EPFL EOS EURASIAN OPENSEES
SPRING SCHOOL
9th international course on:
Seismic analysis of structures using OpenSees:

The Built Environment Data Framework for Simulated Design and Vulnerability Modelling in Earthquake Engineering

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IUSS Scuola Universitaria Superiore Pavia

Powered by DJURA RISK-DATA-ENGINEERING

ROSE Centre for Training and Research on Reduction of Seismic Risk

Background & Motivation

- Past earthquakes in have illustrated the vulnerability of existing RC frames structures

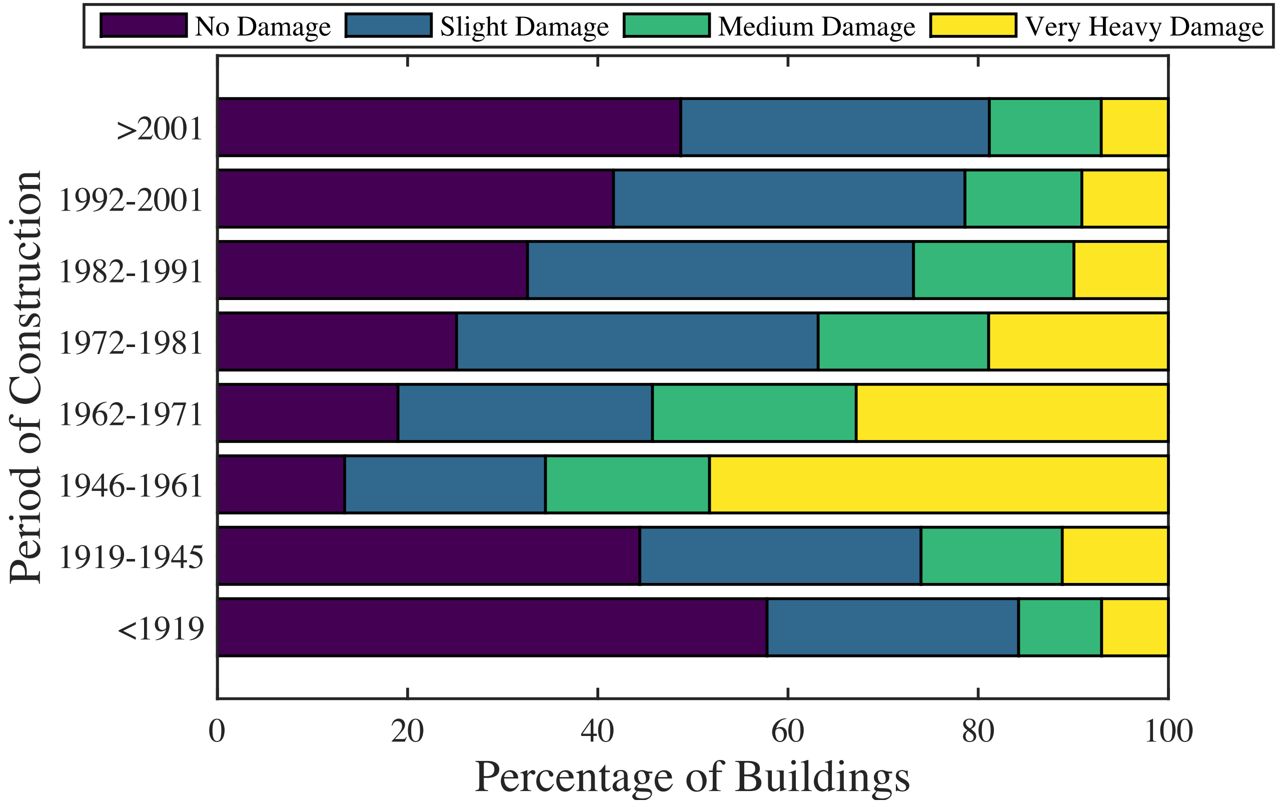
Beam-Column Joint

Masonry Infill Failure

Soft Storey Collapse

Background & Motivation

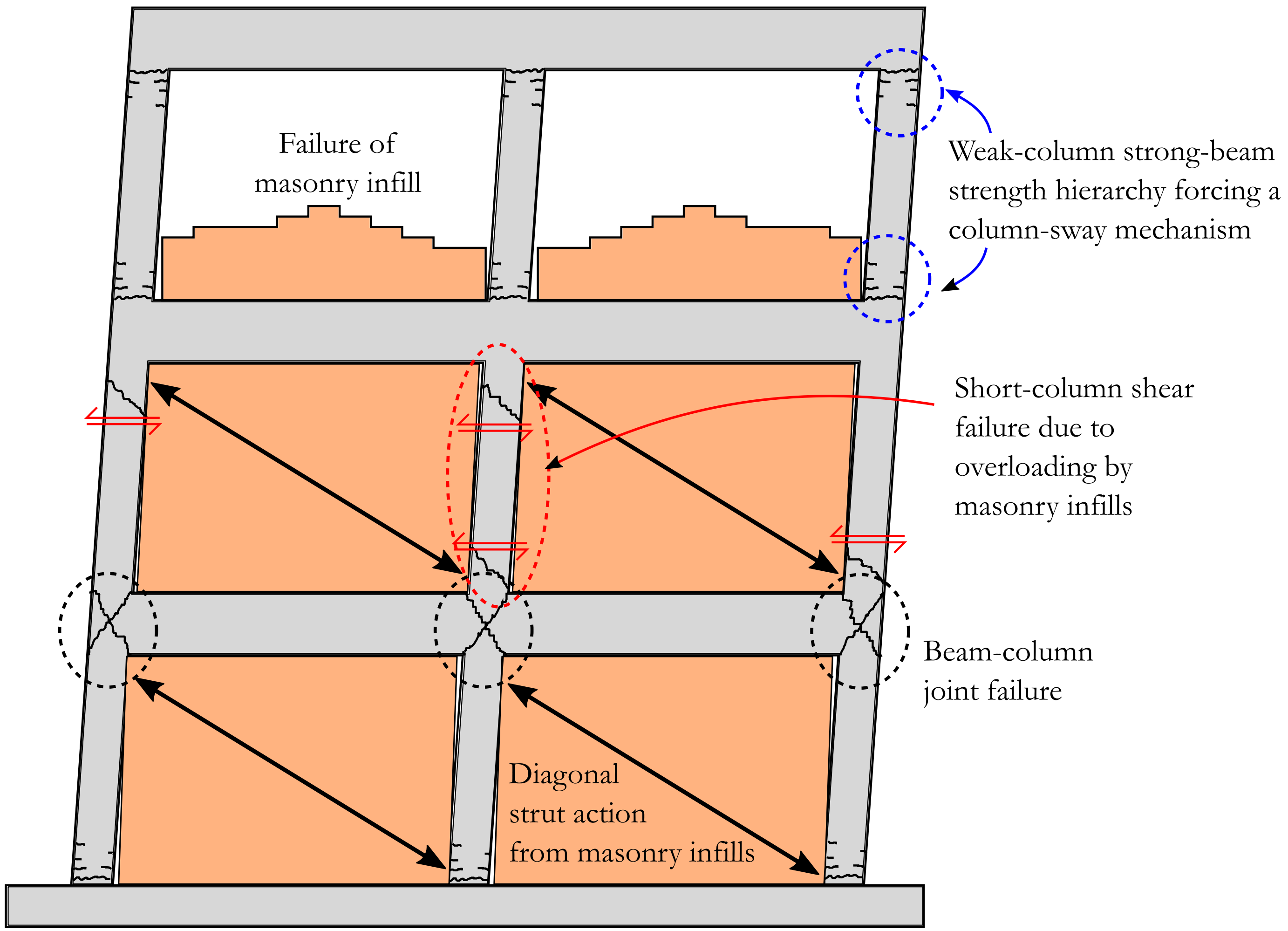
- Damage surveys following the L'Aquila event of 2009 have shown the vulnerability of RC frames constructed prior to the 1970s, when seismic design provisions were introduced



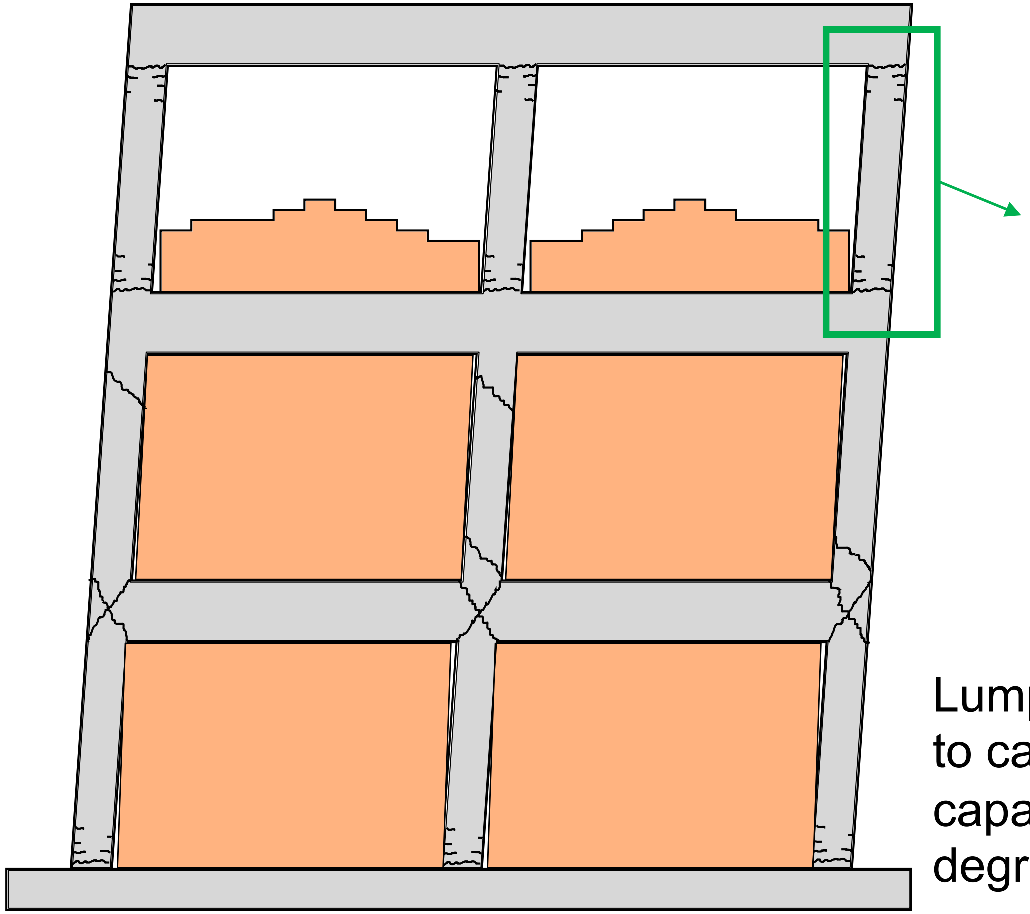
Distribution of observed damage to RC frames in L'Aquila

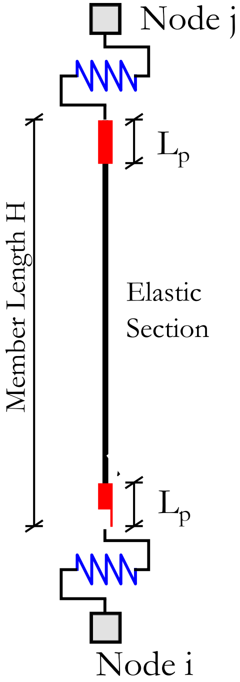
Numerical Modelling in OpenSees

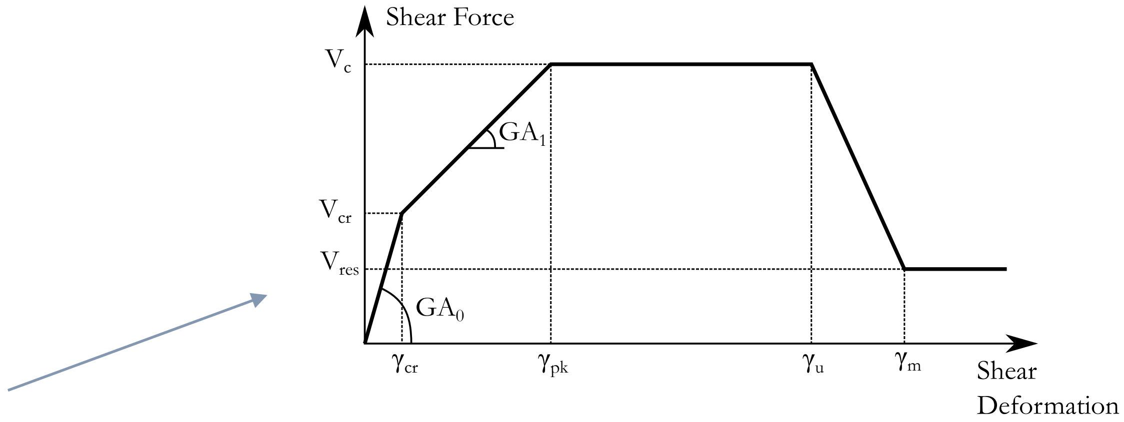
- Efficient numerical modelling approaches that capture the behaviour of the components vulnerable to damage are required
- Experimental testing and past damage observed following earthquakes have highlighted the vulnerability of various elements:
    - Non-ductile columns with modified behaviour due to smooth bars
    - Weak beam-column joints (no transverse shear reinforcement)
    - Shear failure of columns due to poor shear reinforcement and interaction with masonry infill



