# Crack pattern observations into finite element simulation

AN EXPLORATORY STUDY FOR DAMAGE ASSESSMENT OF EXISTING CONCRETE STRUCTURES



## Content

- Background and motivation
- Objective
- Approach
- Validation
- Conclusions and recommendations

# Background

**Detailed assessment of RC structures**

- Need:
  - Uncertainty regarding the structural safety
  - Added opinion
- Reliable assessment should account for existing cracks (Guidelines for Nonlinear Finite Element Analysis of Concrete Structures , RTD 1016-1:2016, Section2.7)



# Background

**Existing approaches to account for pre-damage in NLFEA**

❖ **Approach 1: Model the physical process which causes damage**

Limitation:
- Large number of influencing factors.
- Huge computational cost.
- Structural analysis ambitious.

❖ **Approach 2: Perform phased analysis**

Limitation:
- Load history difficult to predict.

❖ **Approach 3: Analyse with reduced material proper**

Limitation:
- Difficult to account for spatial variability of damage.

# Background

**Phenomenological and probabilistic approach: Take damage as the starting point of the structural analysis through input.**

- Advantage :
  - Circumvents the need to model complex physical processes.
  - Computationally less expensive.
  - Enables analysis of structural behaviour.
  - Can be based on measurements on the damaged structure.
  - Statistical inputs to account for spatial variability.
- Limitation :
  - Reduced accuracy since true physics of the problem is not captured
- Trade-off between feasibility and accuracy



# Background

**Pertinent questions**

- How to define damage?
- How to make measurements on the structure?
- How to account for pre-damage and associated uncertainty through input?
- How to model pre-damaged RC members?

# Objective

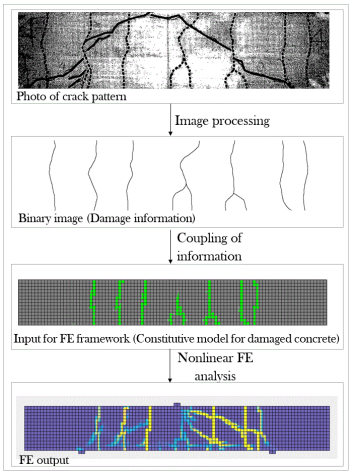
- **Development of a generic modelling approach that:**
  - Brings the information obtained from crack patterns into a finite element model.
  - Enables the study of the effects of damage of concrete, on the structural behaviour.
  - Research question:

**How can the visually observed crack patterns in RC structures be accounted for, in finite element analyses?**



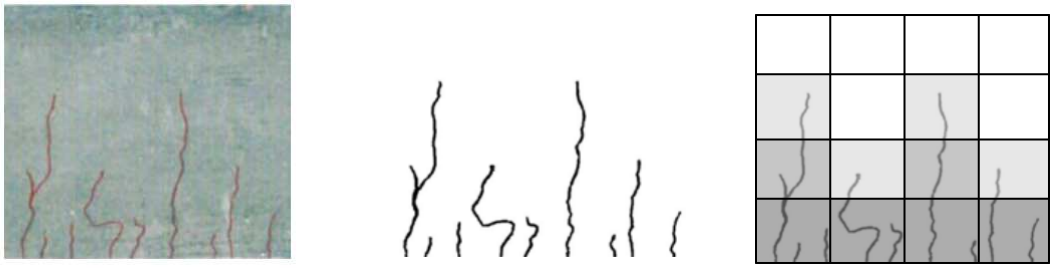
# Approach

## Methodology for finite element analysis



# Approach

## Measurement to damage input : Image analysis of crack patterns

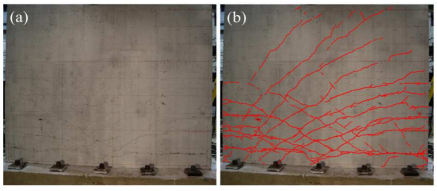


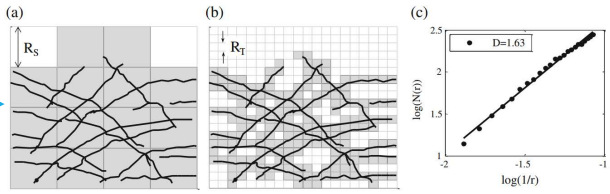
Original image → Image processing → Binary image → Fractal analysis/Mapping → Damage data

