# System Identification and Structural Modelling of Italian School Buildings

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# Background

- The collapse of the Iovene primary school in San Guiliano during the Molise 2002 event, killing 27 students and their teacher, highlighted the vulnerability of the existing Italian school building stock.
- Funded by the Centro di Geomorfologia Integrata per l'Area Mediterraneo, the European Centre for Training and Research in Earthquake Engineering (EUCENTRE) initiated a project entitled "*Progetto Scuole*" in 2015.
- This aimed to assess six school buildings throughout Italy intended to be representative of different typologies of the school building stock.
- Extensive analysis was conducted with the aims of making more informed decisions regarding retrofitting to prevent collapse and mitigate extensive economic losses due to repair of structural and non-structural elements.

# Background

- Selected school buildings located throughout Italy.
- Three different typologies analysed:
  - Reinforced concrete (**RC**)
  - Unreinforced masonry (**URM**)
  - Precast (**PC**).

| School | Region | Typology | No. of Floors | Year |
|---|---|---|---|---|
| Ancona | Marche | **RC** | 3 | 1960’s |
| Avola | Sicilia | **URM** | 2 | 1900’s |
| Carrara | Toscana | **RC** | 2 | 1960’s |
| Cassino | Lazio | **PC** | 2 | 1980’s |
| Ghedi | Lombardia | **URM** | 2 | 1960’s |
| Tito | Basilicata | **RC** | 3 | 1970’s |

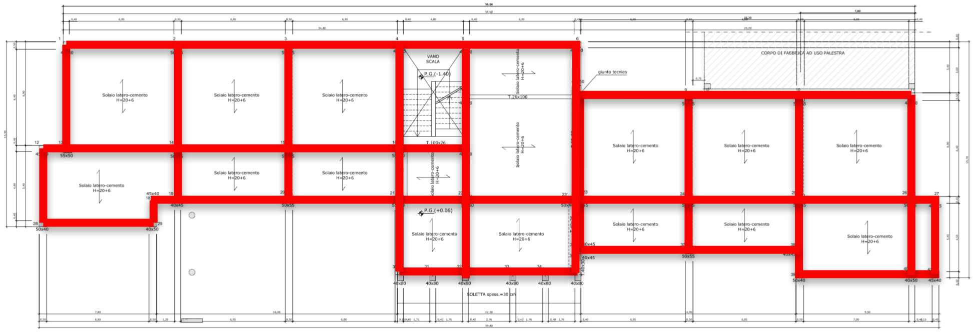
# In-Situ Surveys of School Buildings

- For each of the school buildings selected, in-situ surveys were conducted to identify the structural layout and various non-structural components.
- Available structural drawings used to construct numerical models of each school.
- Non-structural element information catalogued.