Beam-Column Element

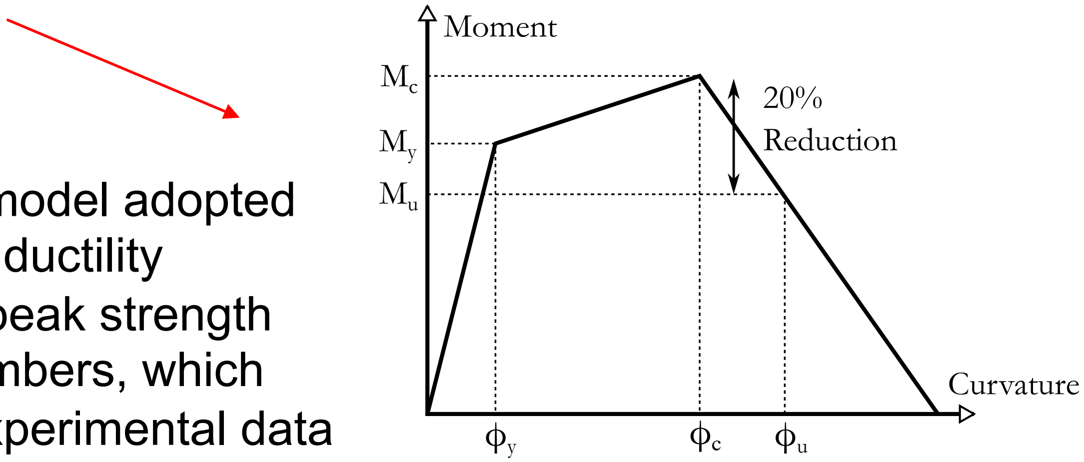




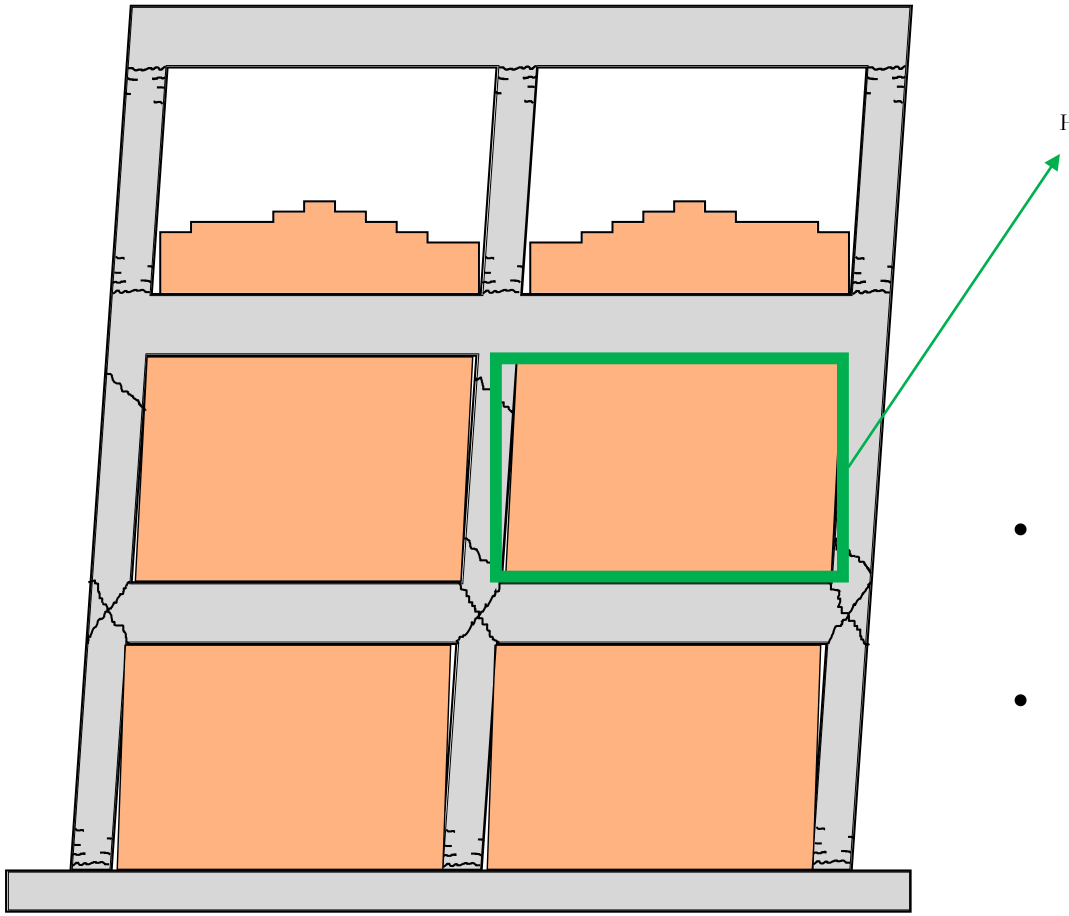


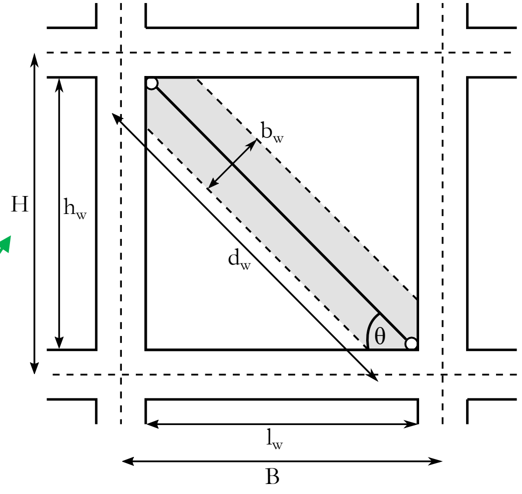
UCSD shear model adopted from previous calibration by Mergos & Kappos [2008, 2012] and Zimos et al. [2015]

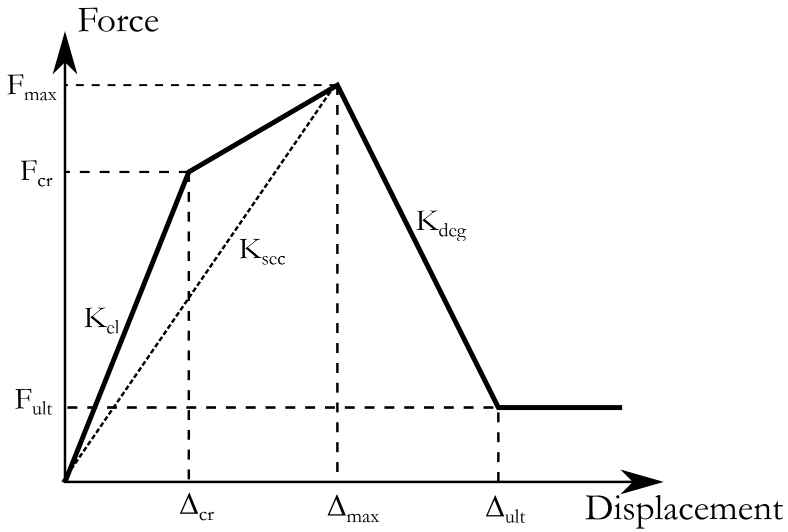
Lumped plasticity model adopted to capture ultimate ductility capacity and post peak strength degradation of members, which are calibrated to experimental data



Masonry Infill

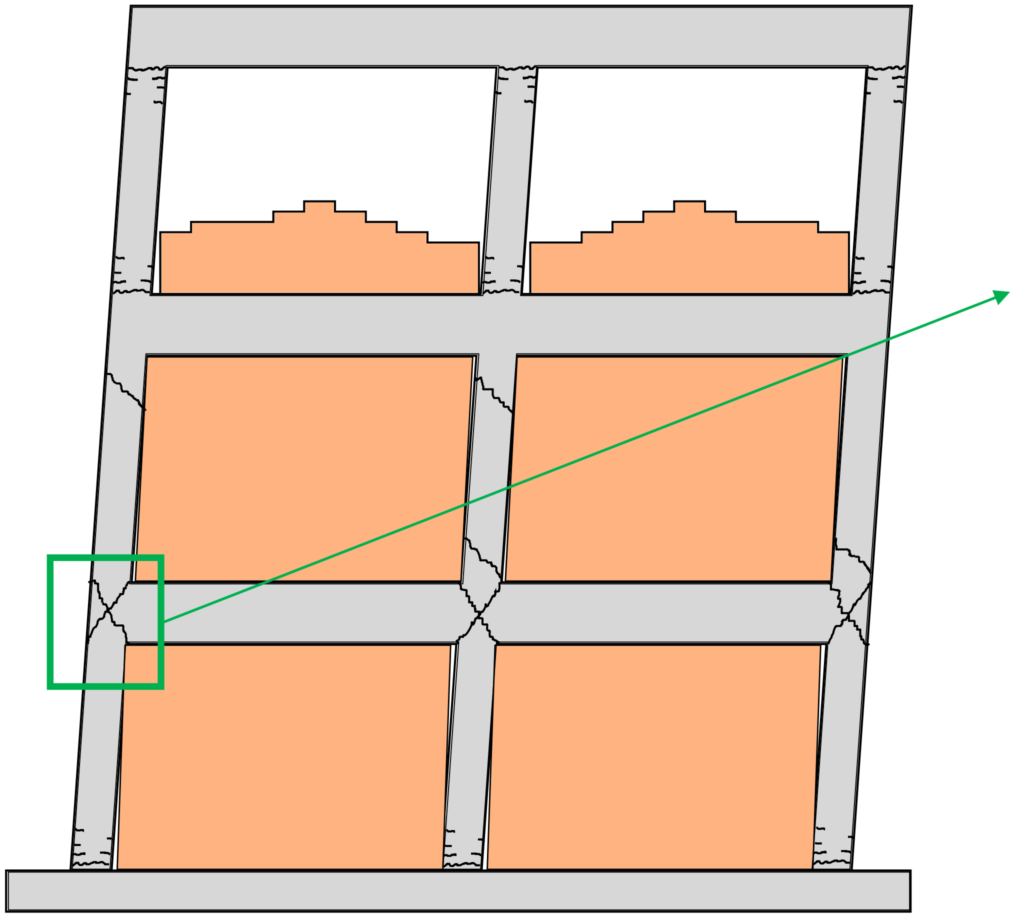


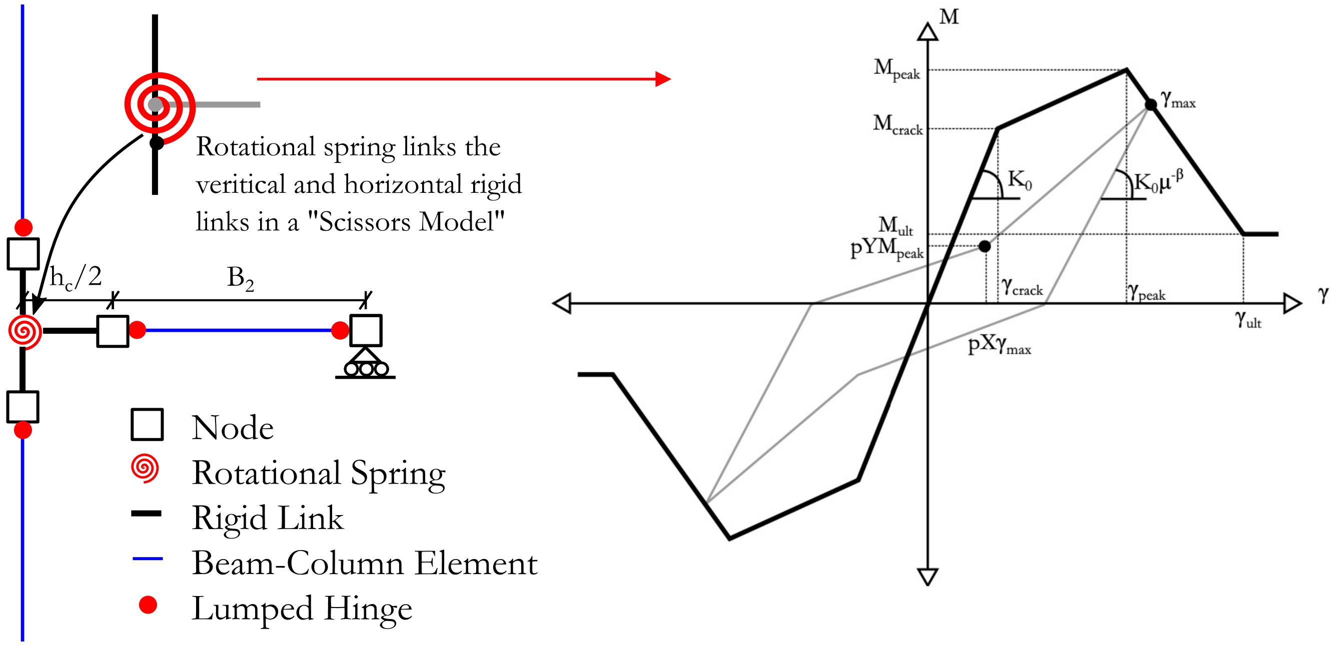




- Equivalent strut force deformation rule adopted from model proposed by Bertoldi et al. [1993] with more modifications by Sassun et al. [2015]
- Both single and double equivalent infill strut layouts outlined in Crisafulli et al. [2000] adopted here to represent the shear forces induced on the columns