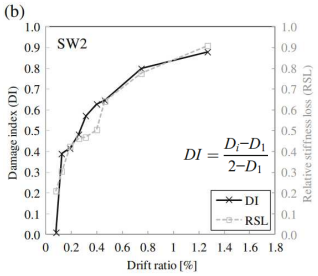


# Approach

## Damage data: Fractal analysis of residual crack pattern



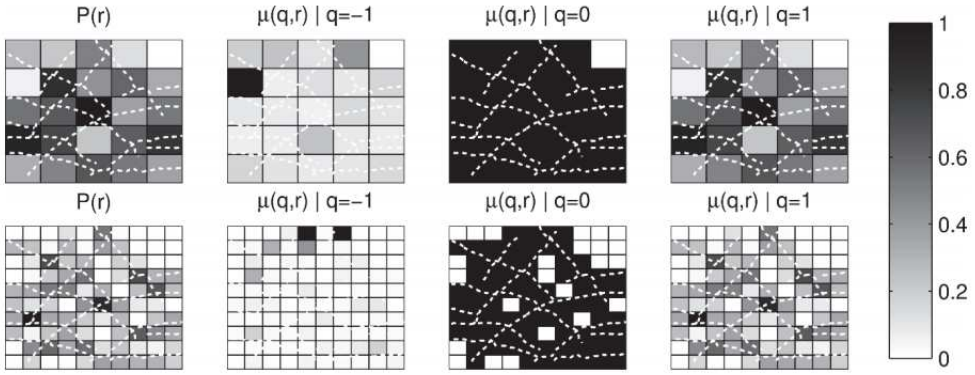




- **Fractal Dimension** – Ratio comparing how detail in a pattern changes with the scale at which it is measured. Varies between 1 and 2

- Using **Box-counting method** $FD = \lim_{r \to 0} \frac{\log N(r)}{\log(r)}$

# Multifractal Analysis

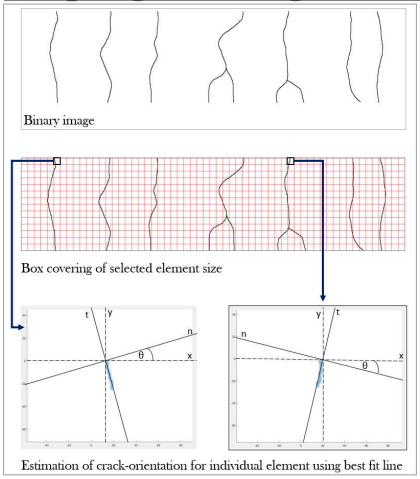
- Generalisation in which FD instead of being a global parameter is a local parameter(called singularity strength(α)), that may change from box to box → Normalised measures for each

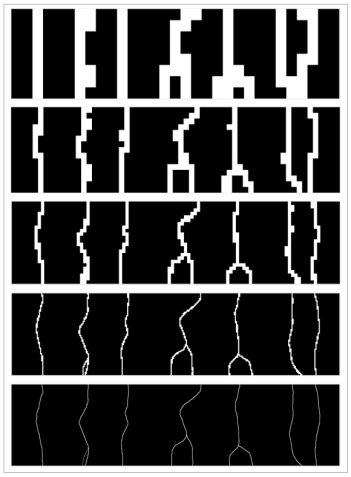





# Approach

## Coupling of damage data with FE mesh



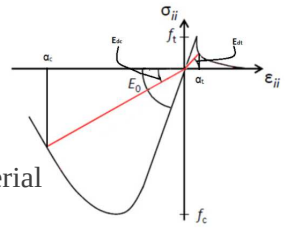



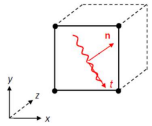
Refining cover with a range of box sizes

# Approach

## Constitutive model for damaged concrete

- Characteristics:
  - Damage definition : Decline of stiffness and strength
  - Damage input ‘d’ in the total strain based smeared crack model
  - $E_d = (1 - d)\, E_0$
  - Domain of d [0,1] ; 0 = undamaged material, 1 = fully damaged material
- Desired characteristics for the material model:
  - Input parameters as a function of measurable damage indicators.
  - Meaningful results on the structural level.
  - Practical to use for real-life RC structural members.
  - Able to handle multiple types/sources of concrete damage.
  - Damage input suited for probabilistic calculations.

