Behaviour of Masonry Spandrels

B.Tech. Project Viva Voce

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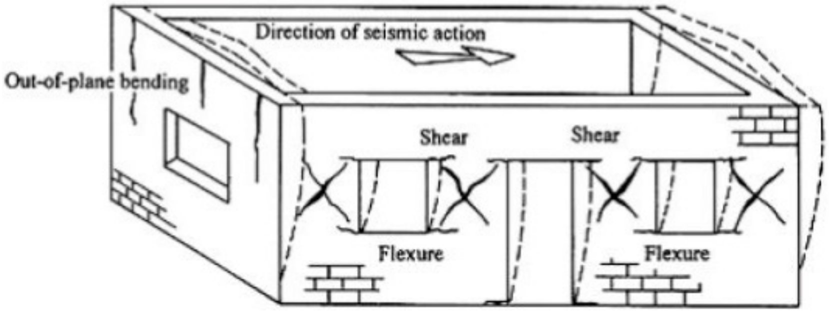
Overview of Presentation

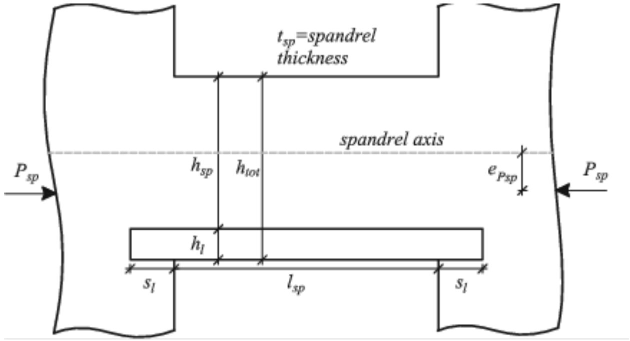
- **Introduction to Masonry Spandrels**
- **Objectives, Scope and Methodology**
- **Failure mechanisms in Masonry Spandrels**
- **Preliminary Study**
    - Review of existing strength models
    - Comparative study: Sensitivity analysis tool
- **Numerical Modelling of Spandrel Behaviour**
    - Element type, material model, input material parameters and validation
    - Overview of parametric study, observations and inferences
- **Machine Learning Approach**
    - Introduction, data samples, data pre-processing
    - Comparison and selection of ML model
    - Predictive equation for spandrel behaviour

Introduction to Masonry Spandrels

- **Pier – vertical load resisting element**
- **Spandrel – structural coupling**
- **Current models have limited capability in capturing OOP.**



Ref.: POLIMI (2010)



Ref.: Beyer and Mangalathu (2012)

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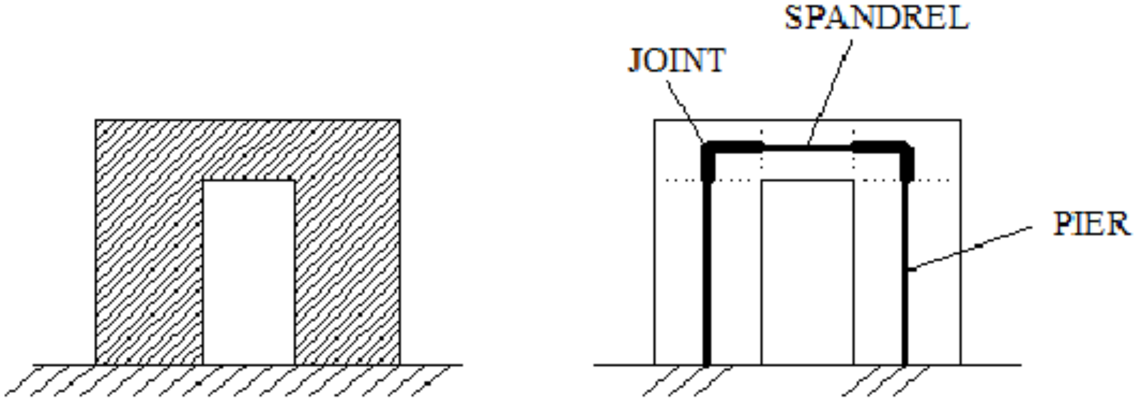
Introduction to Masonry Spandrels

- **Equivalent Frame Method**
  - Used for in-plane capacity estimation.
  - Spandrel – analogous to beam
  - Pier – analogous to column
  - Joint leads to the coupling effect.



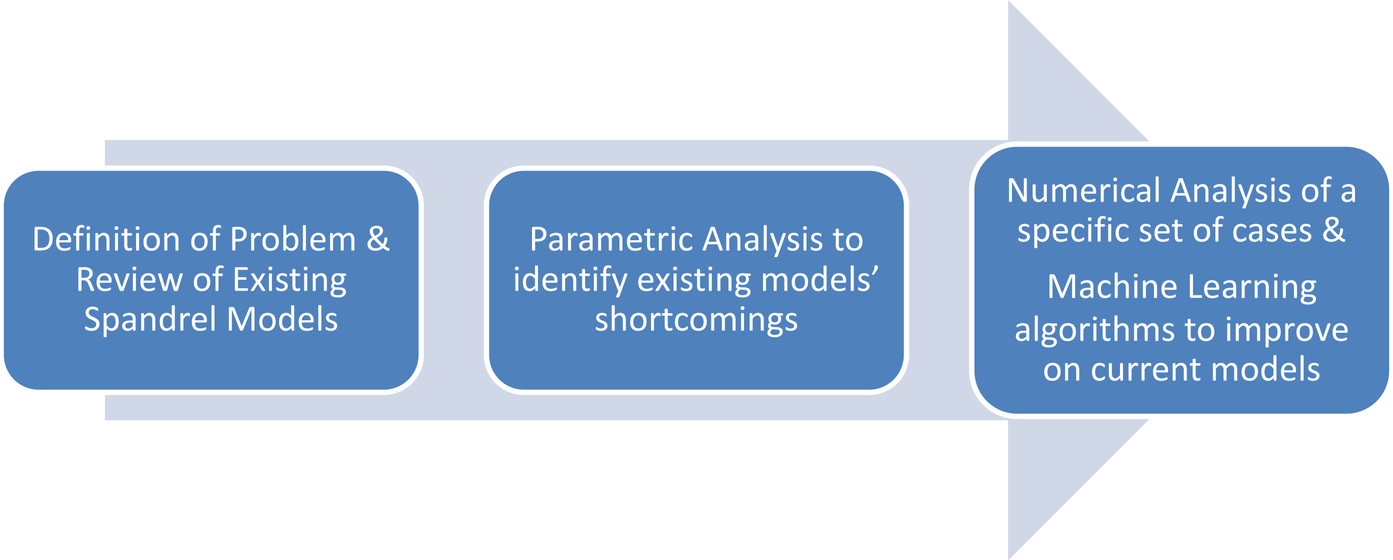
Ref.: Arangio and Bontempi (2013)

Objectives, Scope and Methodology

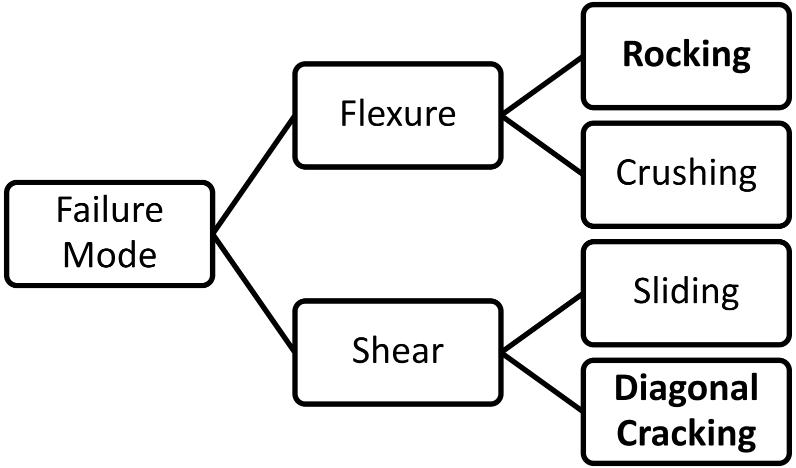
- **Objectives**
  - Review and comparison of existing models
  - Parametric analysis on existing models
  - Numerical study on DIANA
  - Machine learning study