Beam-Column Joints

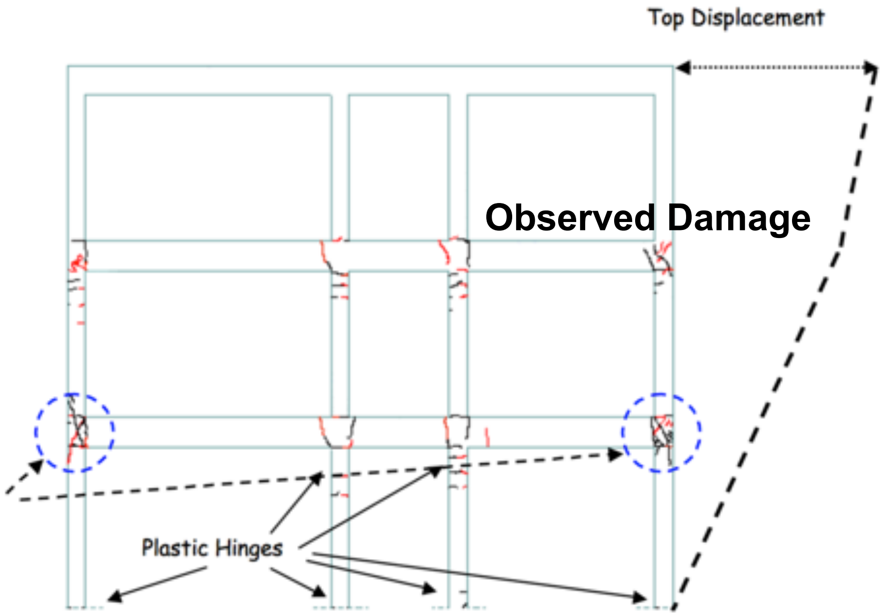




- Scissors Model with rigid offsets in the joint centre are adopted to represent the vulnerable behaviour of the beam-column joints
- Calibrated to experimental data to capture joint strength and potential degradation

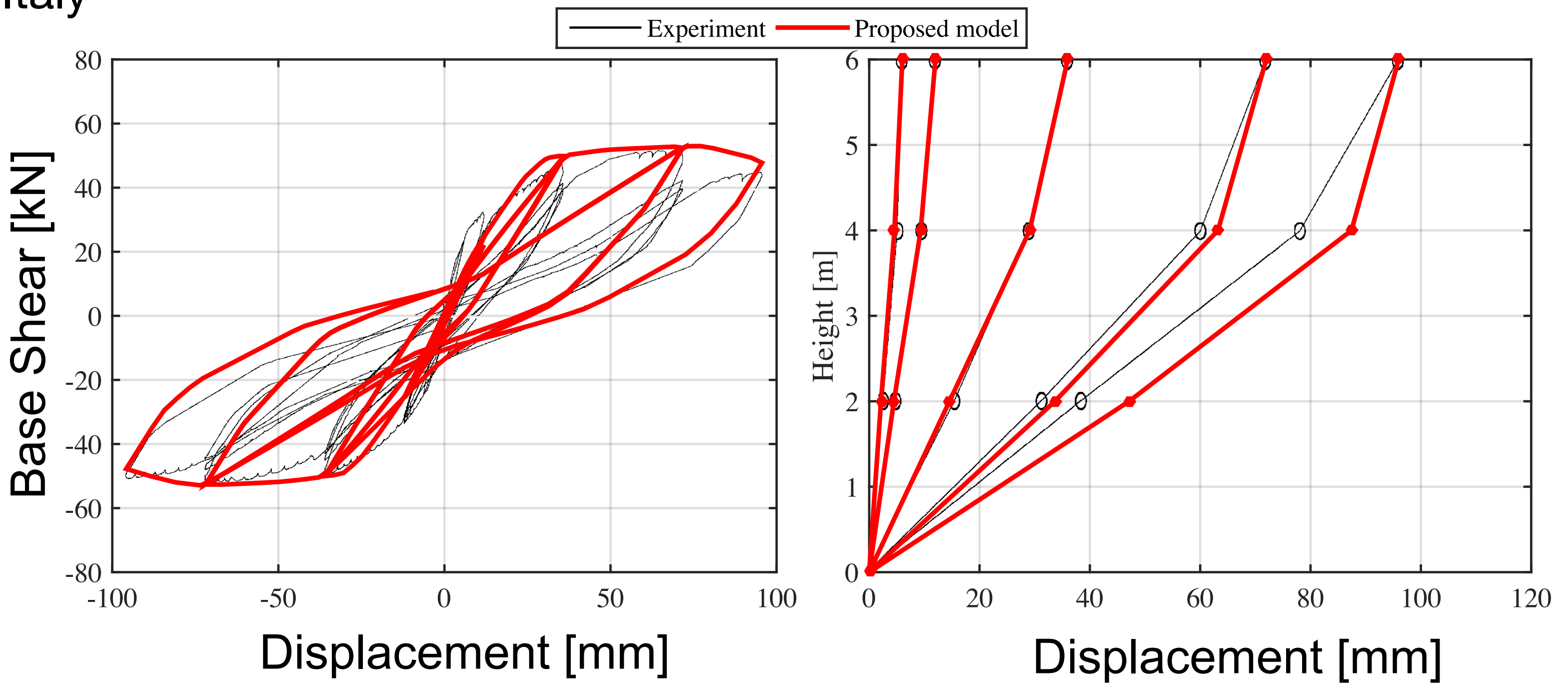
Model validation - Three-storey frame

- Three storey test frame designed to be representative of Italian RC frames constructed prior to 1970s and tested by Calvi et al. [2002] at the University of Pavia
- Damage to the columns and exterior joints led to the formation of a non-ductile mechanism
- The shear deformation of the joints led to a spread in drift over the two adjacent floors rather than a concentration in a single storey



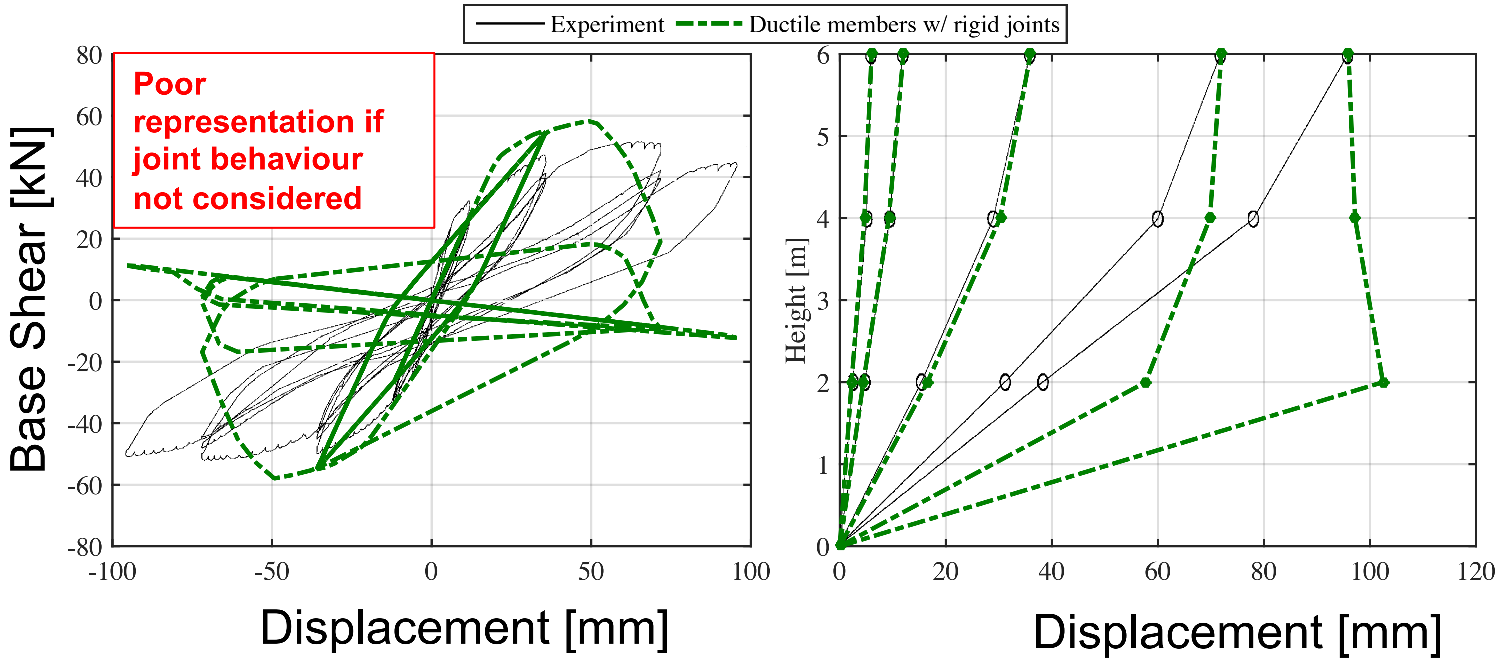
Model validation - Three-storey frame

- The proposed modelling captures the overall strength, stiffness and cycle transitions well
- The displaced shape with each cycle peak is matched well here, the joint failure on the ground floor, along with the column damage on the first floor, both captured
- This highlights the model's ability to adequately capture the different behavioural aspects particular to GLD RC frames in Italy



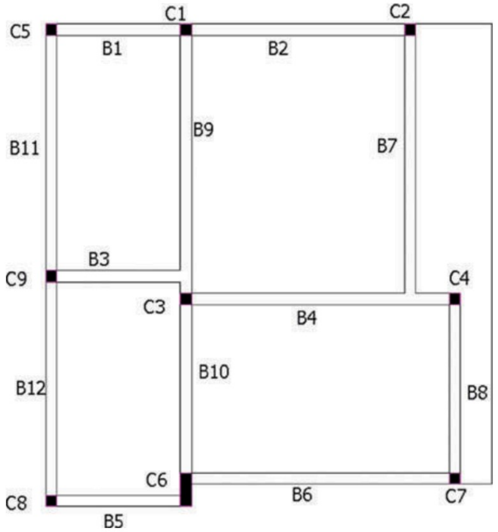
Model validation - Three-storey frame

- Alternatively, lumped plasticity model developed by Haselton et al. [2008] for ductile structures and no explicitly joint modelling is investigated
- The response of the structure is not well represented with the hysteretic loops much fatter than those of the test specimen and the overall displaced shape and governing is not well represented
- Highlights the need to properly consider the various aspects of GLD RC frames



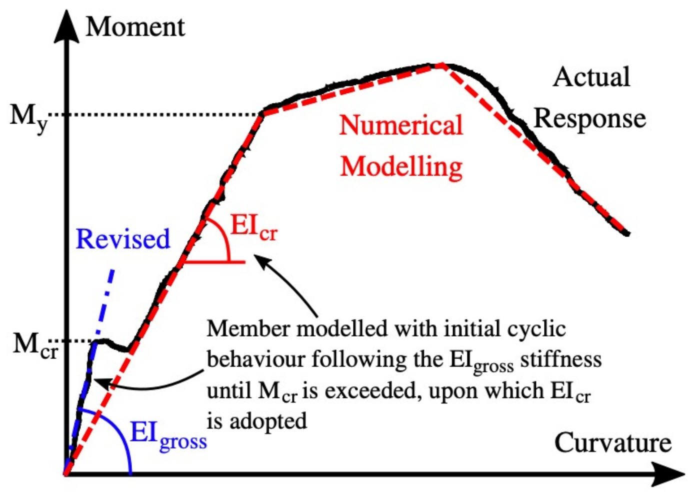
Model validation – SPEAR test frame

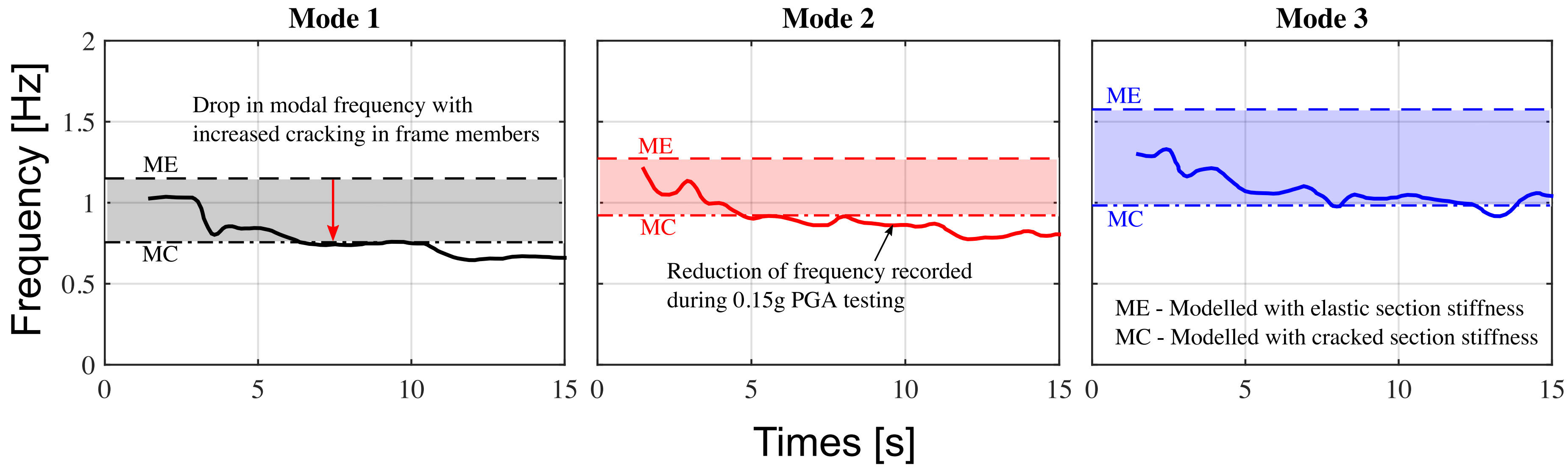
- Designed to the Greek design code in place between 1954 and 1995
- Similar to the construction practice across much of southern Europe
  - Designed to resist vertical gravity loading only
  - Poor structural configuration considerations
  - Lack of capacity design used in modern design codes
- Structure was doubly asymmetric meaning that torsional response was expected to be significant
- It was pseudo-static dynamic test via actuators
- The ground motion record used was from the 1979 Montenegro event and was spectrally adjusted to be compatible with the Eurocode 8 soil type C design spectrum