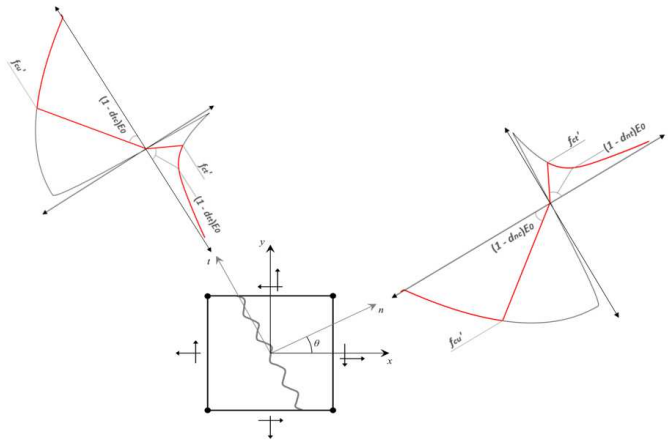





# Approach

## Constitutive model for damaged concrete : Definition




Damage input parameters:

1. dnt
2. dnc
3. dtt
4. dtc
5. θ

# Approach

## MATLAB implementation

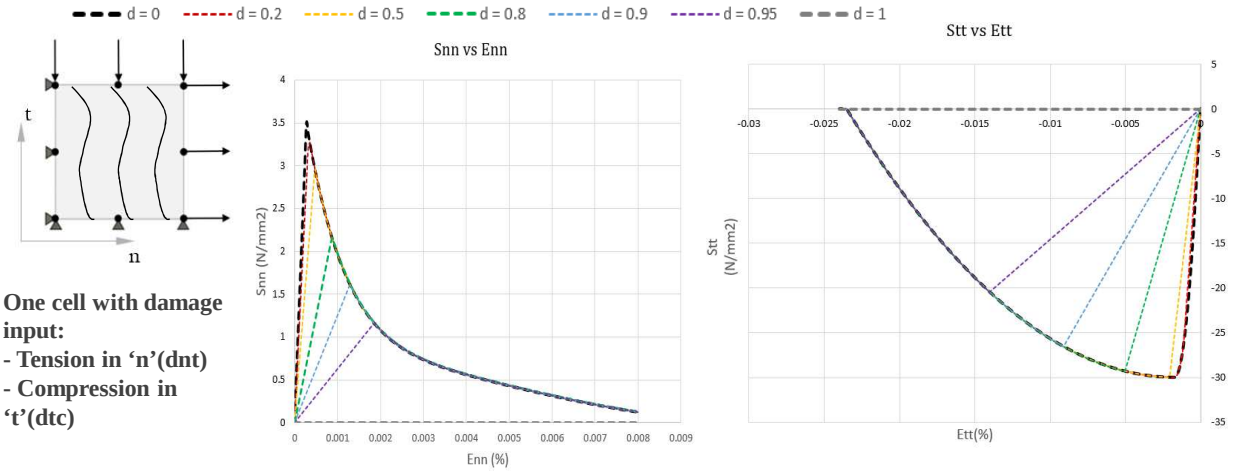
Highlights of FEM tool:

- Standard displacement control
- Full Newton-Raphson solution procedure
- Total strain based orthogonal smeared crack model
- Non-linear softening relationships
  - Tension – Exponential, Hordijk
  - Compression – Hognestad, Parabolic
- Embedded reinforcements
- Coupled damage input from image analysis
- Visualisation of results