Available Drawings

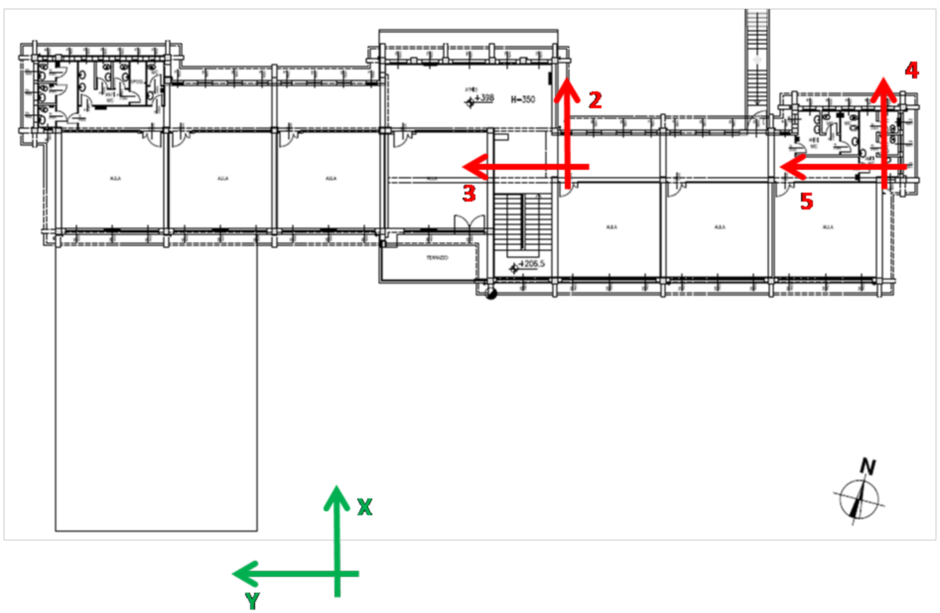

Non-structural Elements

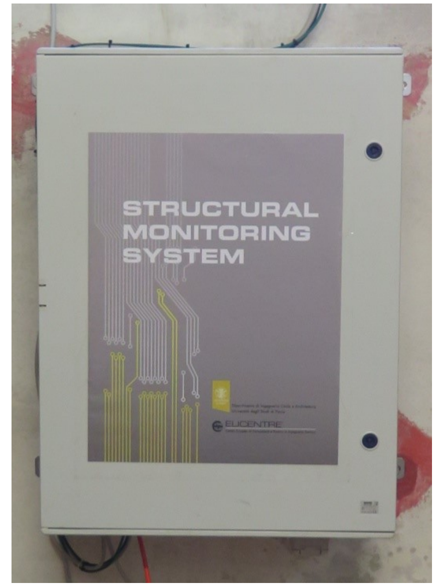
Numerical Modelling of Structural Elements

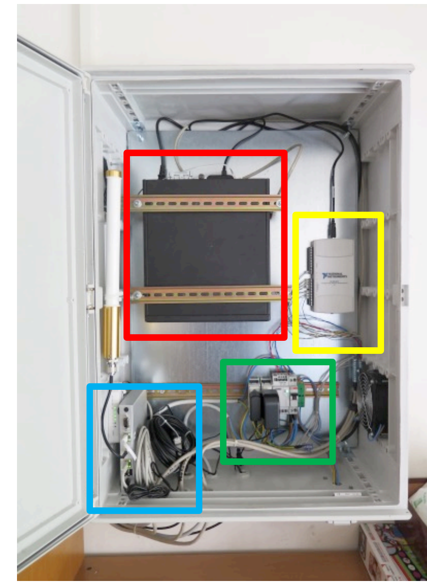


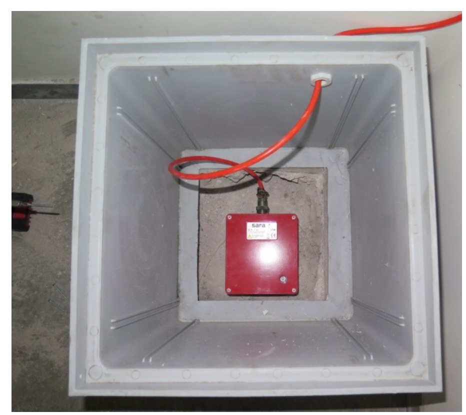
# Instrumentation of School Buildings

- In addition to constructing numerical models and cataloguing the non-structural elements of each school building, accelerometers were installed at a number of locations of each school to record the response of the structure to ambient vibrations and also triggered vibrations.





