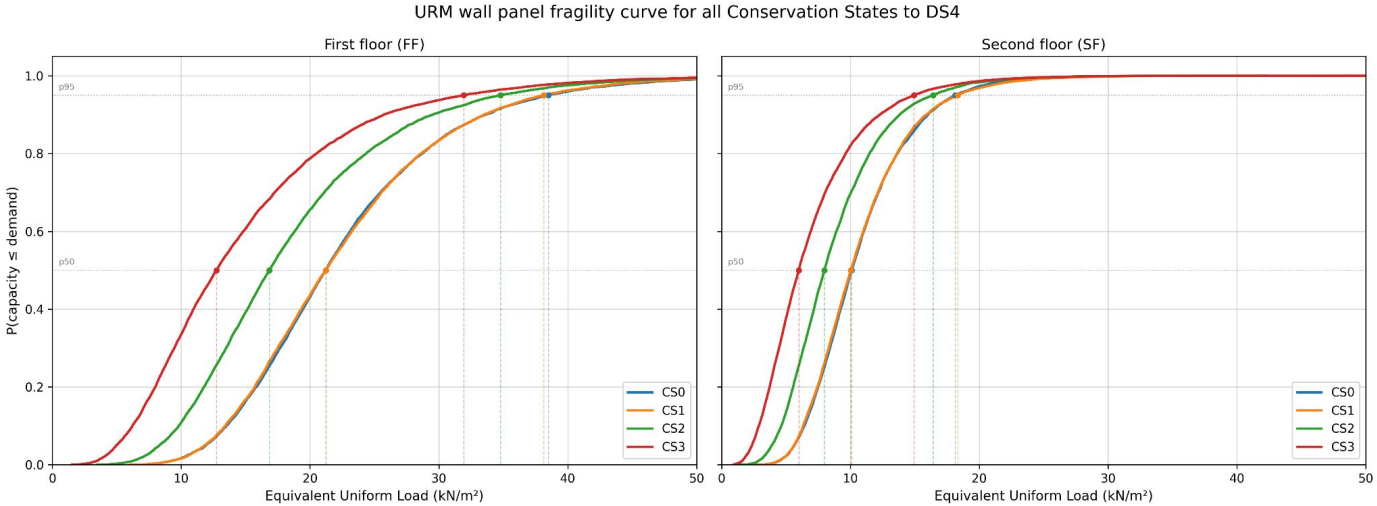
Components Vulnerability

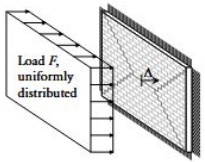


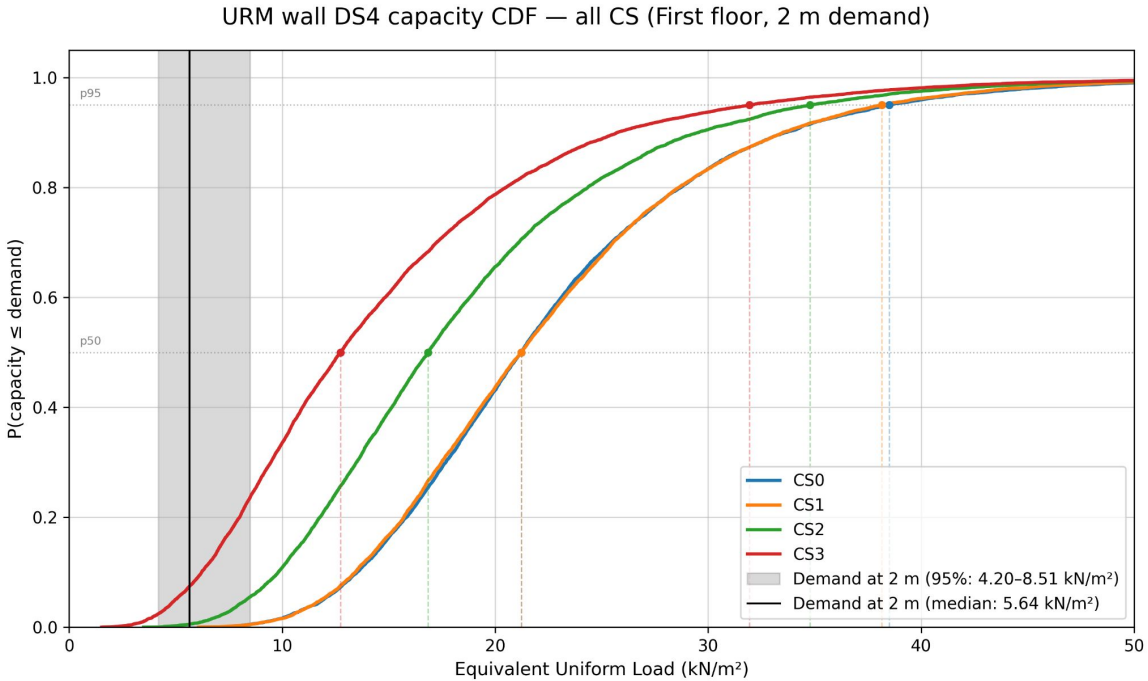

Start
Building Archetype Definition
Initialize simulation data
Evaluate vulnerability per CS
Scenario Risk Assessment
End


Start
Building Archetype Definition
Initialize simulation data
Evaluate vulnerability per CS
Scenario Risk Assessment
End
Forces
Force-driven components
Depth-driven components