Model validation – SPEAR test frame

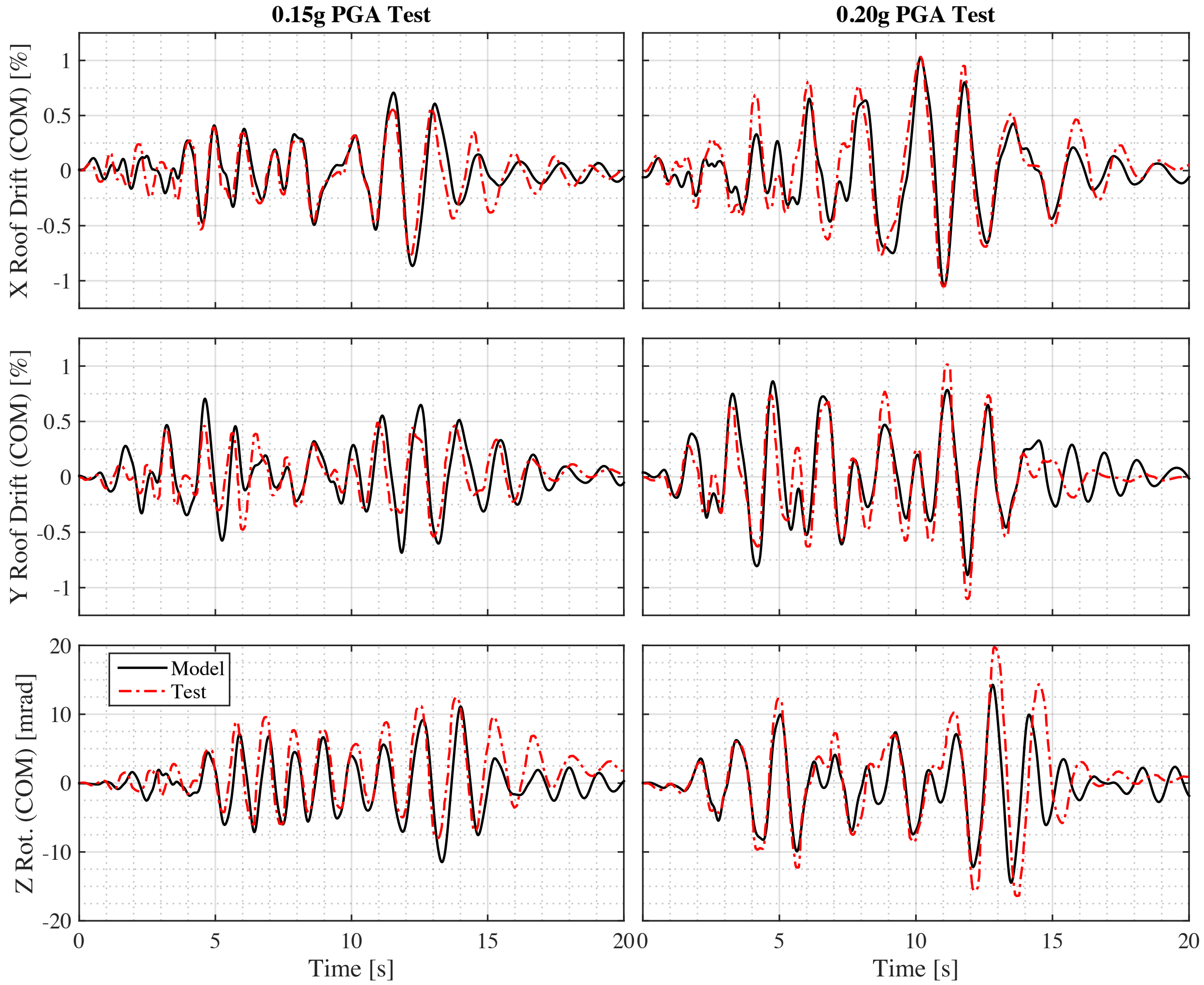
- Throughout the testing, the dynamic properties were continuously monitored
- At the beginning of the test, the cracked section stiffness model tended to underestimate
- As the test progressed and the sections began to crack, the modal properties gradually moved toward the cracked model's frequency





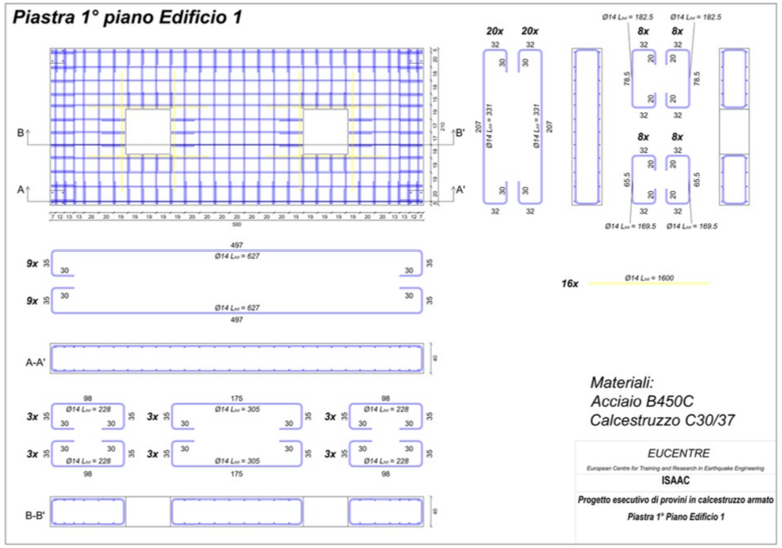
Model validation – SPEAR test frame

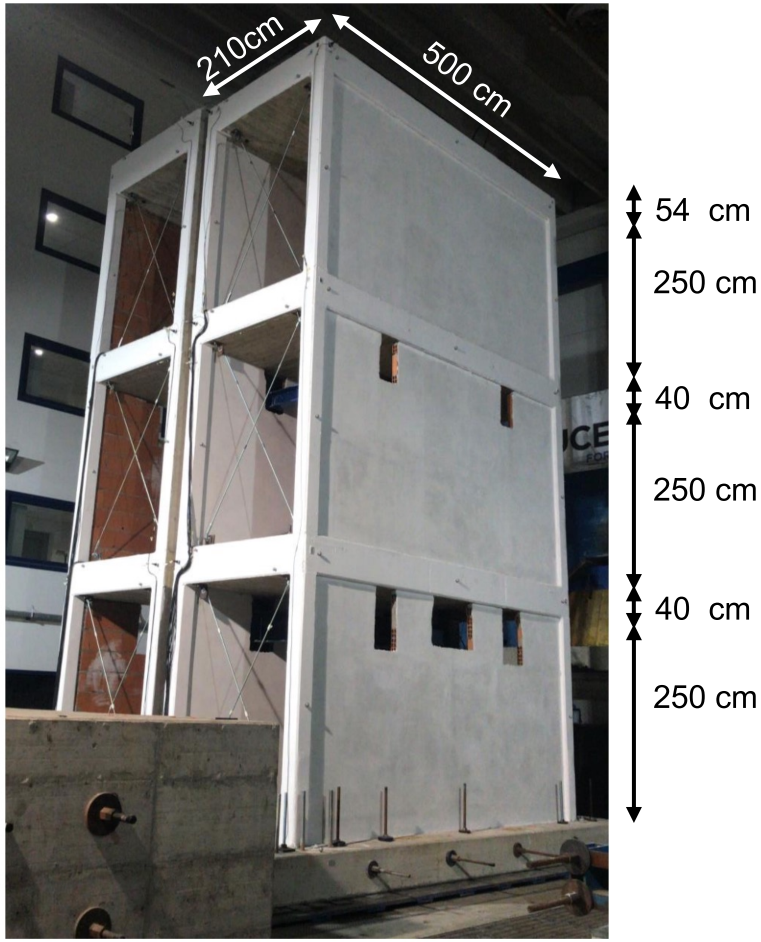
- The response was compared with those predicted using some of the numerical modelling strategies previously outlined
- The maximum displacements in the X direction are matched excellently, whereas the displacements in the Y direction and the torsional response are slightly underestimated, but still reasonably representative
- Comparing test observations with the damage observed in the numerical prediction showed a similar damage pattern with light damage to the column ends, no damage recorded in the beam-column joints and some light damage to beams in the vicinity of column C6



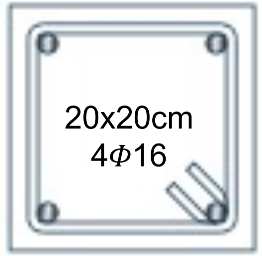
Model validation (ISAAC Blind Prediction Contest)

- Three-storey infilled RC building
- B450C rebars (F_y=420 MPa, F_u = 450 MPa)
- C30/37 concrete (f'_c = 30 MPa)
- Malta M5 infill panels (25x25x8 cm)
- Beams: 54x25cm, 40x25cm
- Columns: 20x20cm



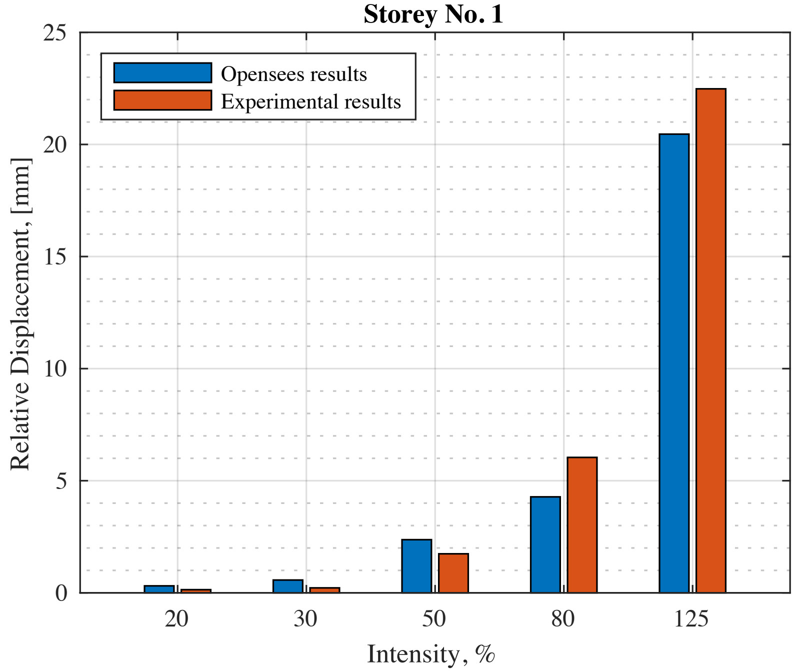


Experimental setup

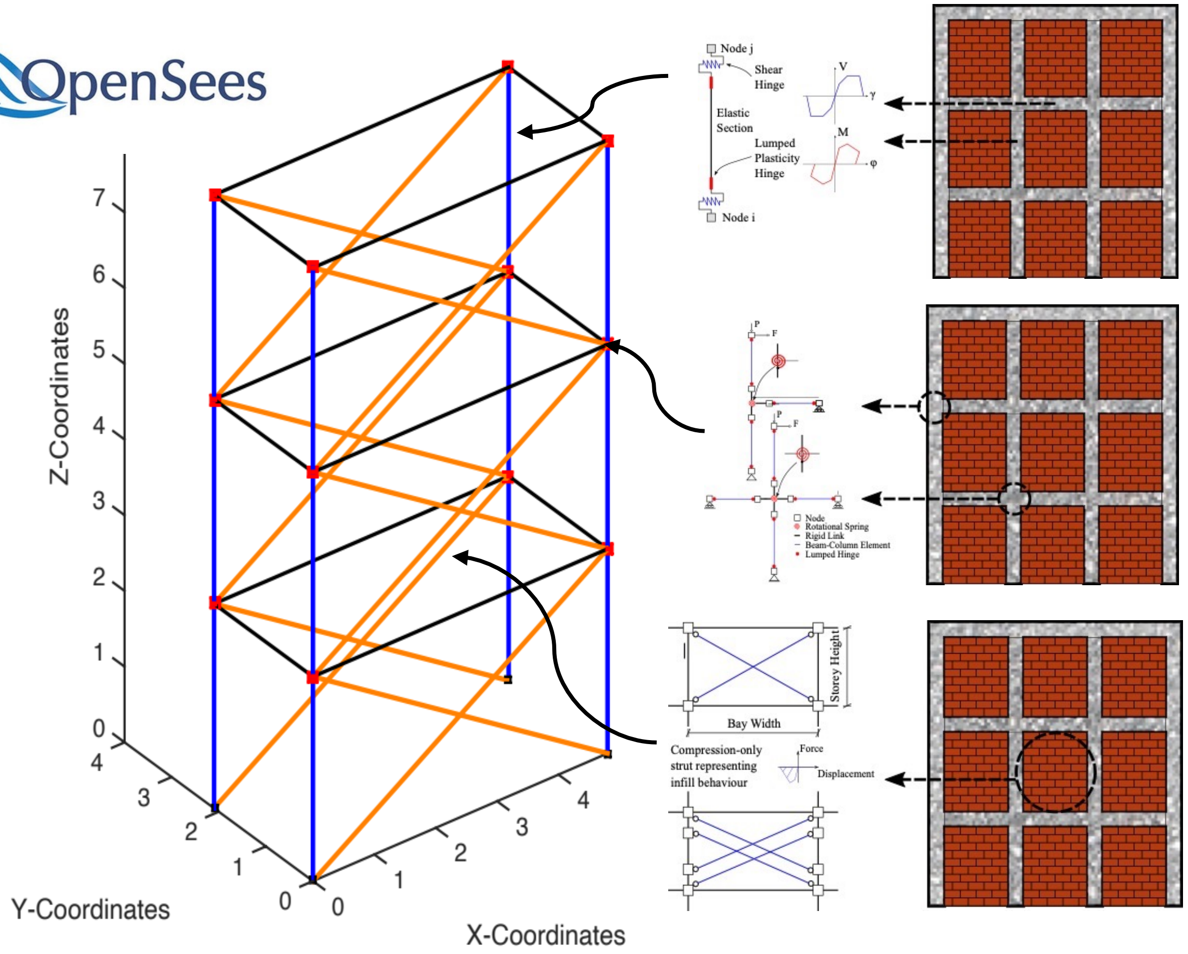


Model validation (ISAAC Blind Prediction Contest)