Red: acquisition unit

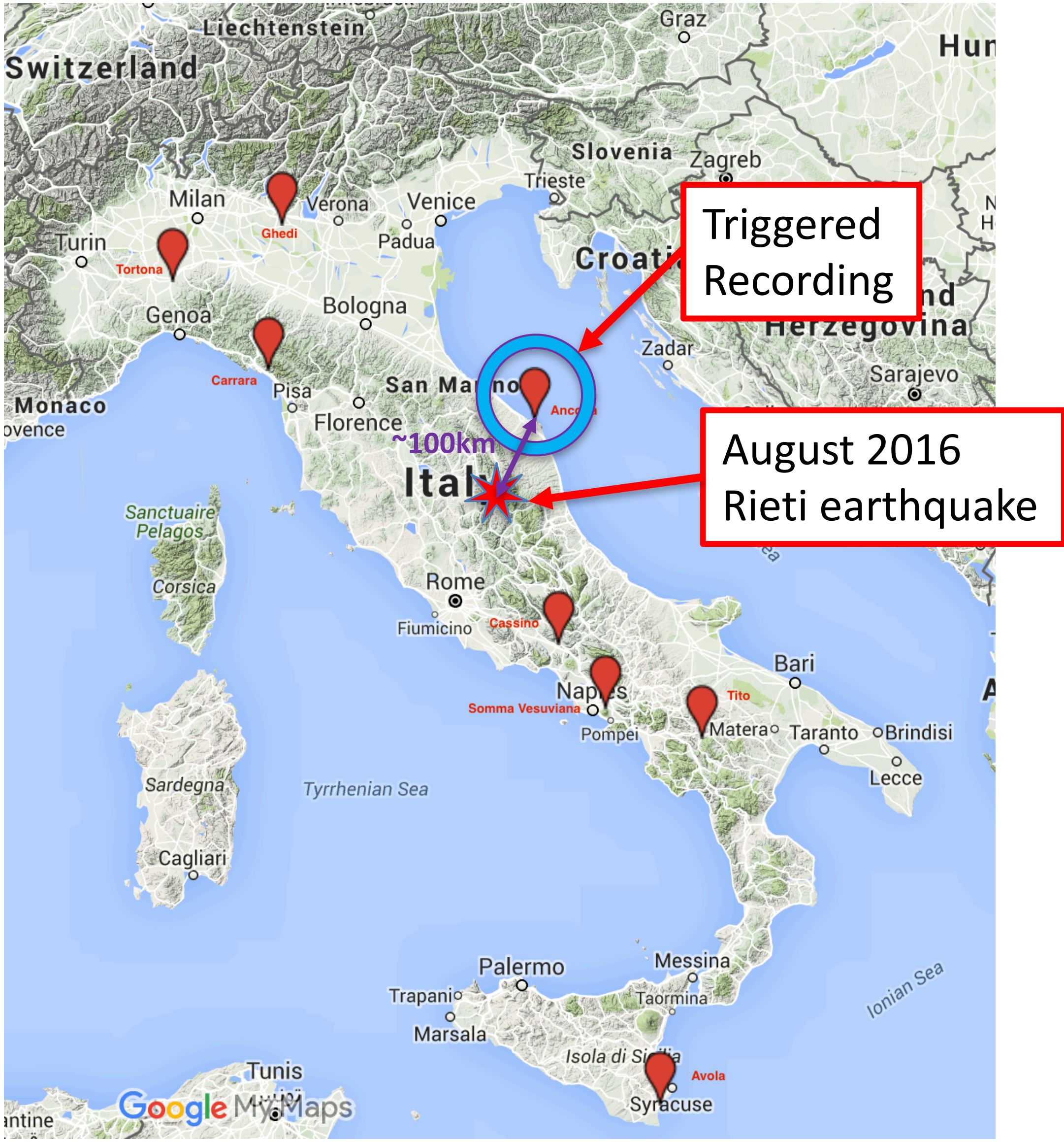
Yellow: Data Acquisition (DAQ) USB board

Blue: 3G modem and existing LAN bridge (when available)

Green: Power supply and accelerometers conditioning

# Triggered Vibration in Ancona

- In addition to the ambient vibrations from each of the school buildings, a triggered response due to the August 2016 event in Rieti, Italy has been recorded at the Ancona school building.
- This earthquake was a $M_w 6.0$ event with an epicentre about 100km from the school in Ancona.
- The modal properties from both the ambient vibrations and also the triggered earthquake vibrations are now compared to the actual predicted modal properties in the numerical models.