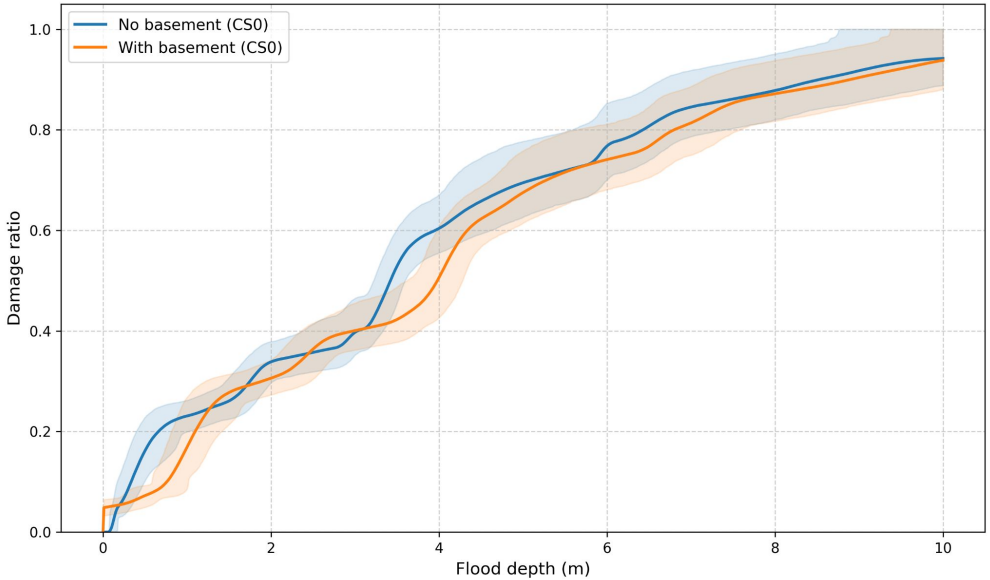
URM Vulnerability

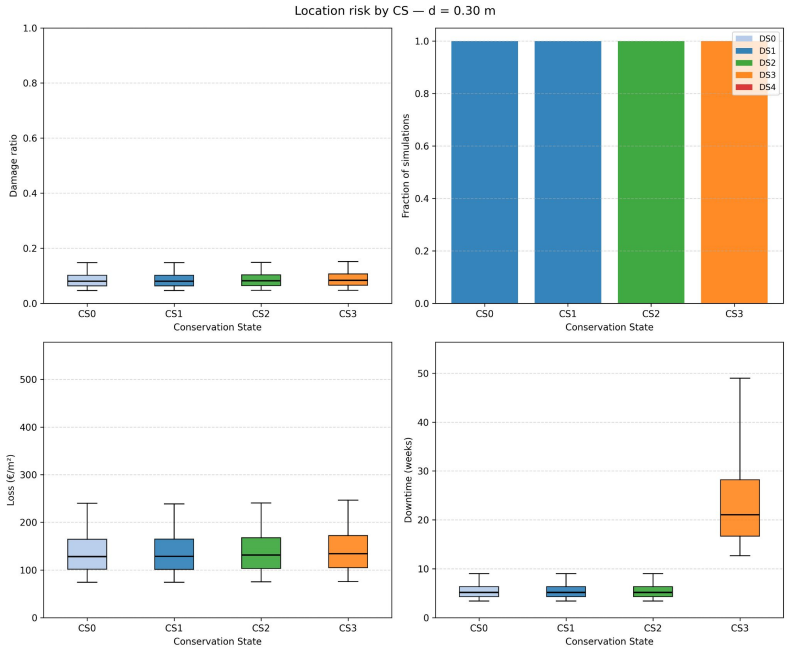


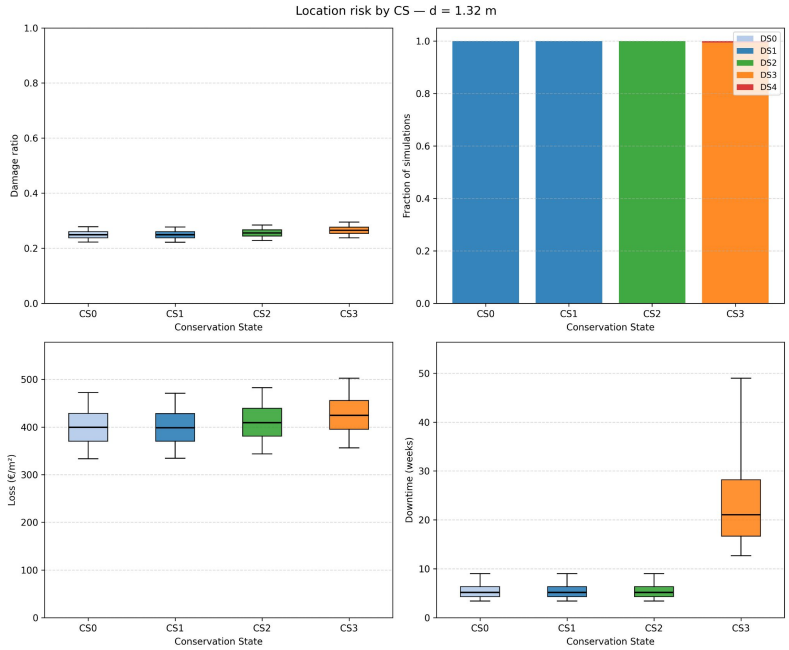



URM wall DS4 capacity CDF — all CS (First floor, 2 m demand)
P(capacity ≤ demand)
Equivalent Uniform Load (kN/m²)
p95
p50
CS0
CS1
CS2
CS3
Demand at 2 m (95%: 4.20–8.51 kN/m²)
Demand at 2 m (median: 5.64 kN/m²)
0.0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
40
50

Vulnerability Curve




Location risk by CS — d = 0.30 m
Damage ratio
Fraction of simulations
Loss (€/m²)
Downtime (weeks)
Conservation State
CS0
CS1
CS2
CS3
DS0
DS1
DS2
DS3
DS4


Location risk by CS — d = 1.32 m
Damage ratio
Fraction of simulations
Loss (€/m²)
Downtime (weeks)
Conservation State
CS0
CS1
CS2
CS3
DS0
DS1
DS2
DS3
DS4

Figures

[1] https://www.noaa.gov/stories/deadly-and-destructive-power-of-water

[2] https://www.istockphoto.com/nl/foto/flooding-in-florida-caused-by-tropical-storm-from-hurricane-debby-suburb-houses-in-gm2169351425-589344473?searchscope=image%2Cfilm

[3] https://apnews.com/article/europe-middle-east-science-environment-and-nature-turkey-e89d7d2ed17cad33eb621aea270e04d2