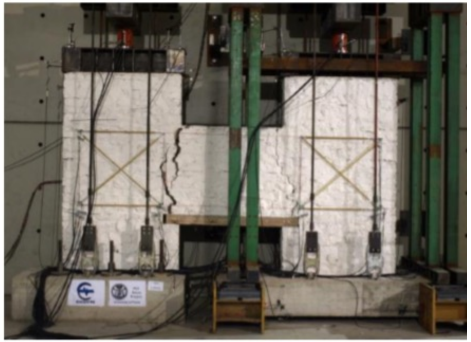
Outcomes:

- Sensitivity Analysis tool
- Spandrel capacity database
- Equation to capture OOP displacements



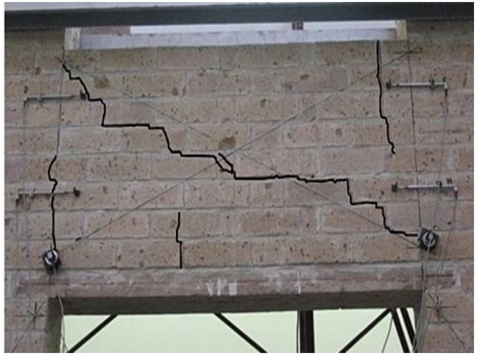
Failure mechanisms in Masonry Spandrels





Rocking

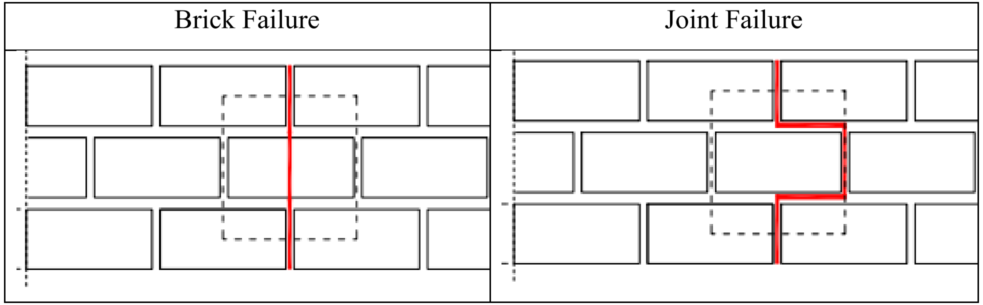
Ref.: Graziotti (2012)



Diagonal / Step-wise Cracking

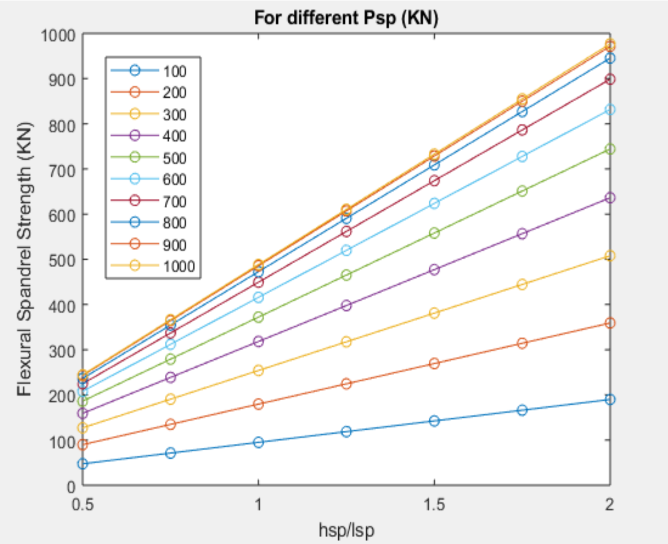
Ref.: Parisi (2014)

- **Rocking and diagonal cracking – predominant in-plane failure mechanisms in masonry spandrels (sliding may occur in some cases).**



Preliminary Study

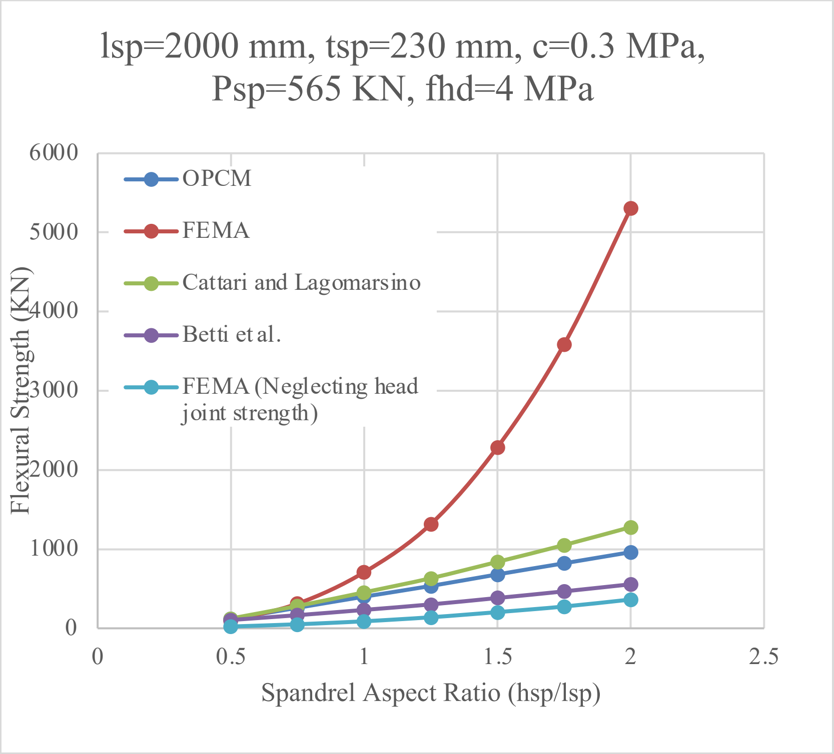
- **Review of existing strength models for masonry spandrels**
  - Detailed study of OPCM
  - <u>Flexural strength found to vary positively with increasing aspect ratio</u>