# RC Frame School Buildings

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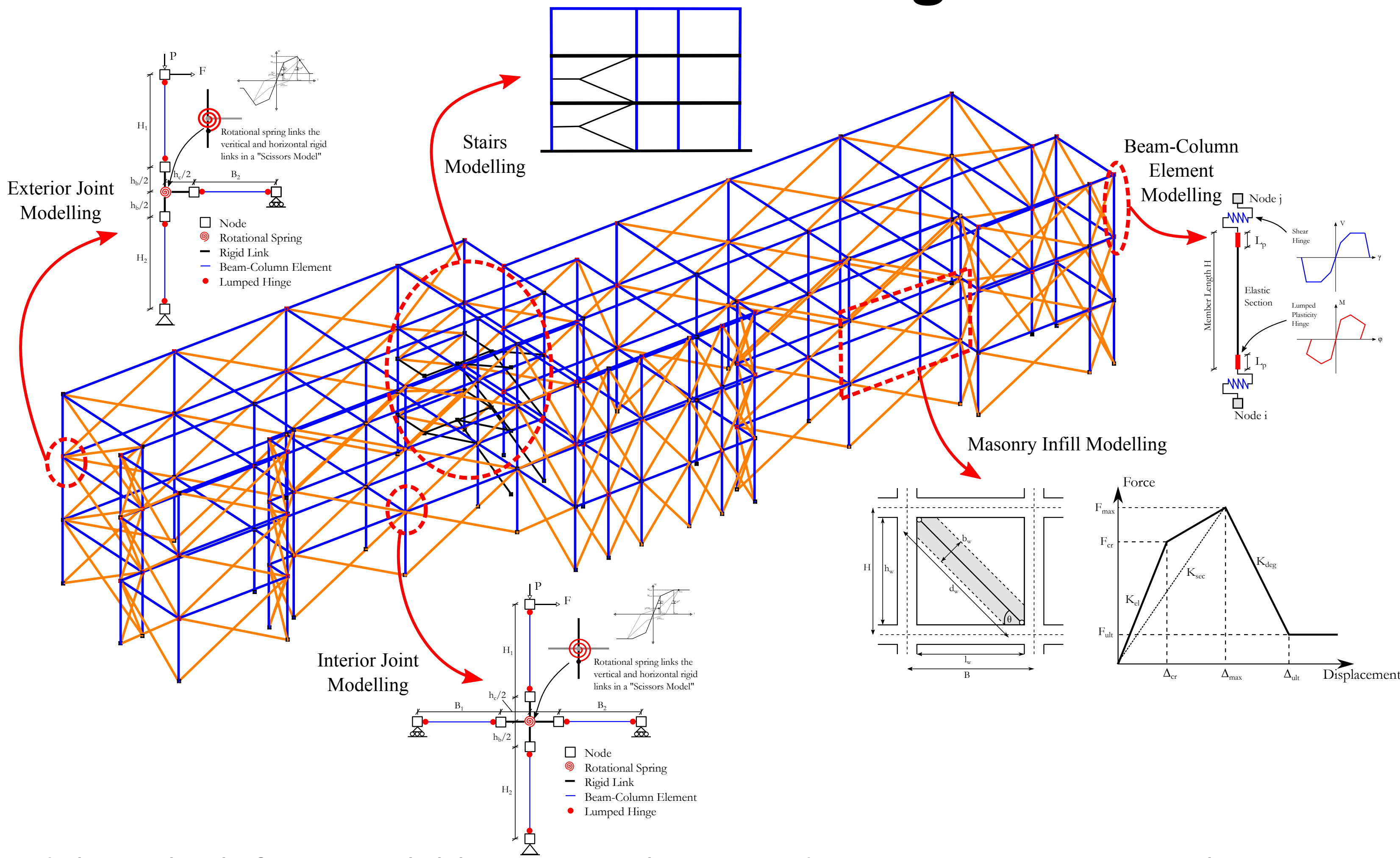
| Tito | Basilicata | RC | 3 | 1970's |

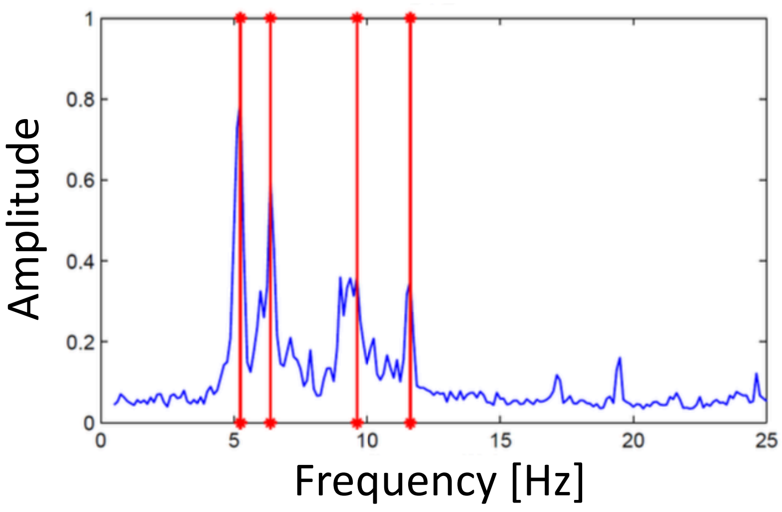
# Numerical Modelling




- Model was built from available structural tests and reports using numerical modelling approach outlined in O'Reilly [2016].