- Three-dimensional lumped plasticity OpenSees model
- Non-ductile RC beam-column elements
- Non-ductile exterior beam-column joints
- Single-strut infill panels



OpenSees



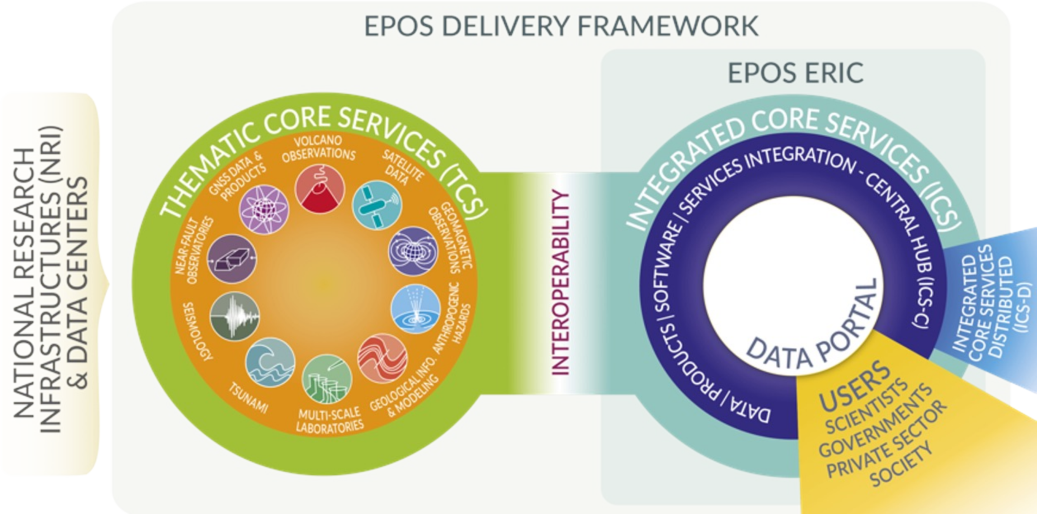
Built Environment Data

- The collection and archiving of data is key in this context
- At the Eucentre Foundation, we are leading an initiative termed Built Environment Data (BED)
- It aims to provide access to data and services related to the built environment
- A memorandum of understanding (MoU) exists with the European Plate Observing System (EPOS) to integrate BED as a Thematic Core Service (TCS)

Built Environment Data

www.builtenvdata.eu

EPOS EUROPEANPLATEOBSERVINGSYSTEM



Built Environment Data

- BED hosts both data and services needed to enhance risk assessment and ensure the safety and resilience of the built environment
- Currently, there are four services within BED led by different institutions around Europe:
  - Experiments (EUCENTRE)
  - RESSLab-Hub (EPFL)
  - Simulated Design (UPORTO)
  - Embodied Carbon (GEM)
  - URM Data (EPFL)
  - Stone Masonry Data (EPFL)
- The scope is to extend and grow these services in the context of risk assessment of the built environment

Built Environment Data

www.builtenvdata.eu

EUCENTRE FOR YOUR SAFETY. — Built Environment Data | Experiments

EPFL — Built Environment Data | RESSLab-hub

U.PORTO — Built Environment Data | SimDesign

GEM GLOBAL EARTHQUAKE MODEL working together to assess risk — Built Environment Data | Embodied Carbon

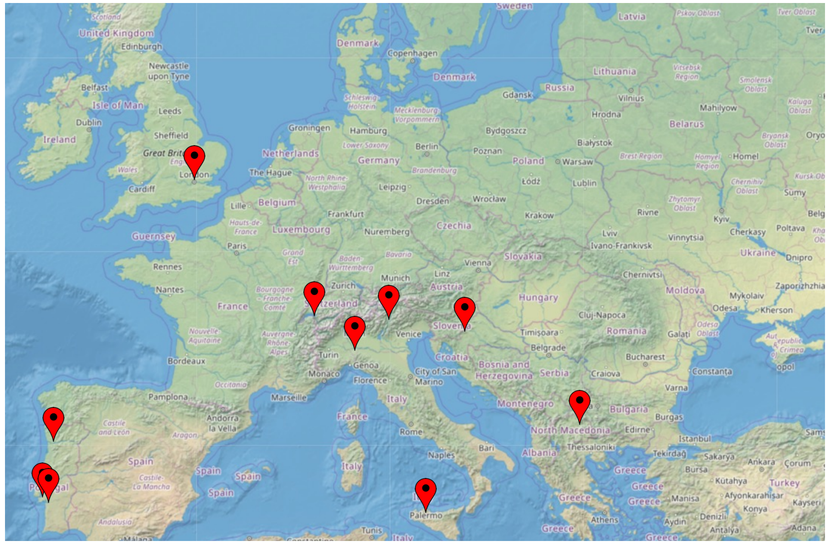
EPFL — Built Environment Data | URM Data

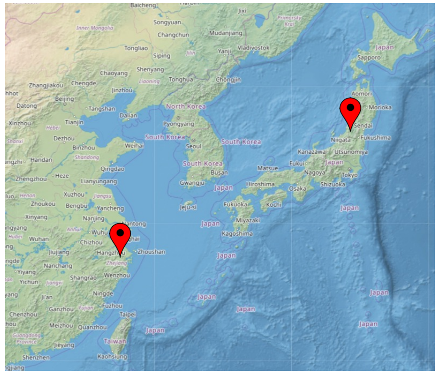
EPFL — Built Environment Data | Stone Masonry Data

BED: Experiments

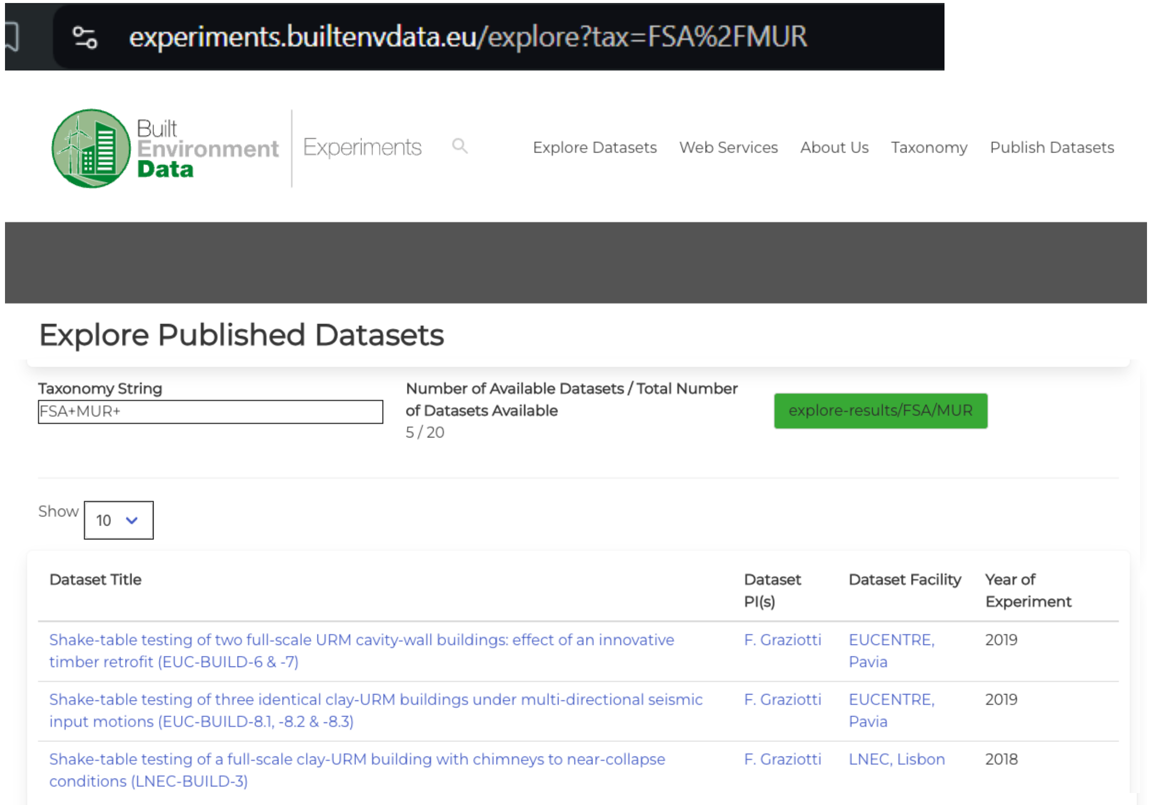
Built Environment Data | Experiments

- One service that is growing quickly relates to experimental test data
- While not directly related to vulnerability modelling, it is fundamental to understand structural behaviour and calibrate numerical models
- Currently contributions from laboratories across Europe and around the world, with more tests added each week





Query the datasets

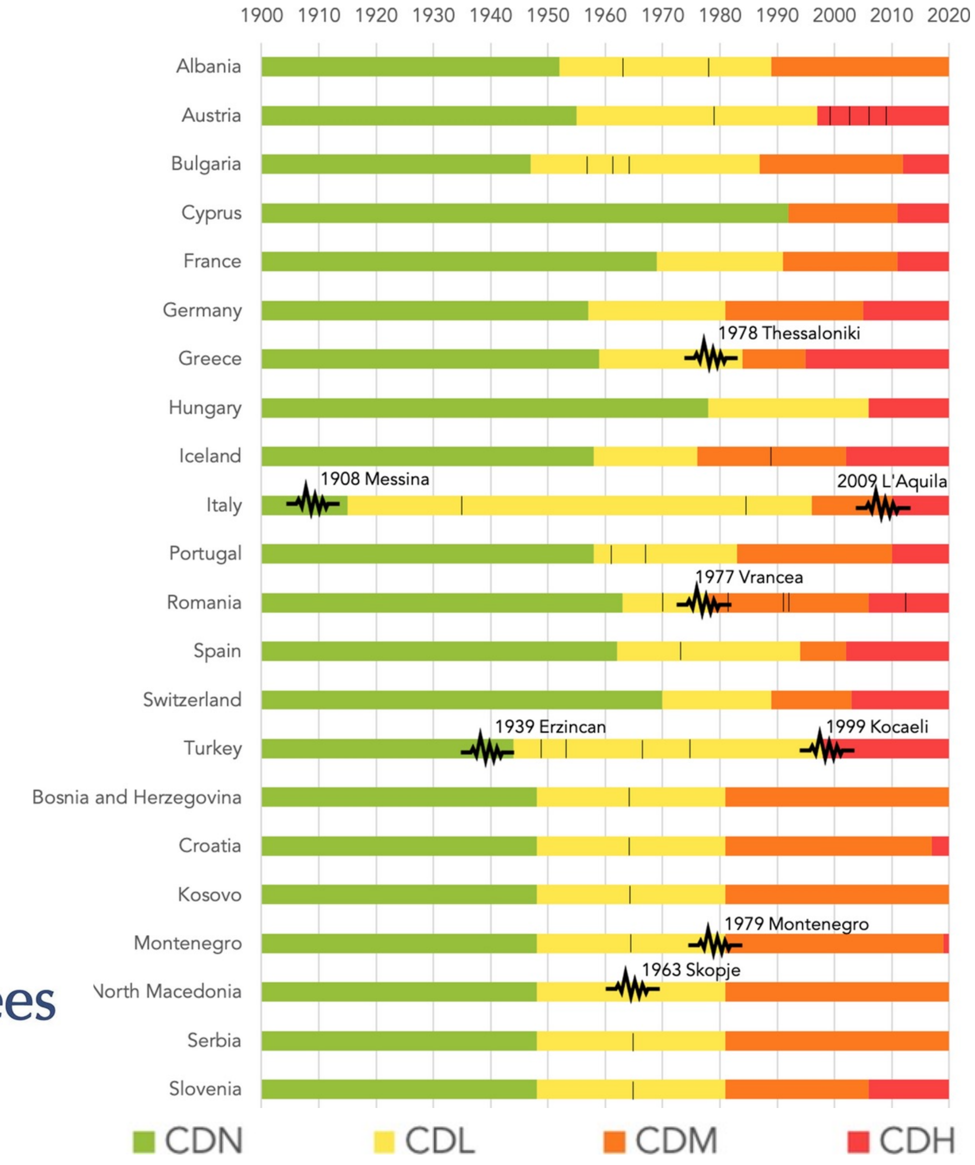


Documentation of web services available at **https://experiments.builtenvdata.eu/web-services**