[4] DGMR Bouw b.v. (2006). *Referentiewoningen nieuwbouw: Kompas energiebewust wonen en werken* (Technical Report No. 2KPWB0620).

[5] https://deakin.pressbooks.pub/buildingmeasurementapproaches/chapter/6-2-technical-details-related-to-masonry-works/

[6] Google Street View

[7] Google Street View

[8] https://www.vecteezy.com/vector-art/42124222-sofa-outline-icon-line-art-illustration-of-couch-modern-lounge-furniture-in-scandinavian-style-for-home-interior-linear-vector-illustration-isolated-on-white-background

[9] https://www.shutterstock.com/nl/image-vector/mineral-wool-roll-icon-transparent-vector-2602055609?trackingId=75353d2a-153d-4a4d-9d95-a3a4741d750c&listId=searchResults

[10] https://www.drawingforall.net/how-to-draw-a-floor/

[11] https://www.magnific.com/premium-vector/minimalistic-line-art-oven-illustration-with-clean-lines-modern-kitchen-design_283117416.htm

[12] Map: Wateroverlast bij kortdurende hevige regenval (2018); https://basisinformatie-overstromingen.nl/#/viewer/12

[13] Map: Maximale waterdieptekaart voor overstroomik.nl; https://basisinformatie-overstromingen.nl/#/viewer/9