# Instrumentation Recordings

- Ambient vibration of building recorded periodically.
- Peaks in the individual transfer functions used to identify modes of vibration in the building.
- Compiling these individual recordings together allows for the overall identification of the modes of vibration in the structure.
- Transfer function of triggered vibration used to identify the modes at the school in Ancona.



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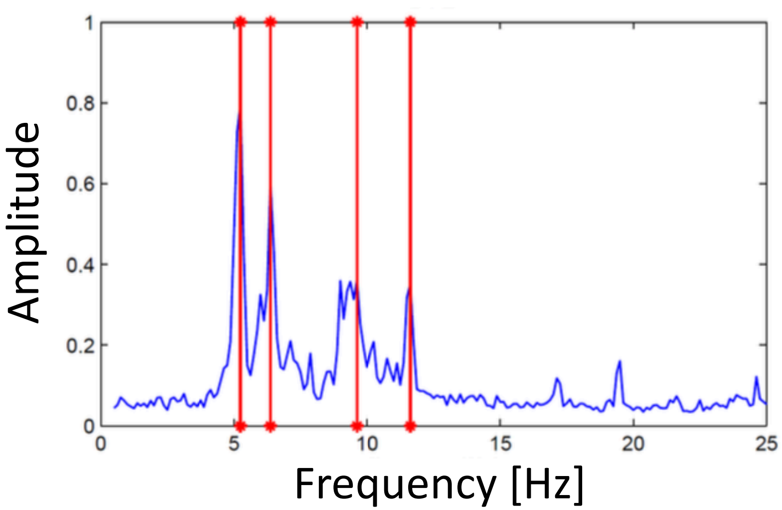