# Approach

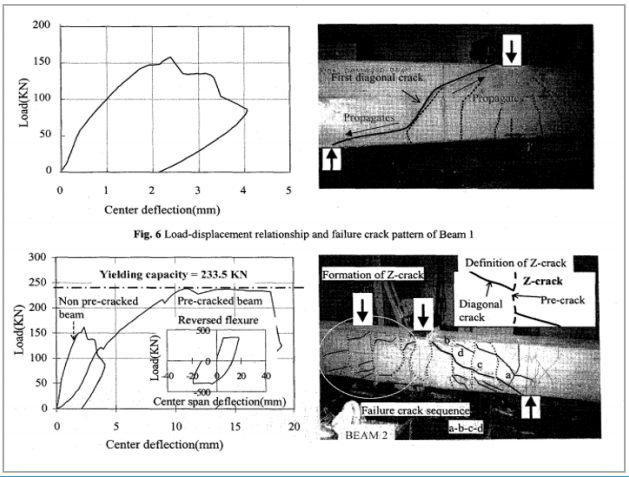
## Verification




**One cell with damage input:**
**- Tension in 'n'(dnt)**
**- Compression in 't'(dtc)**

# Validation

## Selected experiments: Experiment 1

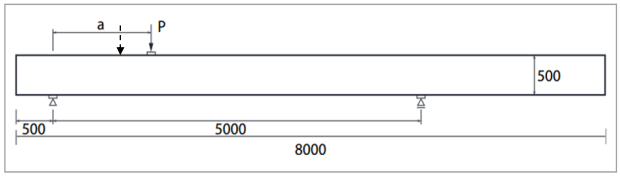


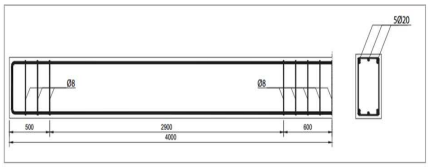

**Experiments on shear capacity of vertically pre-cracked beams**



# Validation

## Selected experiments: Experiment 2

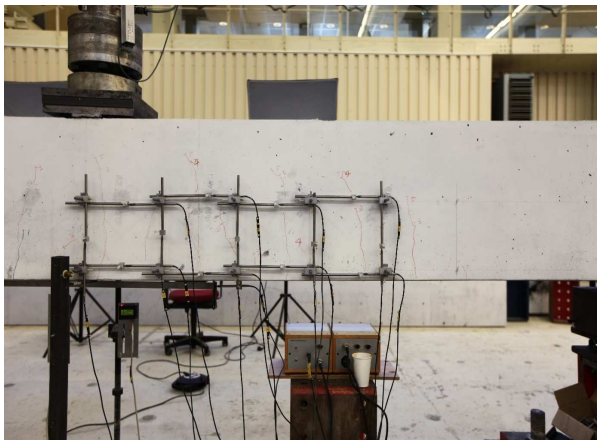


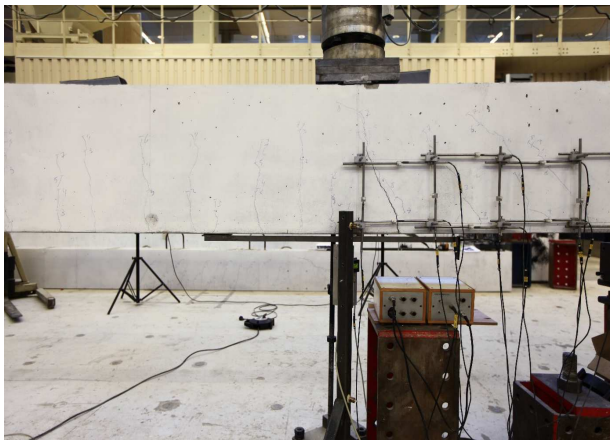

**Investigation of vmin based on experimental research**

# Validation

## Experimental observations of crack patterns: Phase1



a = 2000 mm(Specimen1)

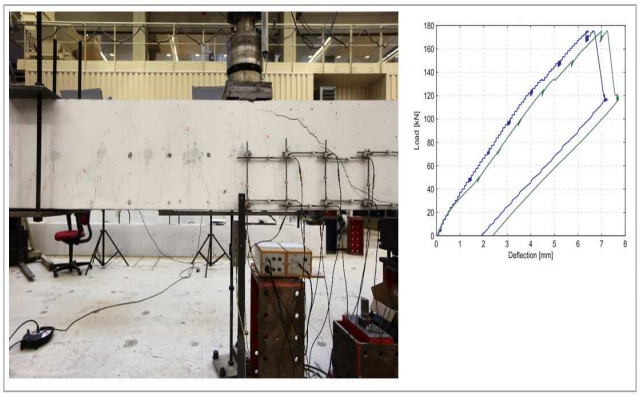


a = 1250 mm(Specimen2)