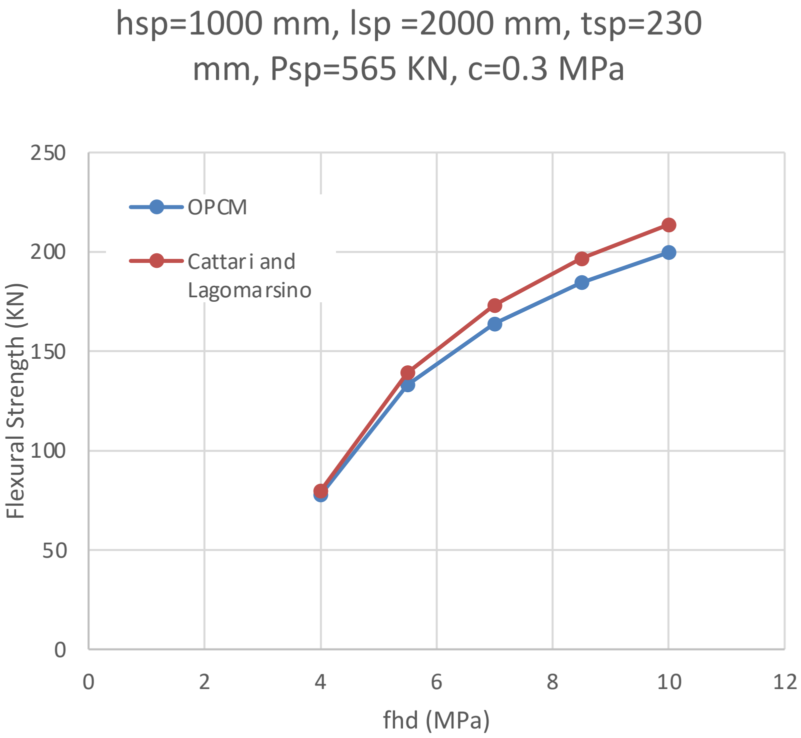


OPCM 3431 (2005)	Flexure	$V_{fl} = P_{sp} \cdot \frac{h_{sp}}{l_{sp}} \left(1 - \frac{P_{sp}}{0.85 f_{hd} h_{sp} t_{sp}}\right)$
	Shear 1	$V_s = h_{sp} t_{sp} c_{red}$ with $c_{red} = c \frac{1}{1+2(h_j+h_b)/(l_b+l_j)}$
	Shear 2	$V_s = h_c t_{sp} \cdot c_{red} + 0.4 \cdot P_{sp}$ with $h_c = \frac{P_{sp}}{0.85 f_{hd} t_{sp}}$ and c_{red} as in Shear 1
FEMA 306 ATC (1998)	Flexure, peak	$V_{p,fl} = \frac{2}{l_{sp}} \cdot \frac{2}{3} h_{sp} \cdot f_{p,tot} \cdot \frac{h_{sp}}{4(h_j+h_b)}$ with $f_{p,tot} = f_{p,bj} \cdot t_b \cdot \frac{l_b}{2} + f_{p,sj} \cdot \frac{l_b}{2} \cdot h_b \cdot (NB-1)$ and $f_{p,bj} = c + 0.5 \cdot \sigma_{pier}$, NB = 1
	Flexure, residual	$V_{r,fl} = \frac{2}{l_{sp}} \cdot \frac{1}{2} h_{sp} \cdot f_{r,bj} \cdot t_{sp} \left(\frac{l_b}{2} - \Delta_s\right) \cdot \frac{h_{sp}}{2(h_j+h_b)}$ with $f_{r,bj} = 0.5\sigma_{pier}$ and $\Delta_s = 0$
Turnsek and Cacovic (1970)	Shear	$V_{p,s} = f_{dt} \cdot h_{sp} \cdot t_{sp} \cdot \beta \cdot \sqrt{1 + \frac{p_{sp}}{f_{dt}}}$
Cattari and Lagomarsino (2008)	Flexure	$V_{fl} = \frac{2}{l_{sp}} \cdot t_{sp} \cdot \left(0.85 f_{hd} h_c \left(\frac{h_{sp}}{2} - \frac{h_c}{2}\right) + f_{tu}(h_{sp} - h_c)\frac{h_c}{2}\right)$ with $f_{tu} = \min\left(\mu \cdot 0.65 \cdot \sigma_{pier} \frac{l_b}{2(h_j+h_b)}; \frac{f_{bt}}{2}\right)$ $h_c = \frac{p_{sp}+f_{tu}}{0.85 f_{hd}+f_{tu}} h_{sp}$
Betti et al. (2008)	Flexure	$V_{fl} = \frac{2}{l_{sp}} \cdot \frac{h_{sp}^2 t_{sp}}{6}(f_{tm} + p_{sp})$ with $f_{tm} = \frac{c}{2\mu}$

Preliminary Study

- **Comparison of strength models**

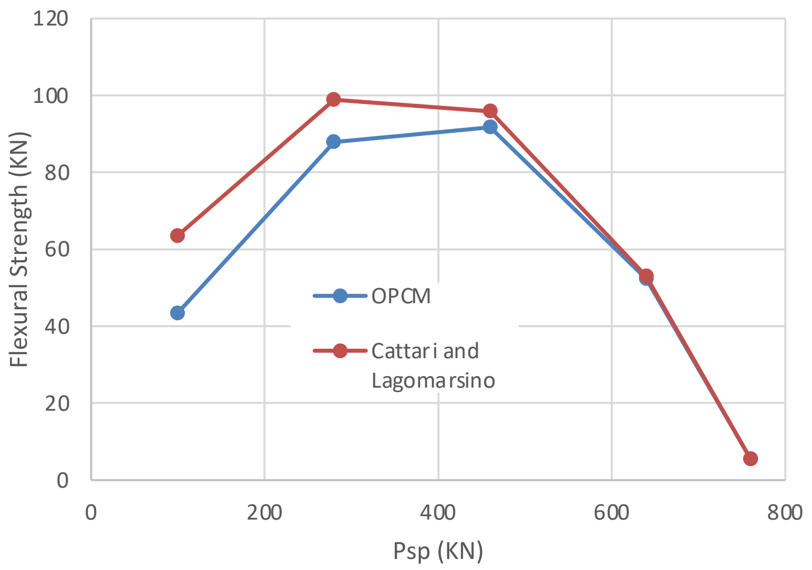




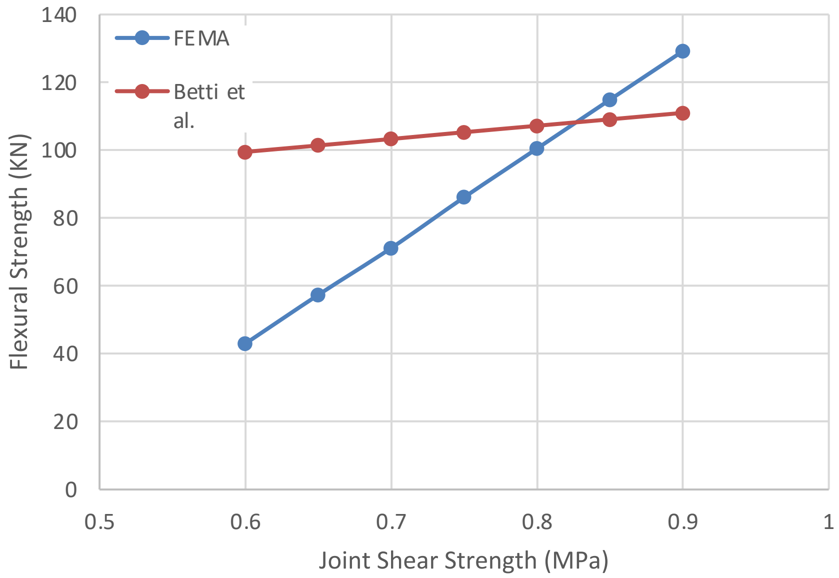
Preliminary Study

- **Continued…**

hsp=1000 mm, lsp =2000 mm, tsp=230 mm, fhd= 4 MPa, c=0.3 MPa



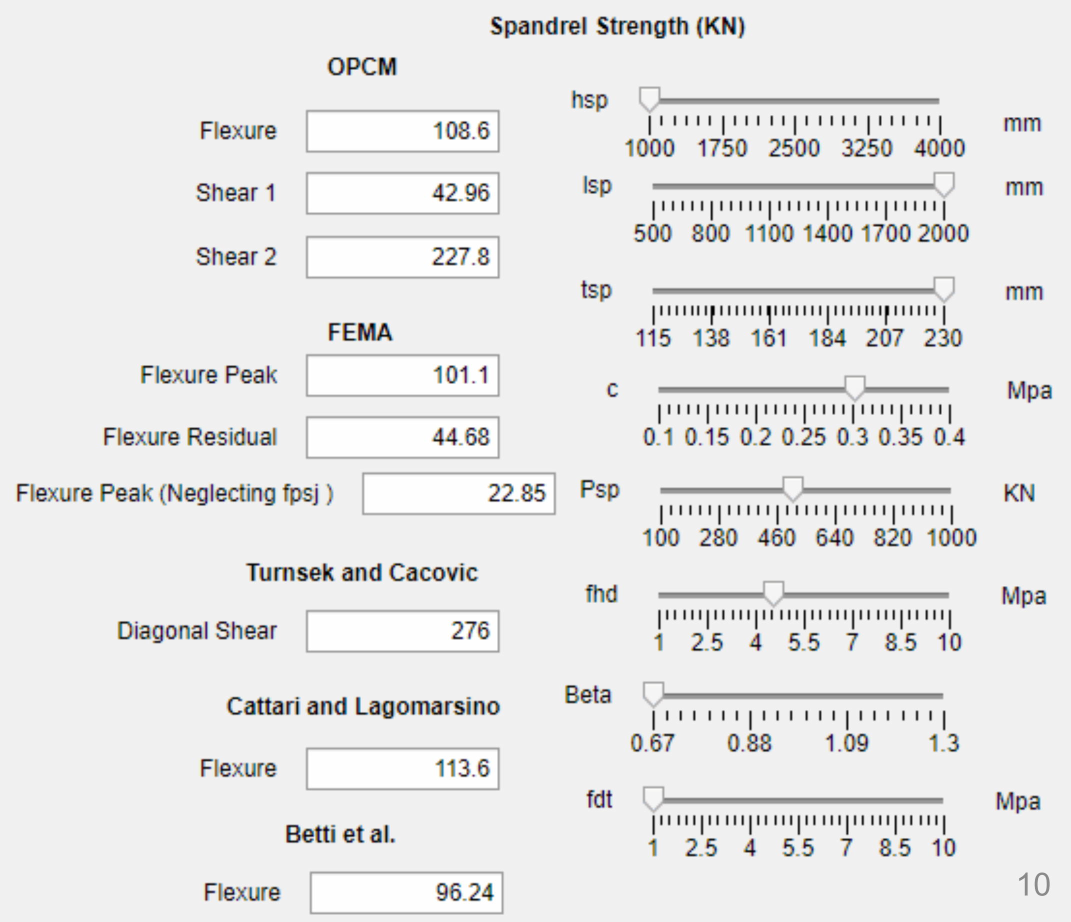
hsp=1000 mm, lsp =2000 mm, tsp=230 mm, fhd= 4 MPa, Psp = 565 KN