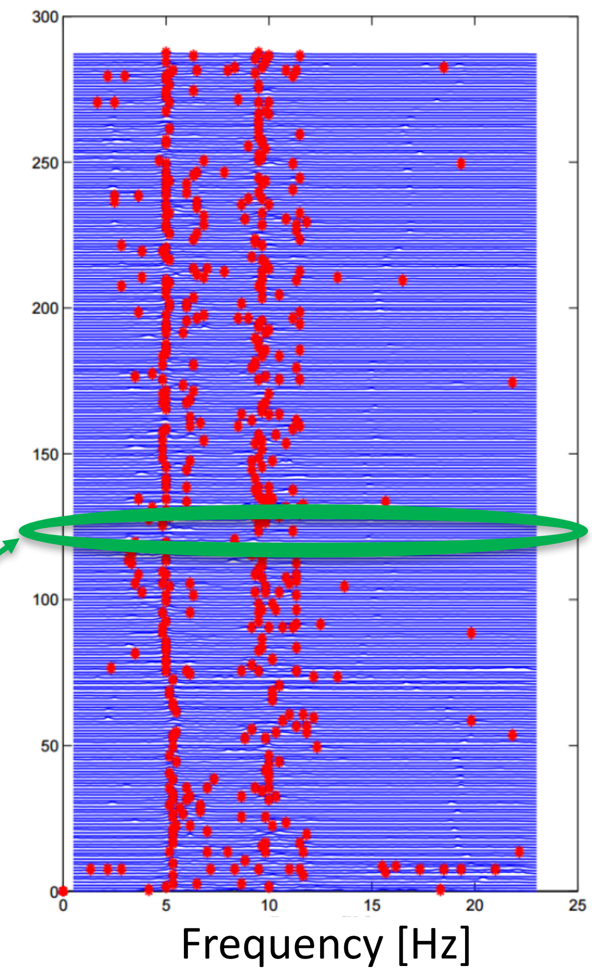

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