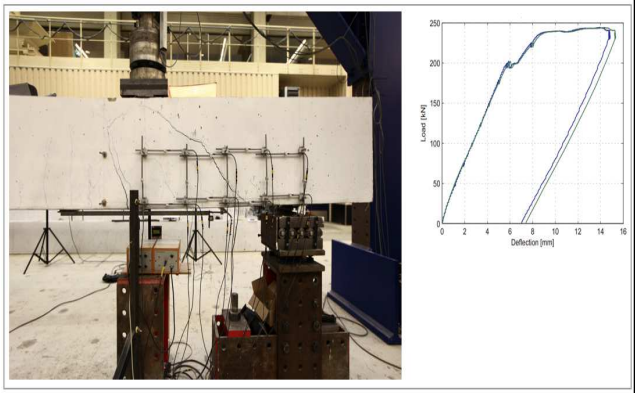


# Validation

## Experimental observations of crack patterns: Phase 2



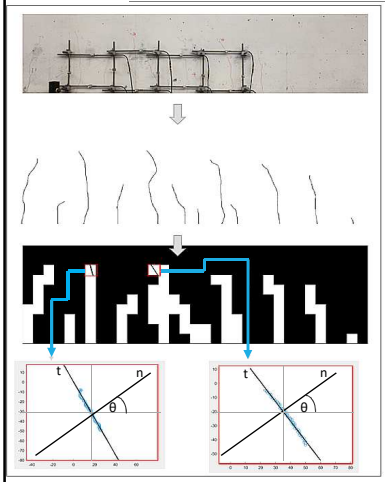

a = 1250 mm (Specimen1)



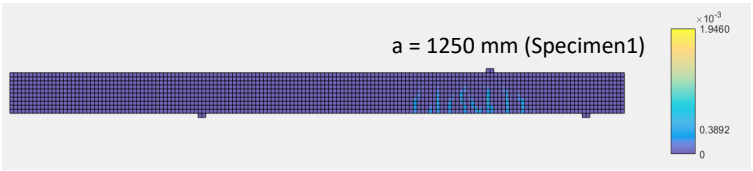

a = 1000 mm (Specimen2)