$$c + \mu \sigma_{pier}$$

Preliminary Study

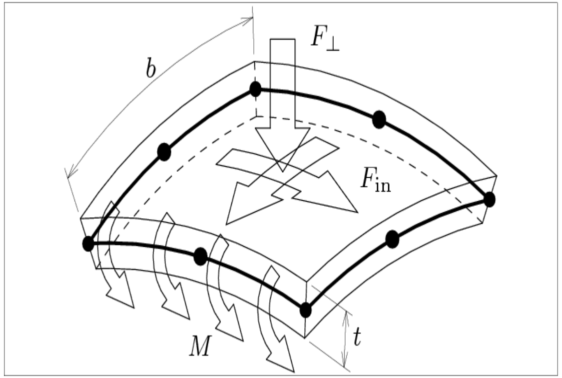
- **Sensitivity analysis tool**
  - Easy and quick comparison across models
  - Parametric Analysis
  - Understanding influence of parameters



Preliminary Study

- **Observations from study**
  - Spandrel lateral strength, by and large is dependent more on geometry than it is on material properties.
  - OPCM, Cattari and Lagomarsino - **force-equilibrium formulation** FEMA and Betti et al. - **mechanics-based formulation**
  - Diagonal shear dominant mechanism for squat spandrels.
  - Spandrel strength formulations currently estimate just the pure-in-plane capacity.

Numerical Modelling of Spandrel Behaviour

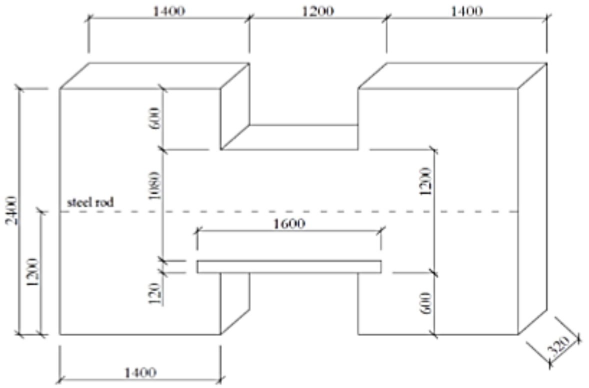


- **Input parameters**
  - **E_x** Young's modulus in x direction
  - **E_y** Young's modulus in y direction
  - **G** Shear modulus
  - **α** Angle between the bed joint and the diagonal stepped cracks
  - **f_{tx}** Tensile strength in x direction
  - **f_{ty}** Tensile strength in y direction
  - **G_{fty}** Tensile fracture energy in y direction
  - **f_{cy}** Compressive strength in y direction
  - **G_{fcy}** Compressive fracture energy in y direction
  - **Φ** Friction angle
  - **c** Cohesion
  - **G_{fs}** Shear fracture energy
  - **ρ** Density

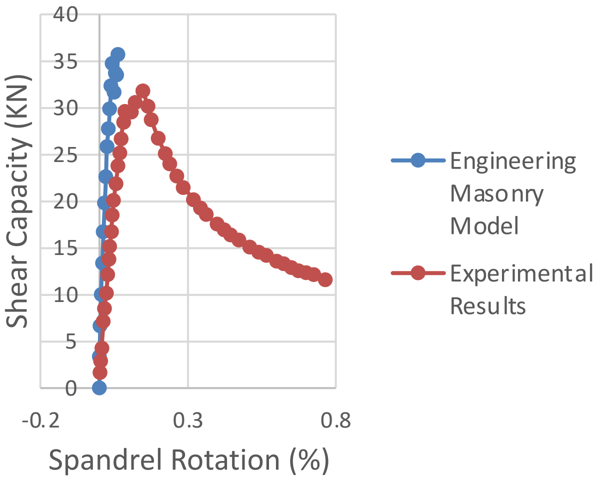
- Element Type
  - Curved Shell Element
- Material model
  - Engineering Masonry Model

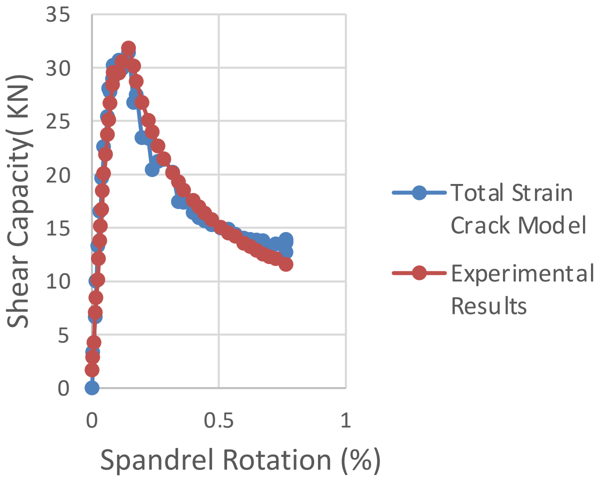
Numerical Modelling of Spandrel Behaviour

- **Validation of numerical model**
  - Engineered masonry model (EM) vs. Total strain crack model (TSC)
  - EM model was unable to trace post-peak softening, but TSC captured it



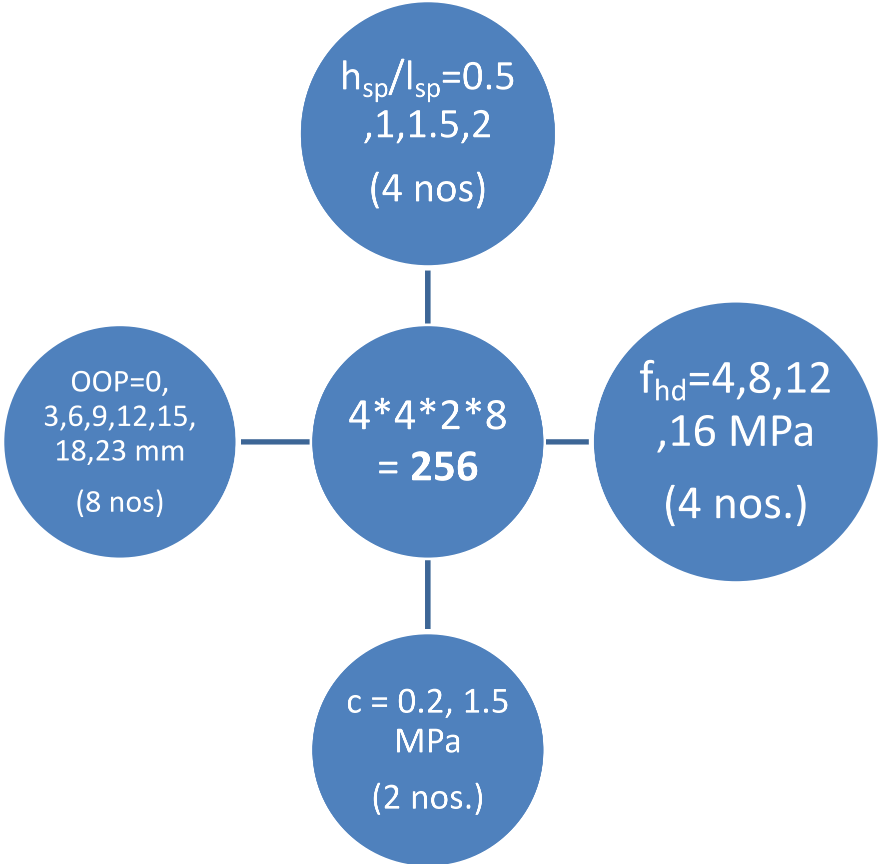
Ref.: Graziotti et al. 2012, Experimental cyclic behaviour of stone masonry spandrels, Proc. of 15th WCEE, Lisbon