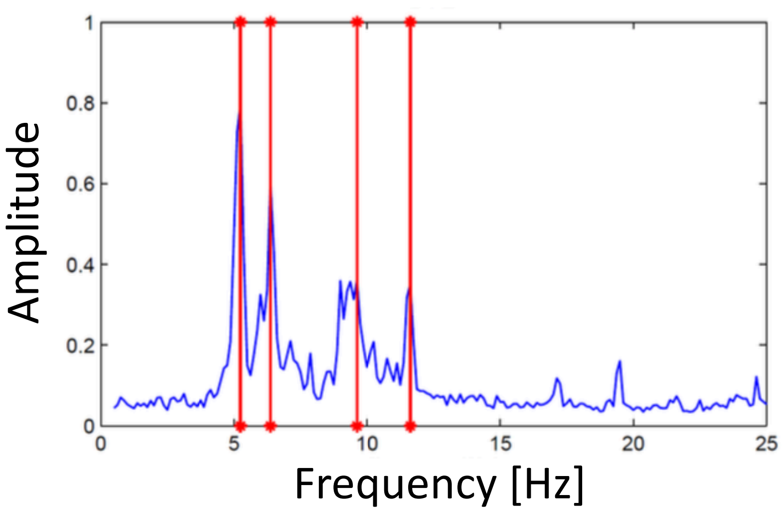
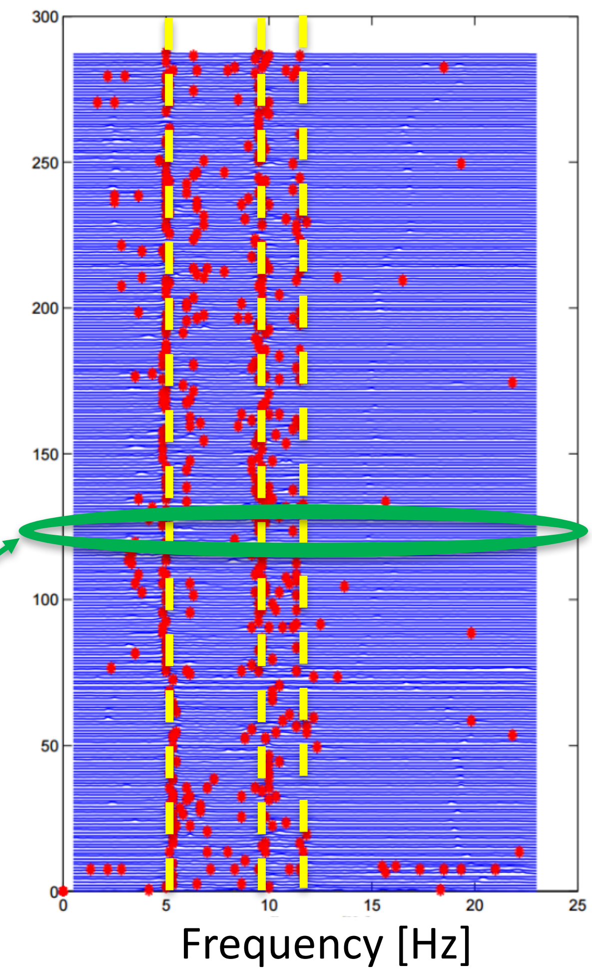
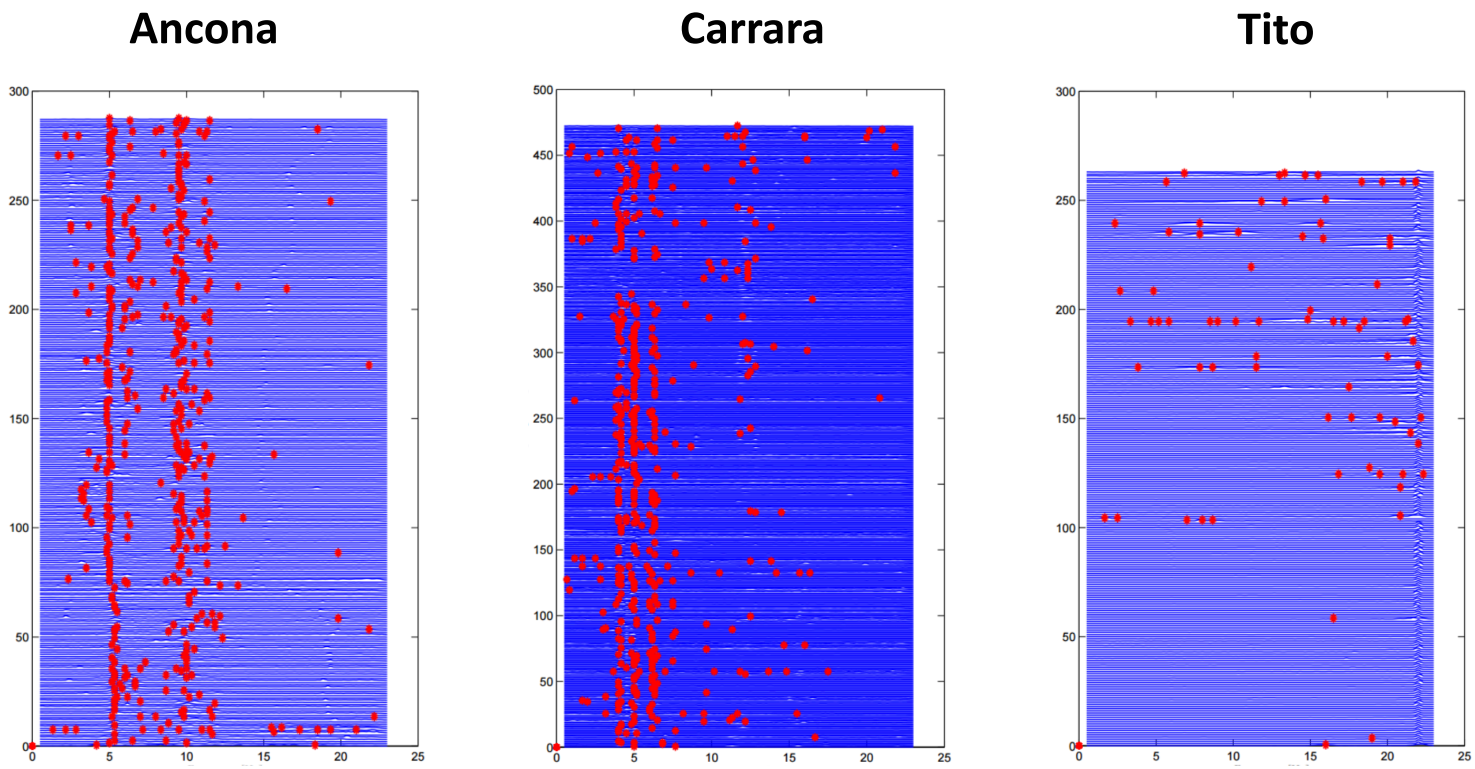