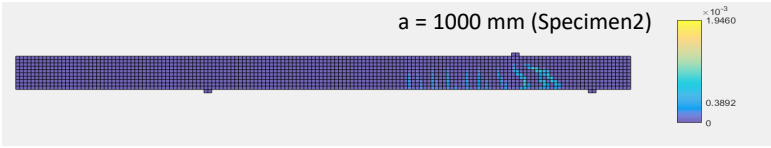
# Validation

## Finite element modelling




dnt = 1
dnc = 0
dtt = 0
dtc = 0



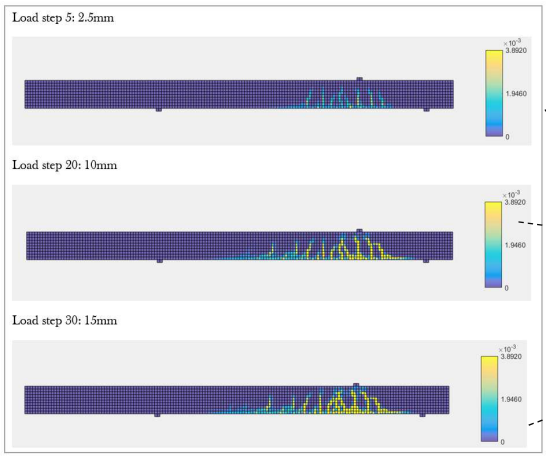



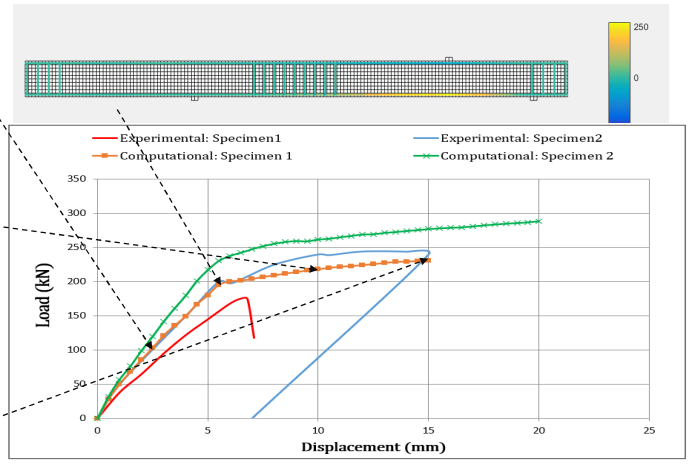

Major principal strains at 0.5mm mid-span deflection



# Validation

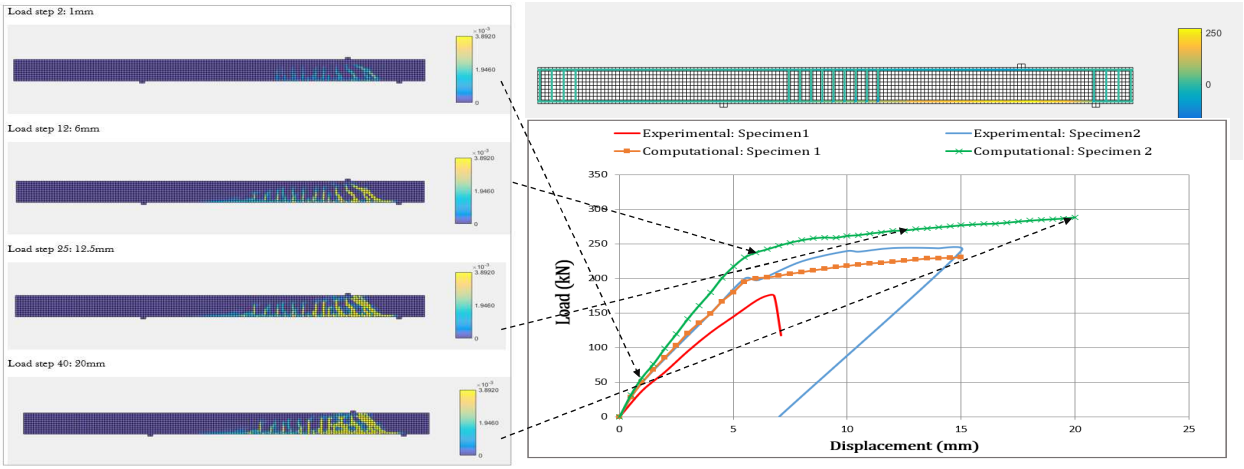
## Results: Specimen 1



# Validation

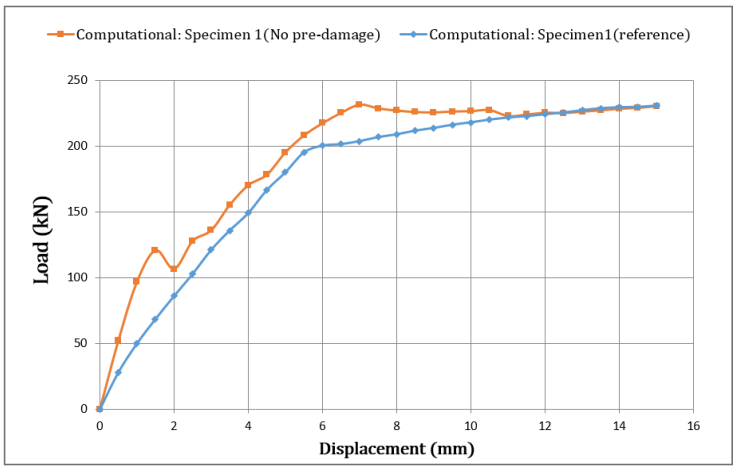
## Results: Specimen 2





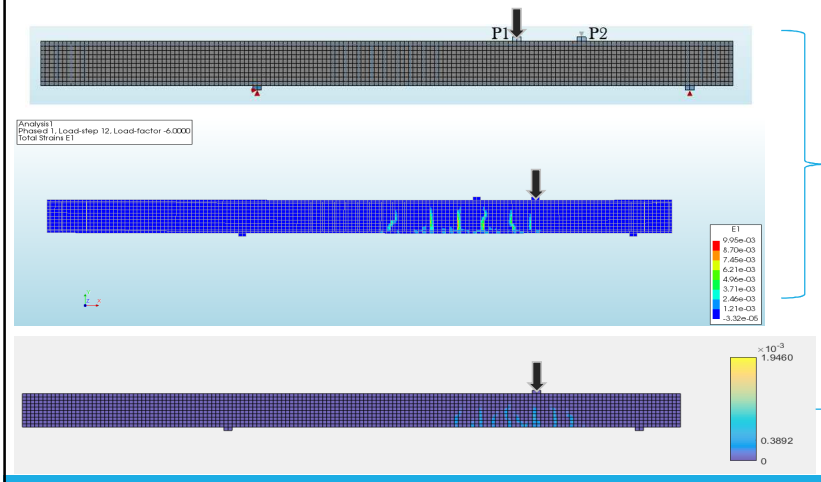

# Validation

## Sensitivity study: No pre-damage input



# Validation

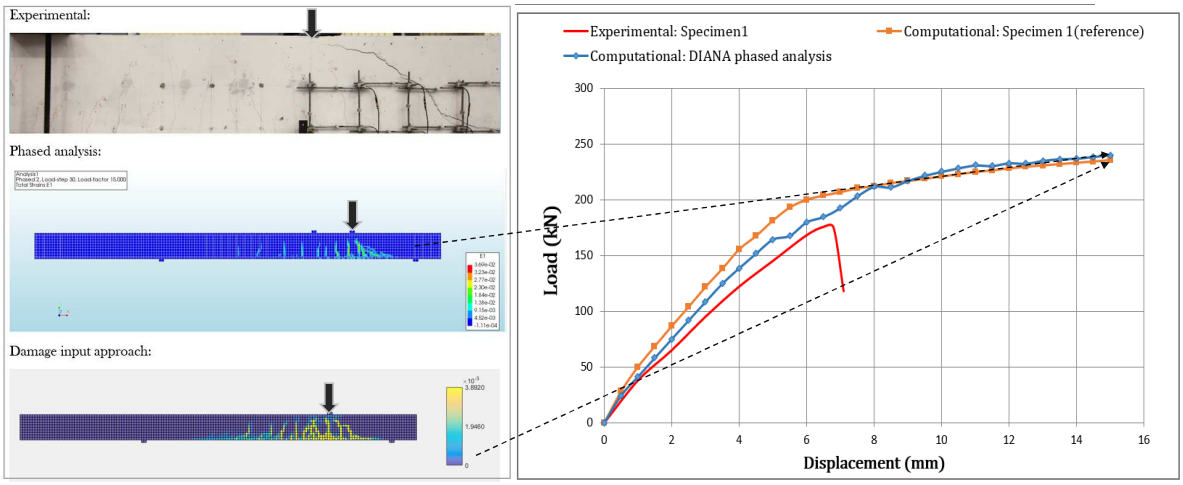
## Comparative study with phased analysis approach: Loading phase 1






# Validation

## Comparative study with phased analysis approach: Loading phase 1



# Conclusions and recommendations

## Conclusions

### How can the information obtained from visually observed crack patterns in RC structures be included in finite element analyses?

- Methodology set up, to input information obtained from visually observed crack pattern into finite element analysis.
- Characteristic impacts on structural response due to damage of concrete observed in the finite element solutions.
- Good efficiency is observed in predicting nonlinear phenomena in RC and results comparable with phased analysis.
- Over all distribution of damage over the structure more important than local inputs for stiffness loss and crack-orientation



# Conclusions and recommendations

## Recommendations

- Use of image analysis is recommended. For 3-d cases, other techniques like acoustic tomography could be incorporated.
- Ideas from fractal geometry could be exploited to study the complex patterns/distributions of damage over the surface of the structure.
- Study using varying element sizes could be performed to determine the most optimum way of damage input into the finite element model.
- The developed methodology could be utilised to study other mechanisms of existing RC damage.

# THANK YOU!

# QUESTIONS?