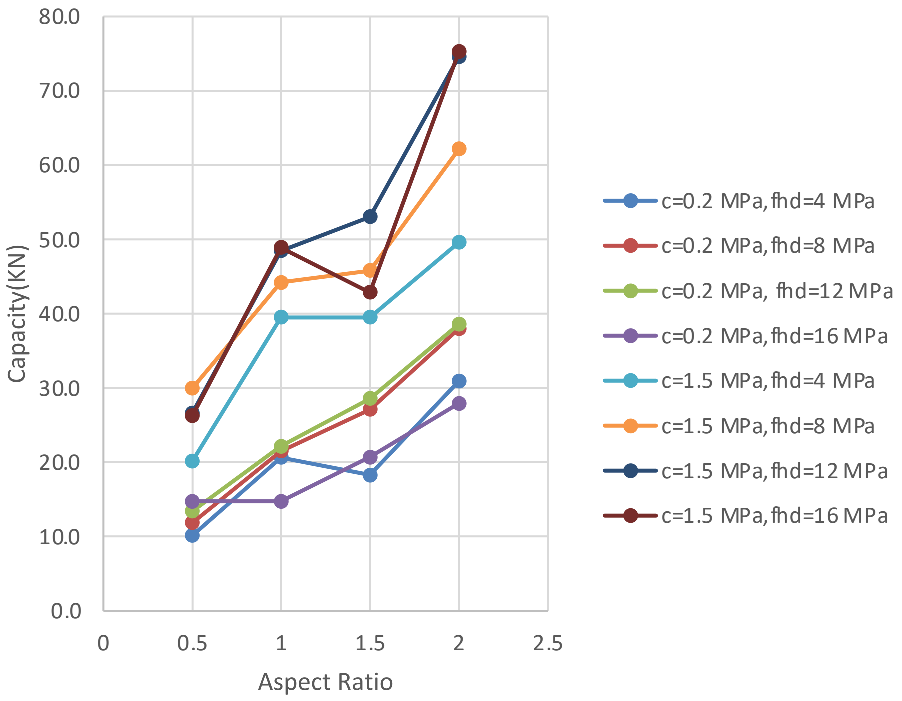
Numerical Modelling of Spandrel Behaviour