BED: Simulated Design

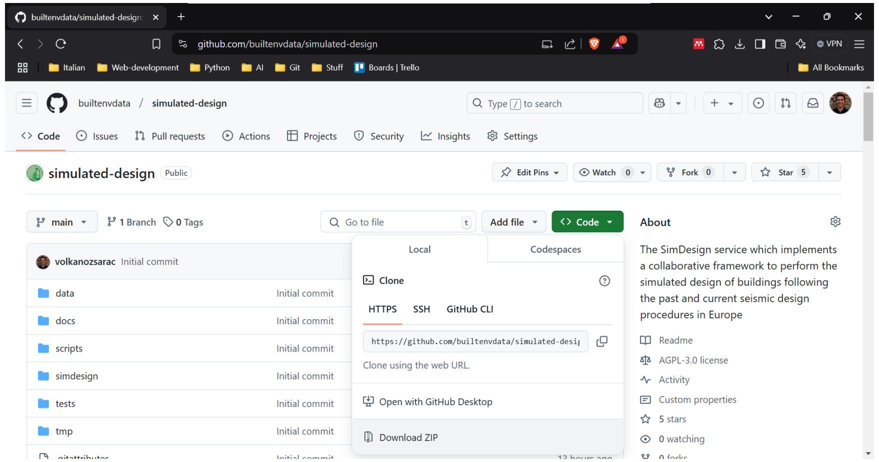
- BED: Simulated Design is an initiative aimed at automating the creation of numerical models
- They are regionally specific and capture the temporal evolution of construction practices across Europe
- The typical choices of engineers at various points in time have been collected and documented
- This allows building designs to be simulated and be representative of what was done at different locations and at different times in the past
- The principal outputs are designs and numerical models for feasible designs

Simple inputs → Built Environment Data | SimDesign → OpenSees



SimDesign Package

- This SimDesign framework is available on GitHub
- Available at: https://github.com/builtenvdata/simulated-design
- This lets you download and use it as part of your Python workflow



Usage

Once installed, you can import and use the package in Python:

```python
# Example usage
from simdesign import rcmrf

# The main inputs for each design class
inputs = {
    'bcim': {
        'design_class': 'eu_cdl',
        'sample_size': 30,
        'num_storeys': 4,
        'beta': 0.1,
        'seed': 2
    },
    'bnsm': {
        "scheme": 'FMP',
        "dincr": 1e-4,
        'max_drift': 0.1,
        'opensees': 'py'
    }
}

# Run the bed-workflow for rcmrf systems and save the outputs
bcim, bdim, bnsm = rcmrf.generate(inputs=inputs, outdir="Outputs")
```

Workflow

Built Environment Data

SimDesign Engine

User Inputs

Typology Taxonomy # Storeys β Coefficient	Year Region

Workflow

Typology → RC-MRF | RC-Wall | Steel-MRF

Built Environment Data

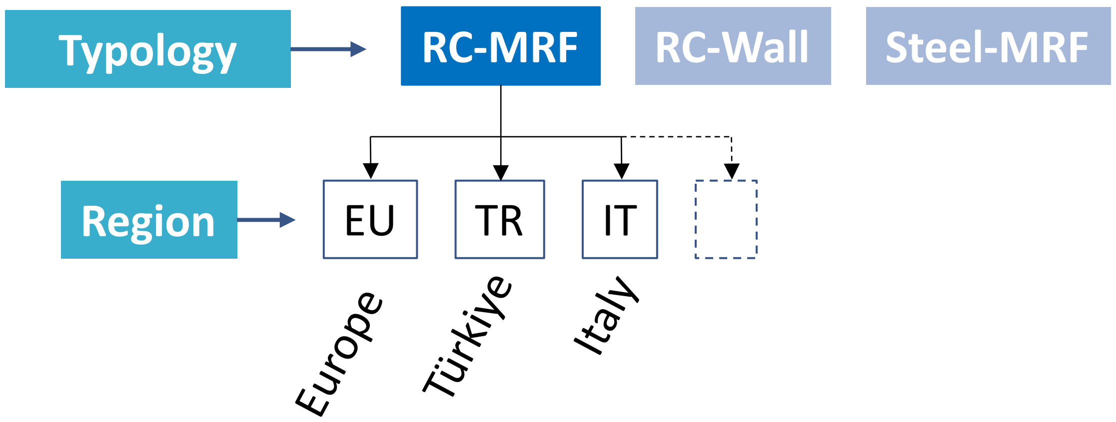
SimDesign Engine

User Inputs

Typology
Taxonomy
Storeys
β Coefficient

{ Year, Region }

Workflow



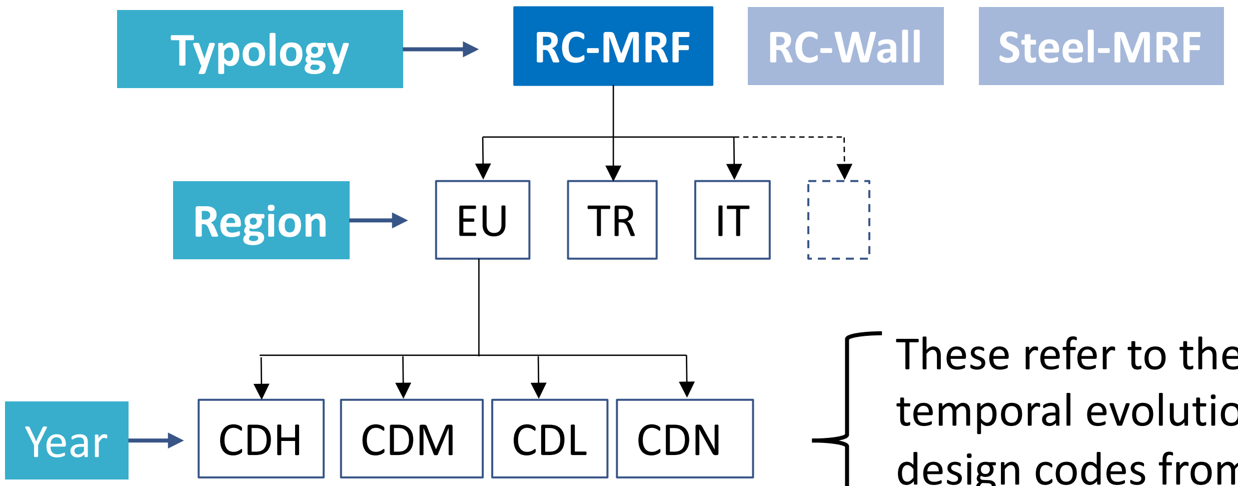
Built Environment Data

SimDesign Engine

User Inputs

Typology Taxonomy # Storeys β Coefficient	Year Region

Workflow



These refer to the temporal evolution of design codes from low to medium and high code

Built Environment Data

SimDesign Engine

User Inputs

Typology
Taxonomy
Storeys
β Coefficient

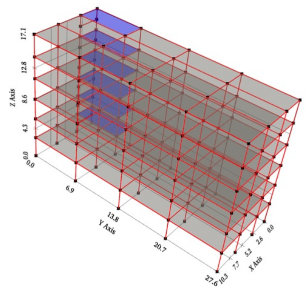
Year
Region

Workflow

Typology → RC-MRF | RC-Wall | Steel-MRF

Region → EU | TR | IT

Year → CDH | CDM | CDL | CDN

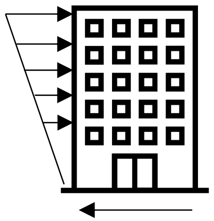


Layouts

Storeys

β Capacity

→ BDIM


β

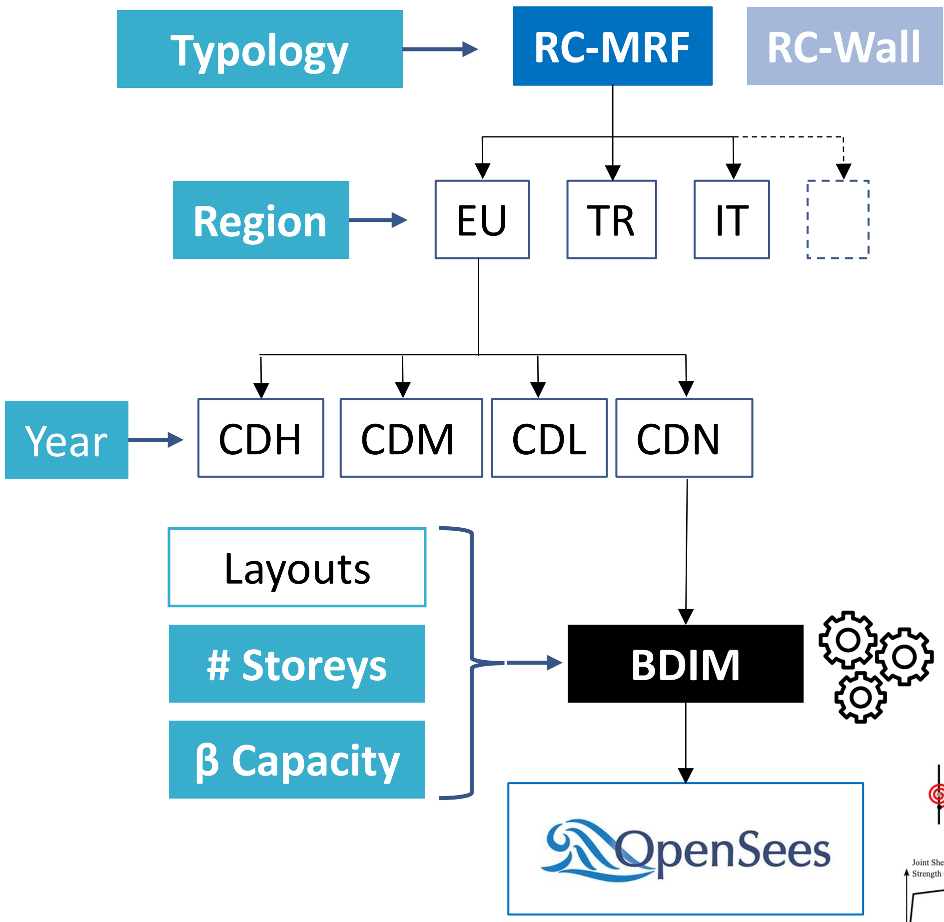
Built Environment Data

SimDesign Engine

User Inputs

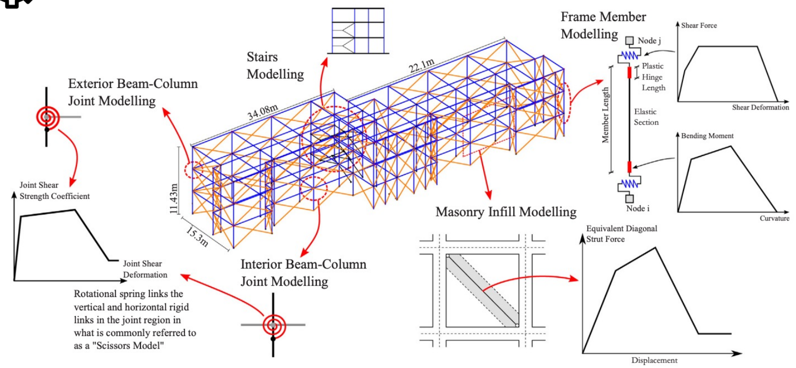
- Typology
- Taxonomy { Year, Region }
- # Storeys
- β Coefficient