- **Overview of Batch Processing**

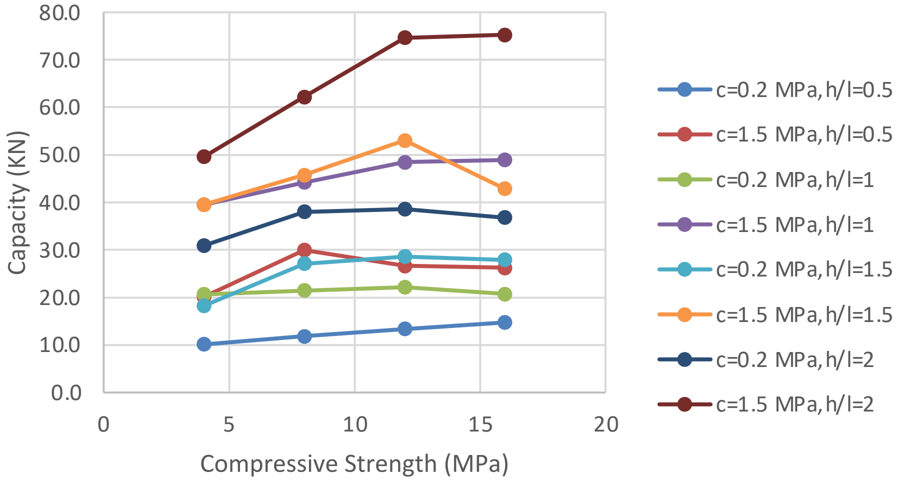


Numerical Modelling of Spandrel Behaviour

- **Observations from in-plane response**



Geometry

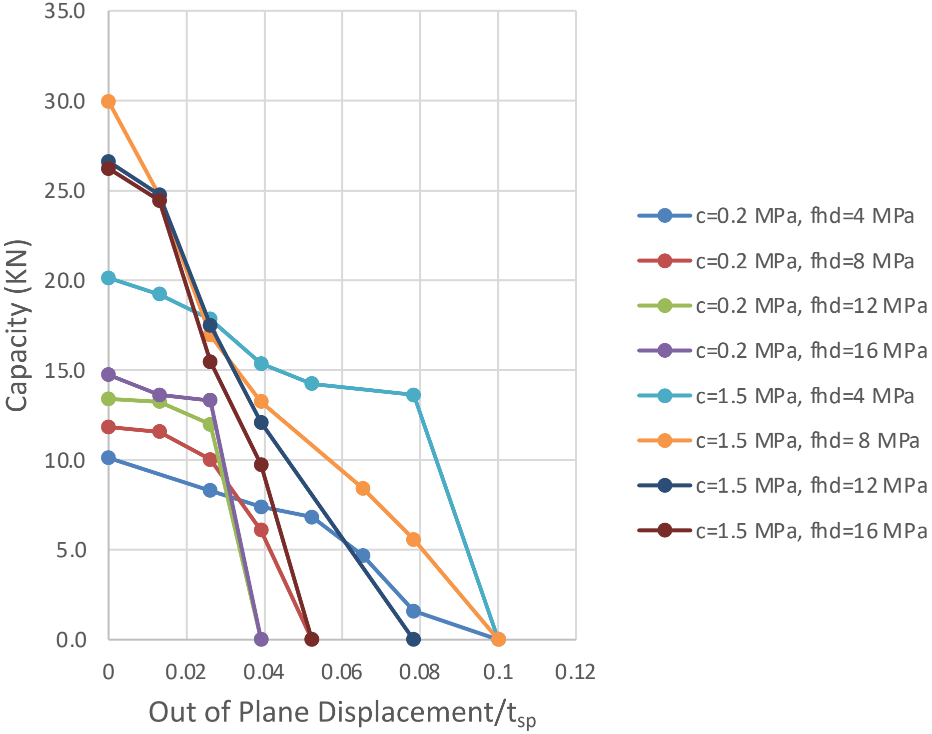


Material Properties

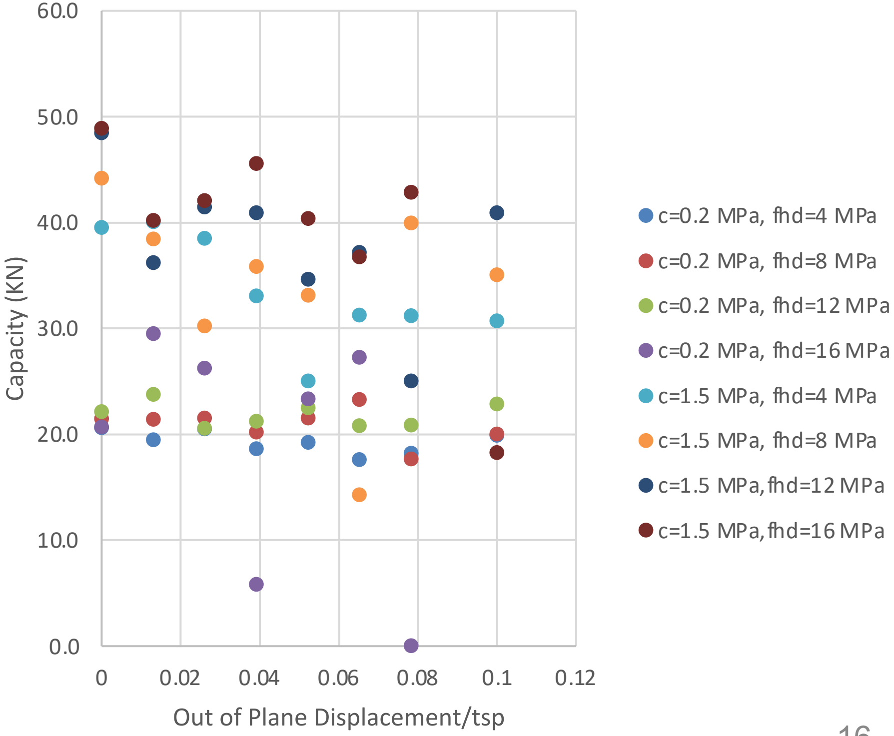
Numerical Modelling of Spandrel Behaviour

- **Observations from interaction with out-of-plane response**

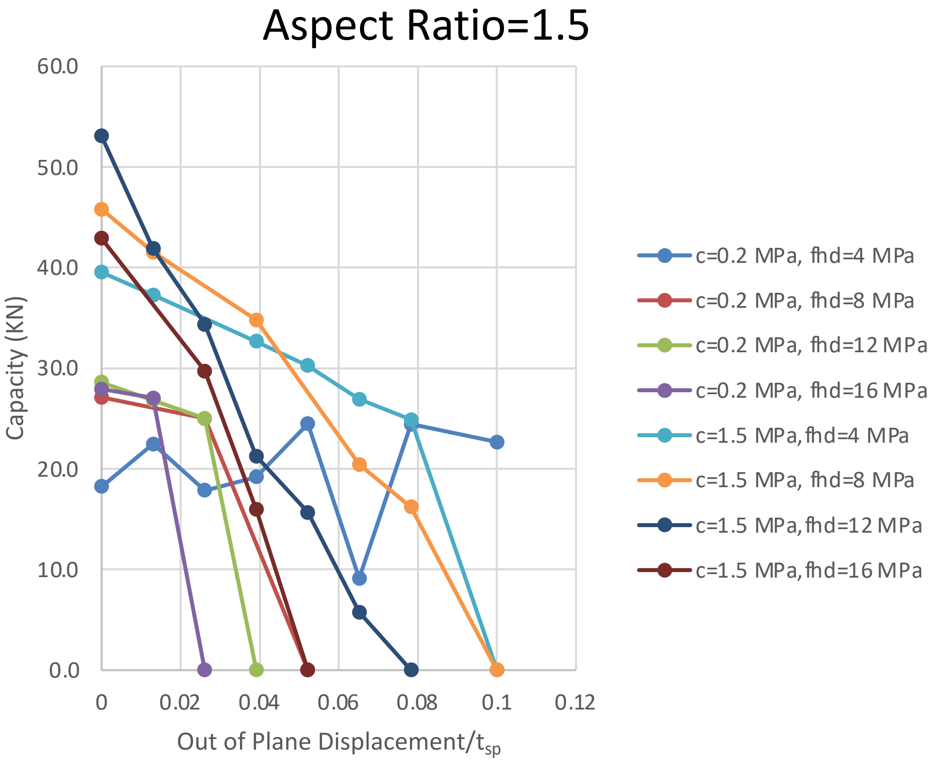
Aspect Ratio=0.5

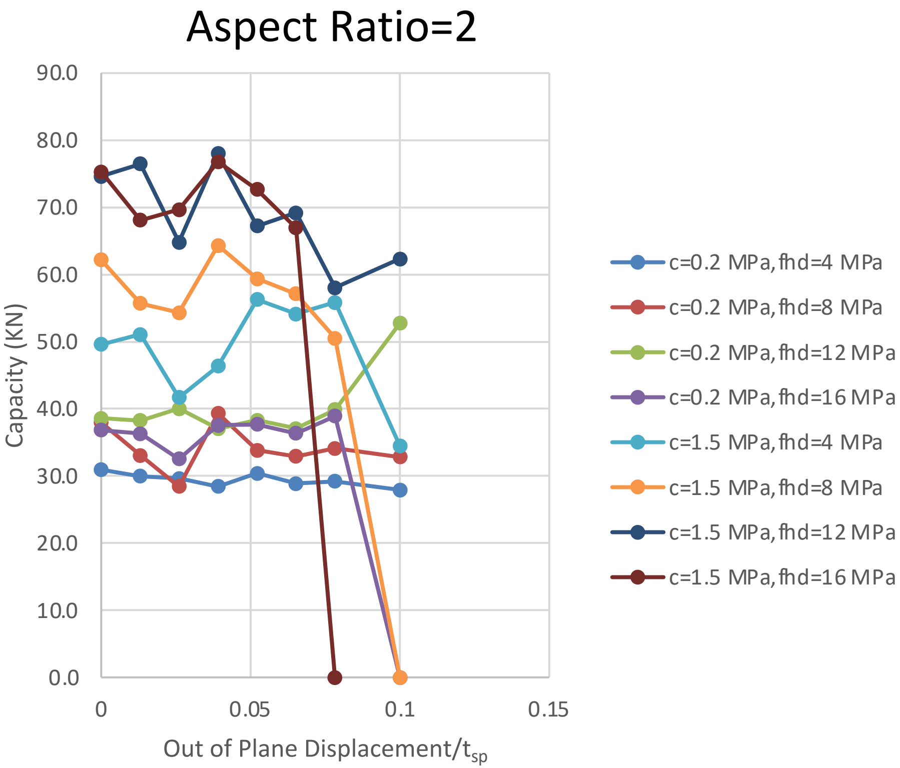


Aspect Ratio=1



Numerical Modelling of Spandrel Behaviour





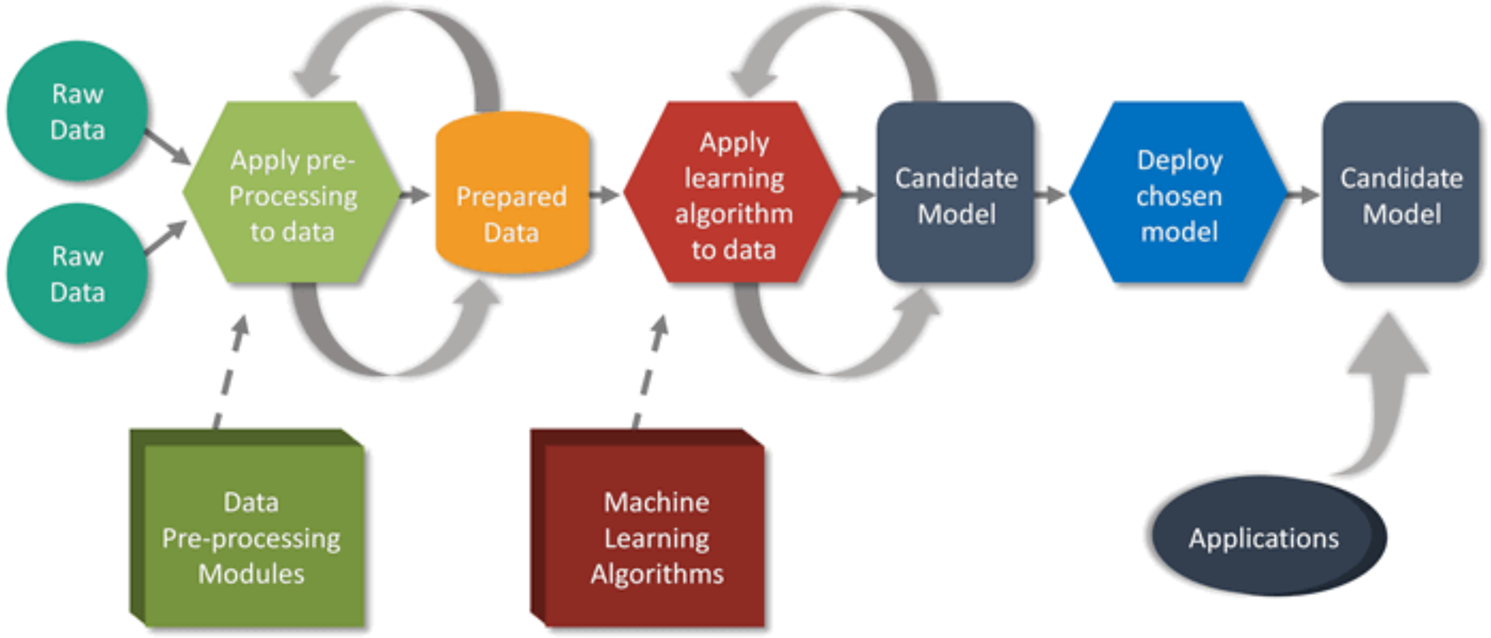
Numerical Modelling of Spandrel Behaviour

- **The out of plane displacement causes minimum reduction in capacity when aspect ratio ≈ 1.**

Aspect Ratio	Average decrease in capacity at Δ_{OOP} = 23 mm	Key Observations
0.5	92%	Out-of-plane failure (capacity=0) was observed in all models with Δ_{OOP} = 23 mm except the cases of c=0.2 MPa, f_{hd}=4 MPa and c=0.2 MPa, f_{hd}=8 MPa where a 44% and 88% decrease in capacity was observed respectively.
1	29%	For c=0.2 MPa, f_{hd}=16 MPa, it was also observed that failure occurred at Δ_{OOP} = 18 mm itself.
1.5	82%	For c=0.2 MPa, f_{hd}=16 MPa, the variation of capacity with Δ_{OOP} was haphazard and the expected decreasing trend was not observed.
2	42%	It was observed that capacity reduction was minimal for all values of Δ_{OOP} except 23 mm.

Machine Learning Approach

- **Introduction**



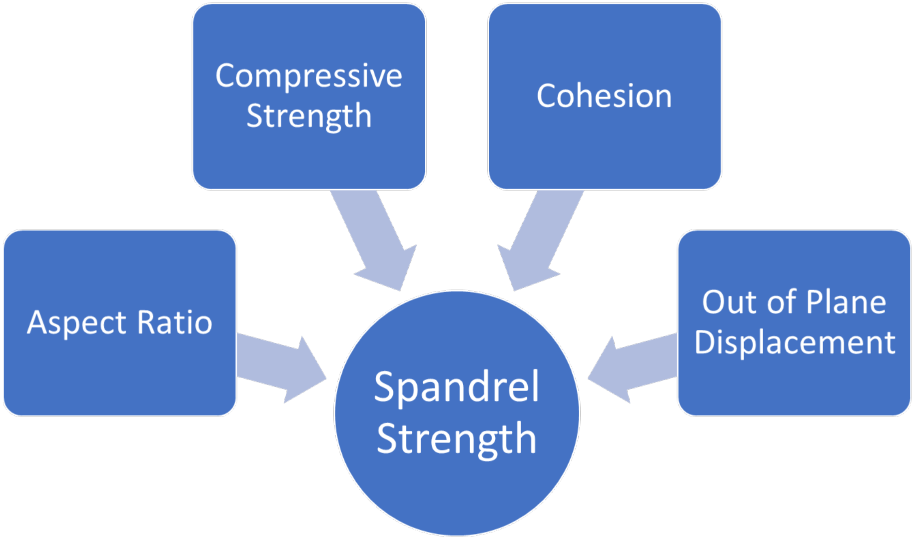
Ref.: https://www.sketchbubble.com/en/presentation-machine-learning.html

Machine Learning Approach

- **Data sample**

hbyl	fhd (MPa)	c (MPa)	OOP (mm)	Cap (KN)
0.5	4	0.2	0	10.1
0.5	4	1.5	0	20.1
0.5	8	0.2	0	11.8
0.5	8	1.5	0	30
0.5	12	0.2	0	13.4
0.5	12	1.5	0	26.6
0.5	16	0.2	0	14.7
0.5	16	1.5	0	26.2
0.5	4	0.2	3	10.3
0.5	4	1.5	3	19.2
0.5	8	0.2	3	11.6
0.5	8	1.5	3	24.7
0.5	12	0.2	3	13.25
0.5	12	1.5	3	24.8
0.5	16	0.2	3	13.6
0.5	16	1.5	3	24.4
0.5	4	0.2	6	8.3
0.5	4	1.5	6	17.8
0.5	8	0.2	6	10
0.5	8	1.5	6	16.9
0.5	12	0.2	6	11.99

Predictor Variables



Target Variables

Machine Learning Approach

- **Data pre-processing**
  - Normalization
  - Binarization
  - Removal of outliers
  - Adding 0 capacity rows initially (found to skew data)
  - Removing all rows with 0 capacity

hbyl	fhd	c	OOP	cap
1	0	0	0	30.9
1	0	1	0	49.6
1	0.33	0	0	38
1	0.33	1	0	62.2
1	0.67	0	0	38.6
1	0.67	1	0	74.6
1	1	0	0	36.8

Normalization

hbyl	fhd	c	OOP	cap
0.5	4	0.2	0	10.1
0.5	4	0.2	3.000	10.3
0.5	4	0.2	6.000	8.3
0.5	4	0.2	9.000	7.4
0.5	4	0.2	12.000	6.8
0.5	4	0.2	15.000	4.7
0.5	4	0.2	18.000	1.6
0.5	4	0.2	23.000	0.0
0.5	4	0.2	26.000	0.0
0.5	4	0.2	29.000	0.0
0.5	4	0.2	32.000	0.0
0.5	4	0.2	35.000	0.0
0.5	4	0.2	38.000	0.0

Extra 0s

hbyl	fhd	c	OOP	cap
1.5	8	0.2	0	27.1
1.5	8	0.2	3.000	22.0
1.5	8	0.2	6.000	25.0
1.5	8	0.2	9.000	25.1
1.5	8	0.2	12.000	0.0
1.5	8	0.2	15.000	0.0
1.5	8	0.2	18.000	0.0
1.5	8	0.2	23.000	6.3