Workflow



Built Environment Data

SimDesign Engine

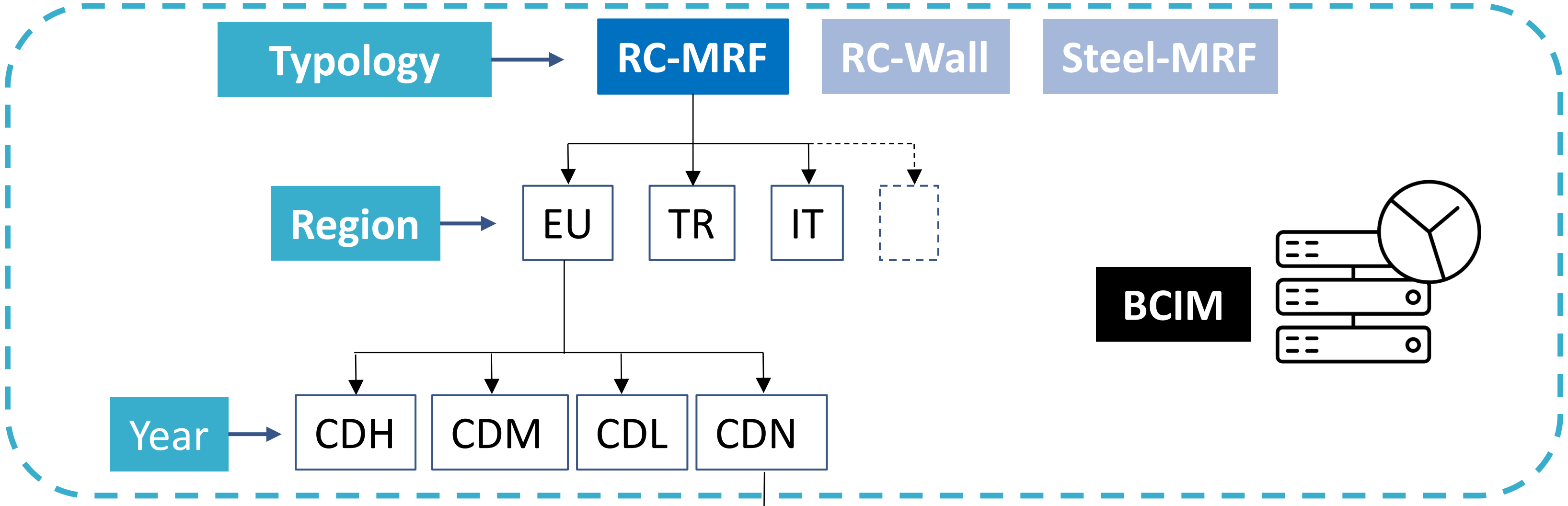


User Inputs

- Typology
- Taxonomy
- # Storeys
- β Coefficient

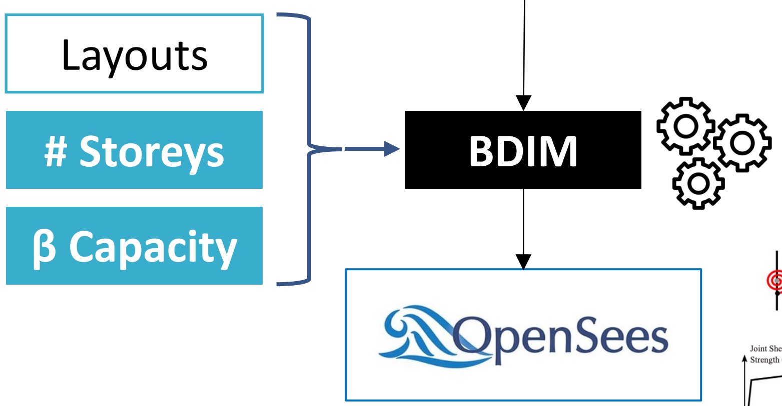
{ Year, Region }

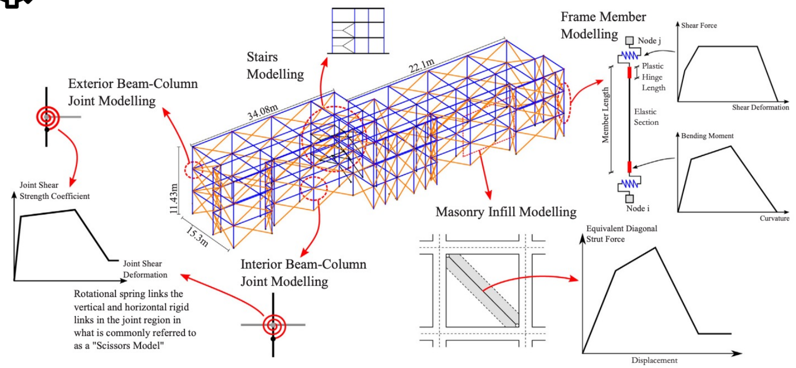
Workflow



Built Environment Data

SimDesign Engine





User Inputs

Typology
Taxonomy
Storeys
β Coefficient

{ Year, Region }

User Input

- The scope of the Simulated Design framework is to allow risk analysts to generate representative building models for large-scale analysis
- Detailed inputs are difficult to obtain systematically
- Hence, the user needs to provide some general parameters and the framework takes care of the rest:
    - `typology`
    - `design_class (region/year)`
    - `num_storeys`
    - `beta coefficient`
    - `layout`
    - `sample_size`
- These are provided in simple JSON file format

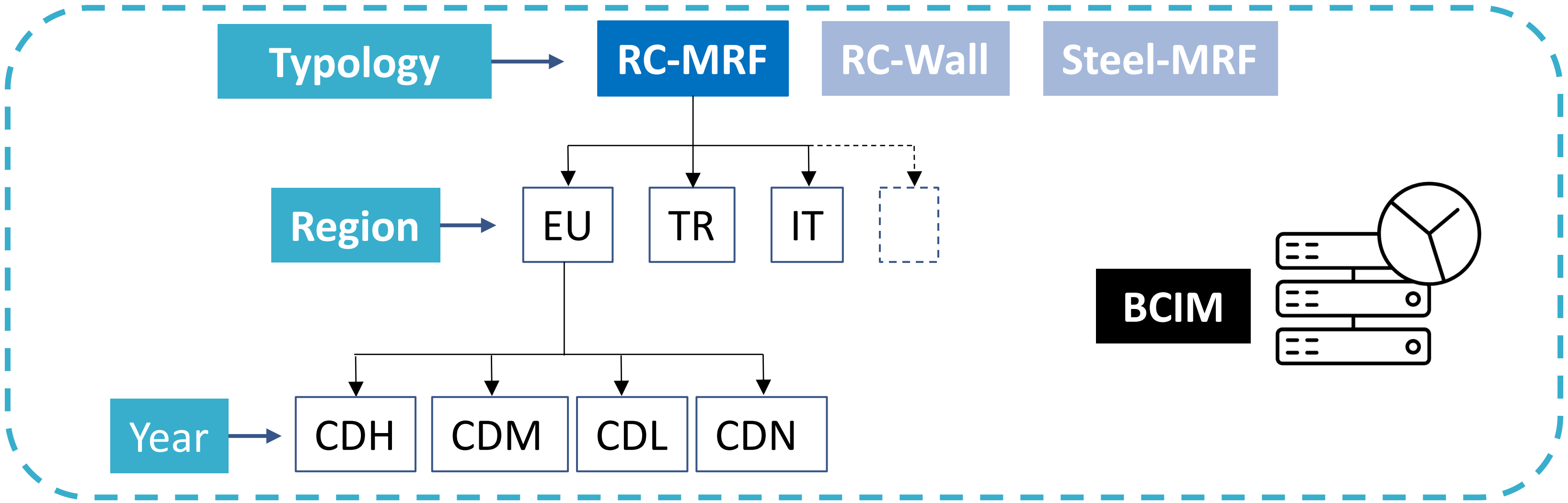
User Inputs

Typology
Taxonomy
Storeys
β Coefficient

{ Year, Region }


```
"square_column_ratio": 0.50,
"layout": "all",
"beta": 0.25,
"num_storeys": 5,
"design_class": "eu_cdh",
"seed": 1987,
"sample_size": 150
```

Building Class Information Model (BCIM)



Building Class Information Model (BCIM)

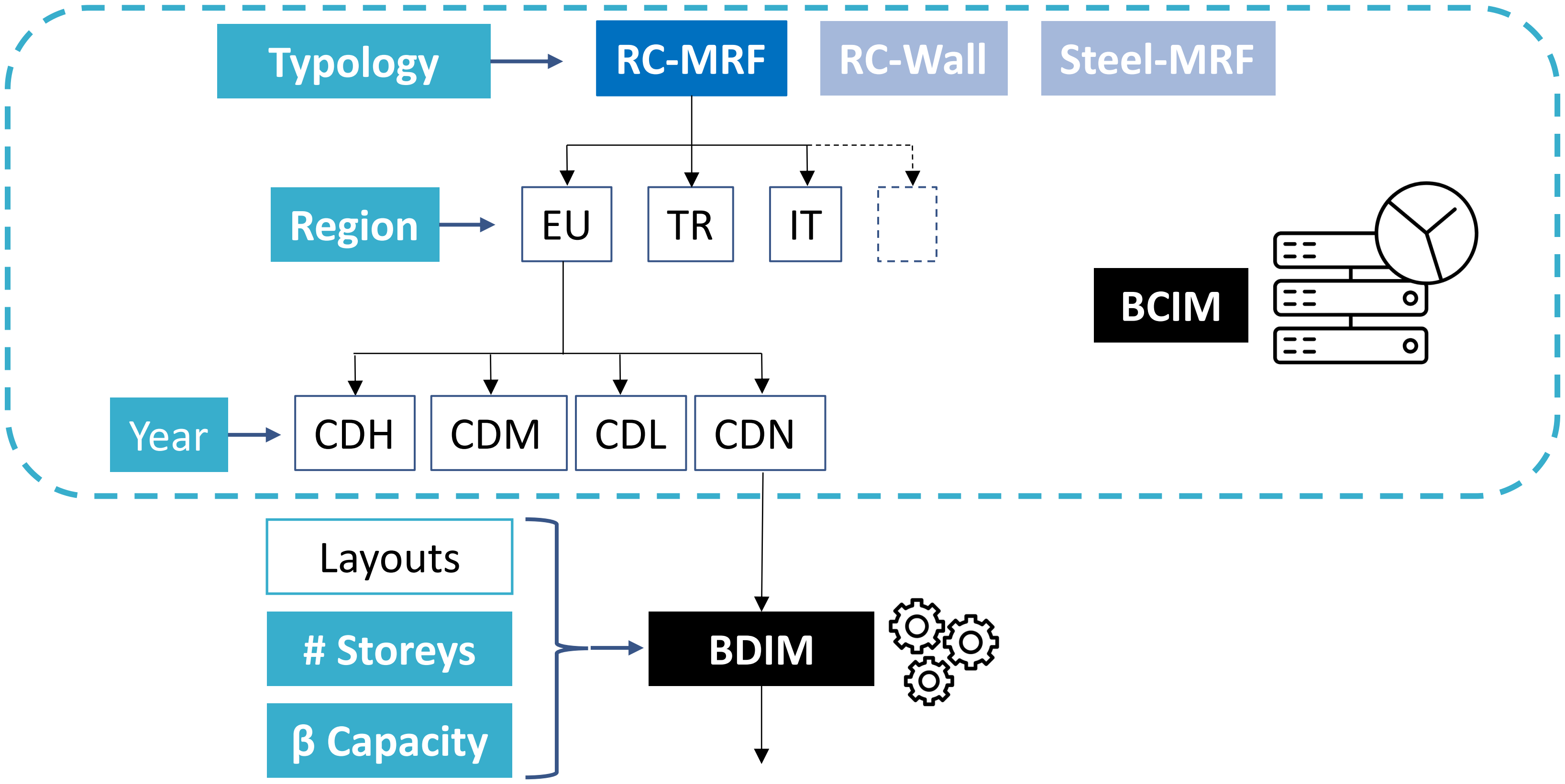
- The **building class information model** (BCIM) contains statistical information about a country's construction and evolution over time
- It answers the question:

  "What kind of buildings were constructed in this region?"

- It is obtained from case studies, census data, practitioner interviews, etc.
- It is stored in JSON file format also and is developed in specific studies:
  - `typical_storey_height`
  - `staircase_bay_width`
  - `standard_bay_width`
  - `steel`
  - `concrete`
  - `ground_storey_height`
  - `construction_quality`
  - `slab_properties`
  - `square_column_ratio`


```
"steel":
  {
    "grade": ["S400", "S500"],
    "probability": [0.10, 0.90]
  },
"concrete":
  {
    "grade": ["C20", "C25", "C30", "C35"],
    "probability": [0.30, 0.45, 0.20, 0.05]
  },
"ground_storey_height":
  {
    "maximum": 4.20,
    "factor": [1.0, 1.1, 1.2, 1.3, 1.4],
    "probability": [0.55, 0.10, 0.20, 0.10, 0.05]
  },
"construction_quality":
  {
    "probability": [0.6, 0.3, 0.1]
  },
"slab_properties":
  {
    "one_to_one_and_comp_ratio": 0.50,
    "two_to_two_and_comp_ratio": 0.65,
    "max_solid_length": 6.0,
    "max_thickness": 0.85,
    "staircase_slab_depth": 0.15
```

Building Design Information Model (BDIM)

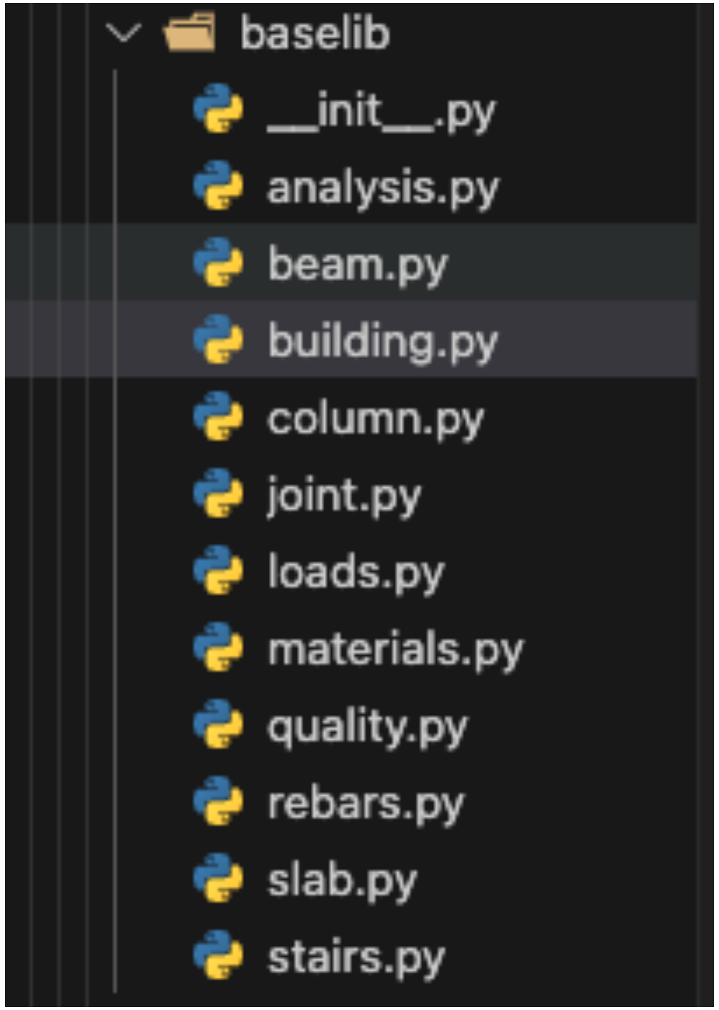


Building Design Information Model (BDIM)

- This **building design information model** (BDIM) defines the way in which engineers designed these buildings
- It answers the question:

  "For these kinds of buildings that were constructed in this region, how did the engineers typically design them during that period?"