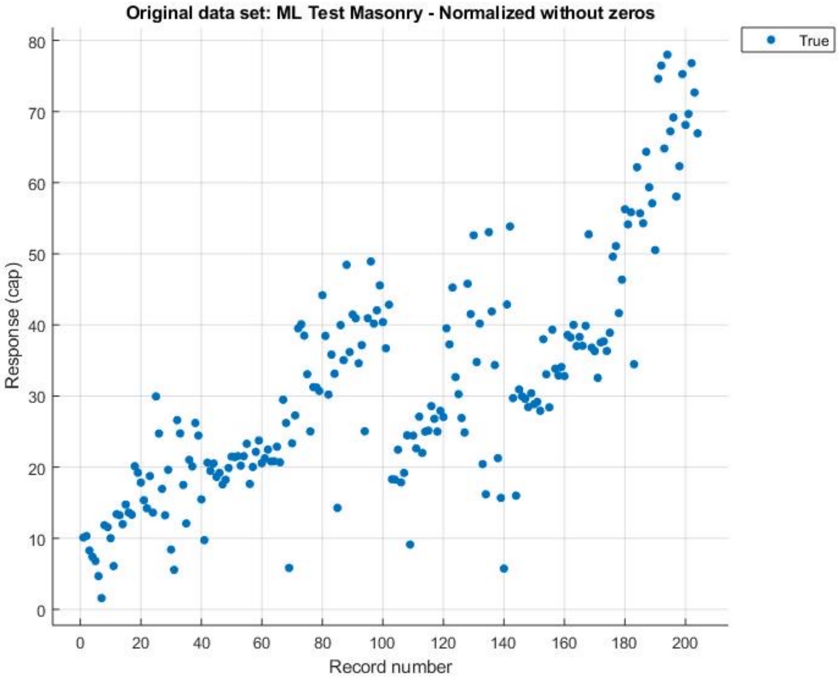
Removal of outliers

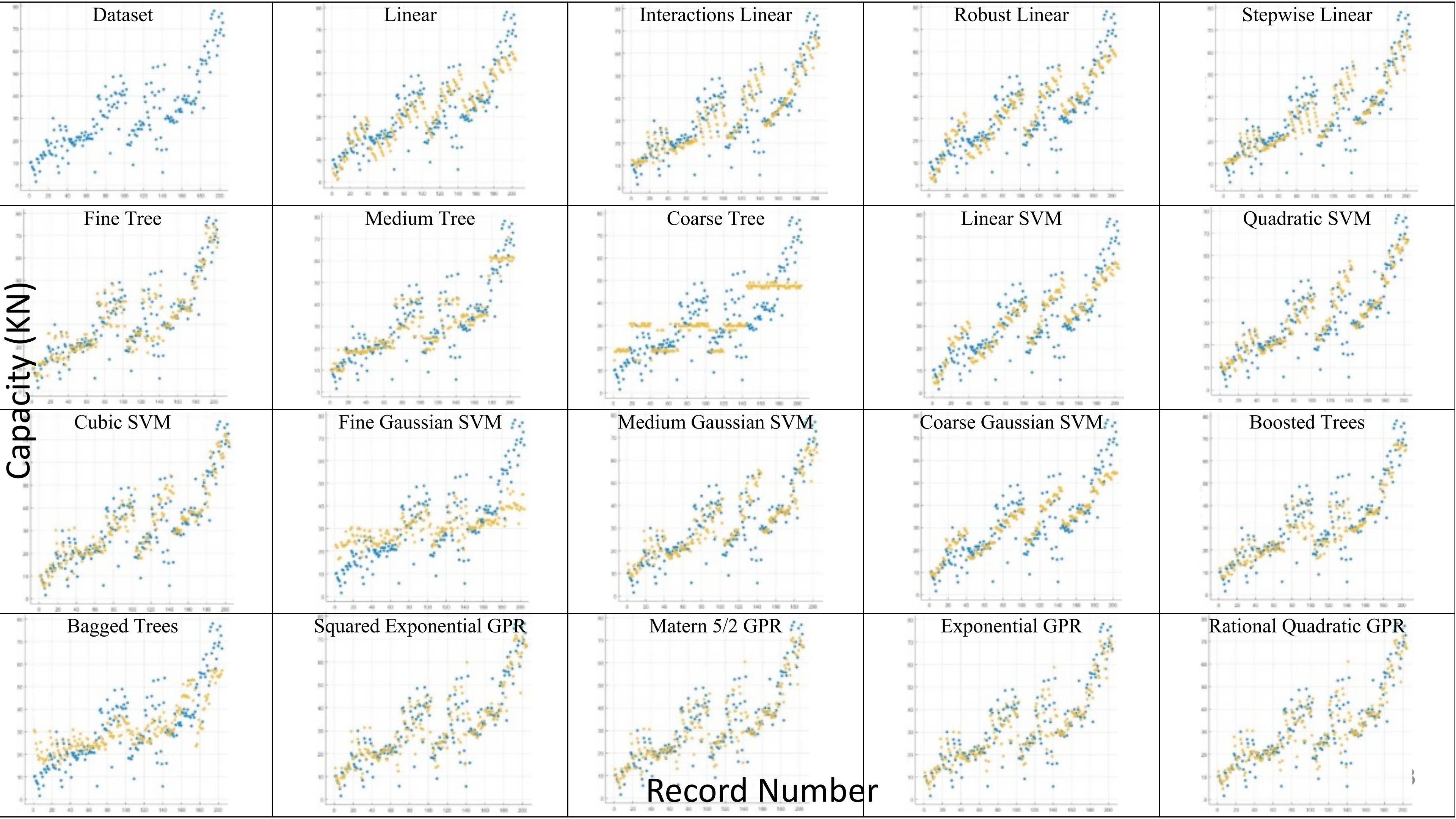
hbyl	fhd (MPa)	c (MPa)	OOP (mm)	Cap (KN)
0.5	4	0.2	0	10.1
0.5	4	1.5	0	20.1
0.5	8	0.2	0	11.8
0.5	8	1.5	0	30

Raw Data

Machine Learning Approach

- **Comparison of ML models**
  - Selection of the final algorithm with the best fit was made from an initial set of 19 different ML algorithms
  - Relatively small size of the data set permitted such an approach.



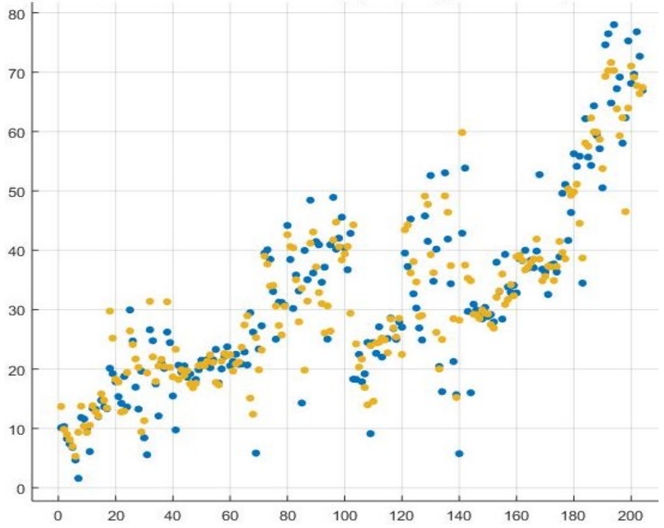

Dataset
Linear
Interactions Linear
Robust Linear
Stepwise Linear
Fine Tree
Medium Tree
Coarse Tree
Linear SVM
Quadratic SVM
Cubic SVM
Fine Gaussian SVM
Medium Gaussian SVM
Coarse Gaussian SVM
Boosted Trees
Bagged Trees
Squared Exponential GPR
Matern 5/2 GPR
Exponential GPR
Rational Quadratic GPR
Capacity (KN)
Record Number

Machine Learning Approach

- **Predictive equation**
  - Proposed form of equation (approximate):

$$Spandrel\ Shear\ Capacity\ (V_{sp}) = \alpha \sqrt{\frac{h}{l}\frac{c}{\Delta_{OOP}}} {f_{hd}}^{0.1}$$

Note: Logarithm was applied on the dataset.
X axis: Record number, Y axis: Capacity (KN)



- Rows in the dataset with 0 out-of-plane displacement were removed, and 0 capacity were removed.
- Logarithms were taken on all the predictor variables and the target variable.
- Predictor variables were normalized as before, and the dataset was trained on all the ML models.

Summary

- **Conclusions**
  - Spandrel capacity does not have a linear variation with dependent variables.
  - Capacity varies as the inverse square root of OOP displacement.
  - Capacity reduction is minimal when aspect ratio is close to unity.

- **Limitations**
  - Thickness of spandrel has not been varied (t_{sp}=230 mm)
  - Only two extreme values of cohesion (0.2 MPa and 1.5 MPa) have been used.
  - The final dataset (without the zero capacity and zero OOP rows) had just 173 data points.
  - The proposed equation cannot be used to find the in-plane capacity.

Summary

- **Scope for Future Research**
  - A comprehensive database is to be developed with variation in
    - Spandrel thickness (t_{sp})
    - Spandrel and pier axial load
    - Boundary conditions
  - Classification Learner - predict failure mechanism.
  - Database - compared with practically tested models.
  - A study can be conducted on the different masonry models to identify the most suitable model depending upon the loading scenario, detail of failure profile required, post-peak requirements etc.