- It is obtained from past design manuals, reference textbooks, case studies, practitioner interviews, etc.
- It is implemented as several classes and methods in what is termed the base library
- The BDIM for specific regions, periods and typologies can be modified and extended



Example 1: Building-to-Building Variability

- Case-study portfolio generation (RC-MRF buildings)
  - Design class: CDL → **Seismic Design Practice**
  - Design lateral load coefficient, β: 0.1 → **Seismic Hazard Level**
  - Number of storeys: 4
  - Sample size: 30

Seismic Design Practice + **Seismic Hazard Level** } **Expected Ductility Level**

$$\beta = K_s \cdot K_o \cdot K_d \cdot K_p$$

K_s: coefficient based on seismic intensity (e.g., PGA_{475} in g)

K_o: coefficient based on the type/importance of the building

K_d: coefficient that accounts for dynamic response (e.g., lambda factor of EC8-1 section 4.3.3.2.2)

K_p: coefficient that accounts for ductility and energy dissipation

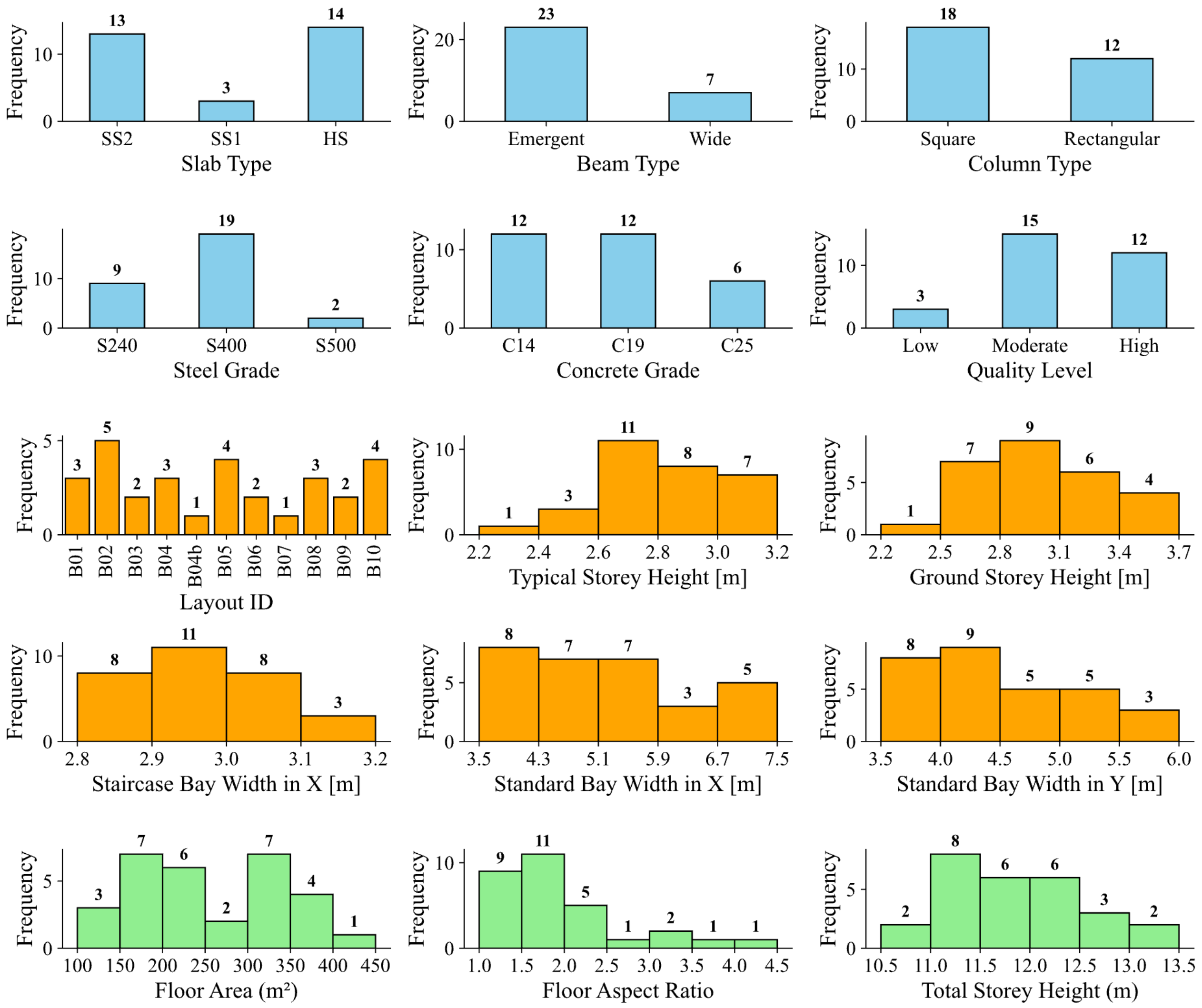
```python
# Example usage
from simdesign import rcmrf

# The main inputs for each design class
inputs = {
    'bcim': {
        'design_class': 'eu_cdl',
        'sample_size': 30,
        'num_storeys': 4,
        'beta': 0.1,
        'seed': 2
    },
    'bnsm': {
        "scheme": 'FMP',
        "dincr": 1e-4,
        'max_drift': 0.1,
        'opensees': 'py'
    }
}
```

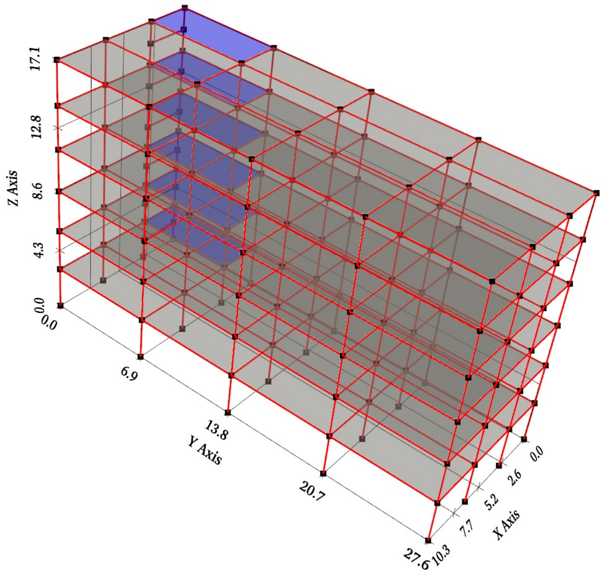
Example 1: Building-to-Building Variability

Sampled secondary attributes

Sampled geometry variables

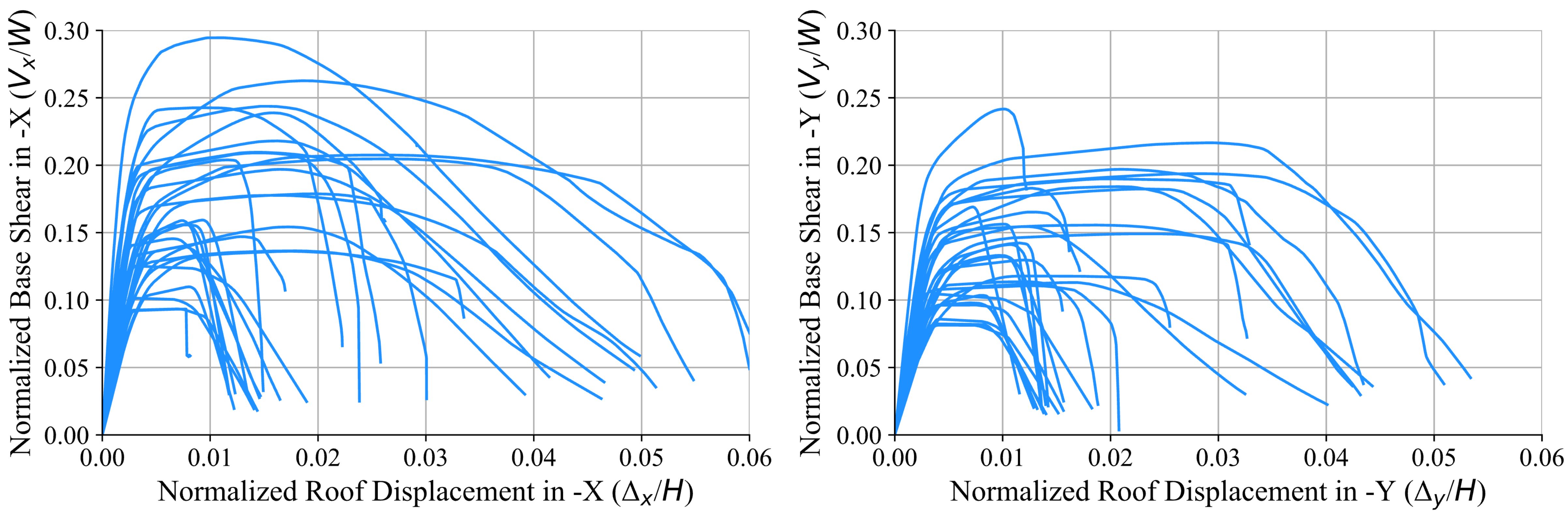
Resulting geometrical properties





Example 1: Building-to-Building Variability

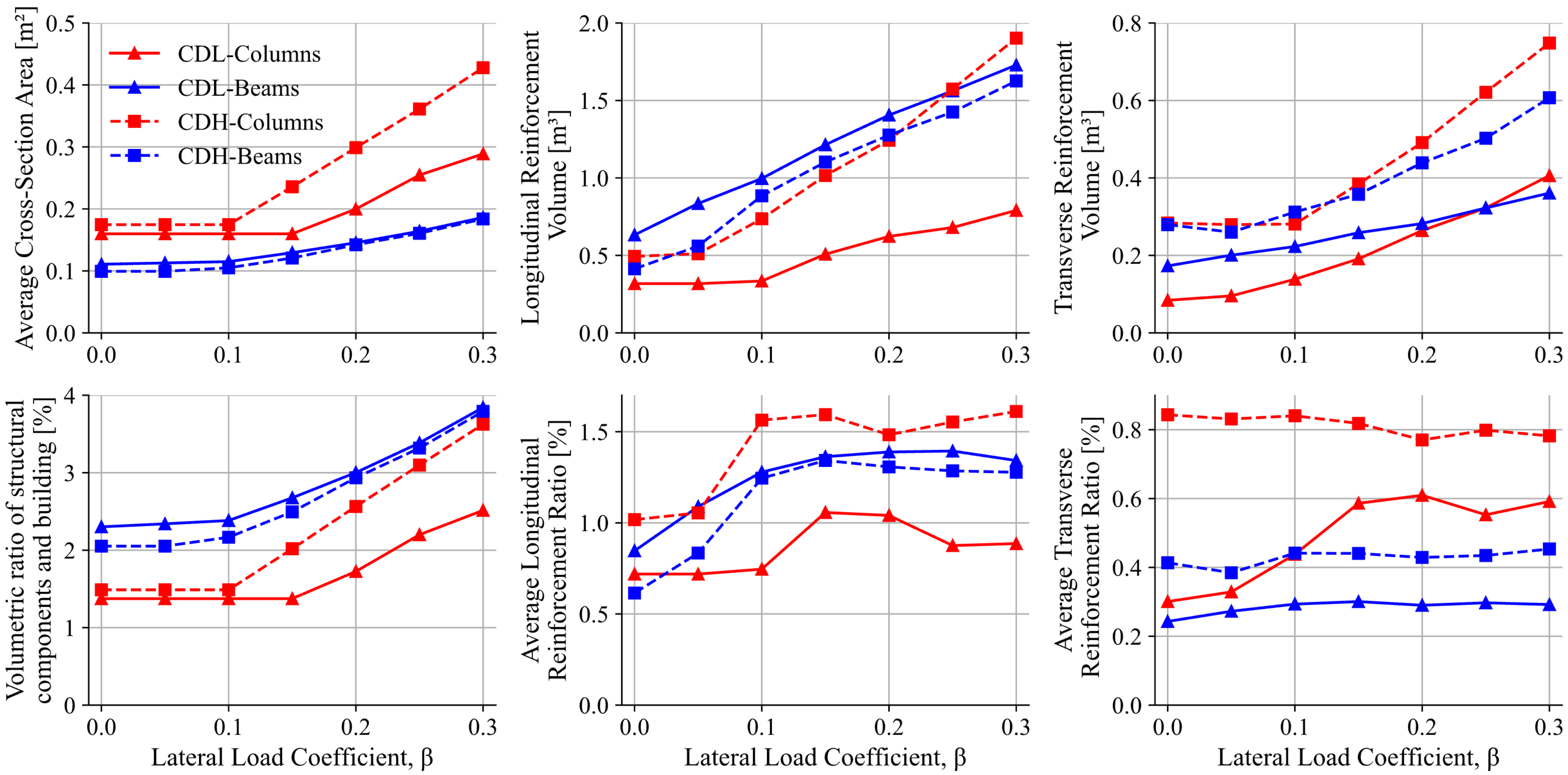
- Nonlinear static pushover analyses results



Example 2: Simulated Design Capabilities

- The same BCIM data for two different design classes, CDL and CDH, across varying seismic hazard levels (β values).
- CDL: Designed for lateral resistance using first generation of seismic codes
  - Based on Portuguese specifications (common in Europe, 1960s–1970s)
  - Uses allowable stress design
  - Seismic action is represented by equivalent lateral forces computed only from floor weights
- CDH: Designed for lateral resistance using Eurocodes
  - Uses limit state design coupled with ductility requirements (e.g., capacity design)
  - For seismic design, DCM requirements in Eurocode 8 are followed, as more commonly adopted in Europe
  - Seismic forces computed based on both floor weights and storey heights

Example 2: Simulated Design Capabilities



Summary and future possibilities

- A powerful tool **BED: Simulated Design** was presented help recreate designs for risk analysis
- The output is a numerical model of existing structures in OpenSees (both Py and Tcl)
- It has several functions but possible modifications:
  - Adding different national contexts (i.e., BCIM)
  - Adding different structural typologies
  - Adding different modelling approaches
- With modest modifications, this can be extended to other contexts: tsunami, wind, etc.
- Overall aim is to make these tools available and integrate them on the broader sphere of EPOS

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Questions?

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