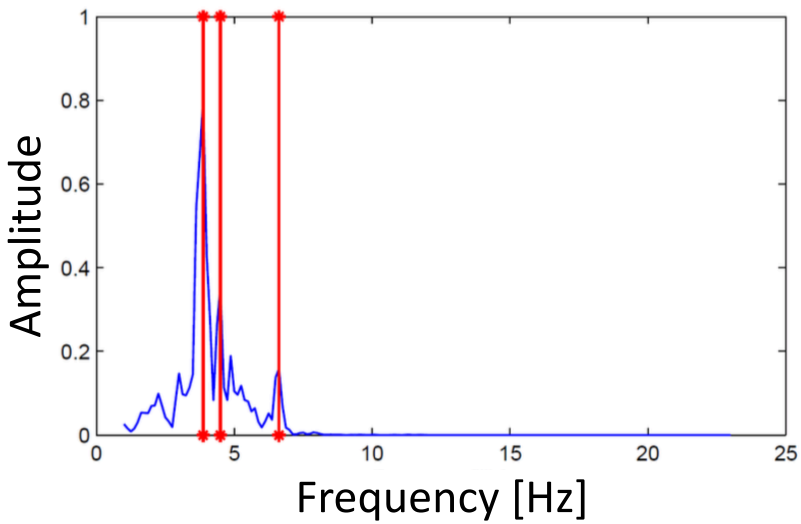



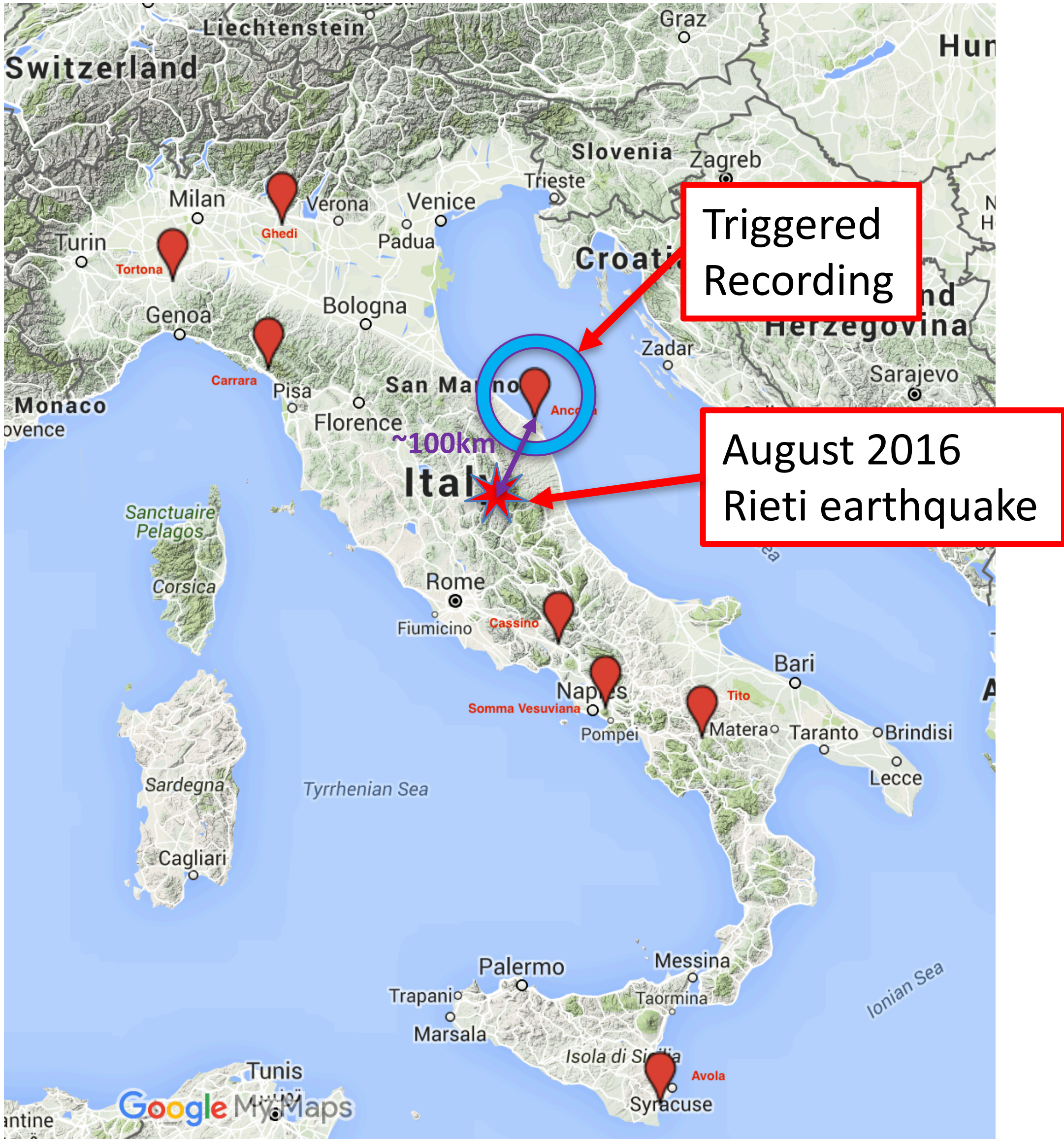
# System Identification from Ambient Vibration




- Similar analyses carried out for each of the schools to identify the prominent modes of vibration.
- Data shows general consensus as the natural frequencies for the first 3 modes, except in the case of the school in Tito that has no obvious trend.

# System Identification from Triggered Vibrations




- Similar analysis conducted for the school in Ancona triggered during the 2016 earthquake.
- Transfer function of the recording used to identify the prominent modes of vibration in the building.

# Numerical Model Parametric Study

- The influence of the following modelling parameters was investigated in the modal response of the schools:
  1. Uncracked RC member stiffness ($EI_{cracked}$ vs. $EI_{gross}$)
  2. Initial Stiffness of Masonry Infill Equivalent Struts
  3. Floor Loading

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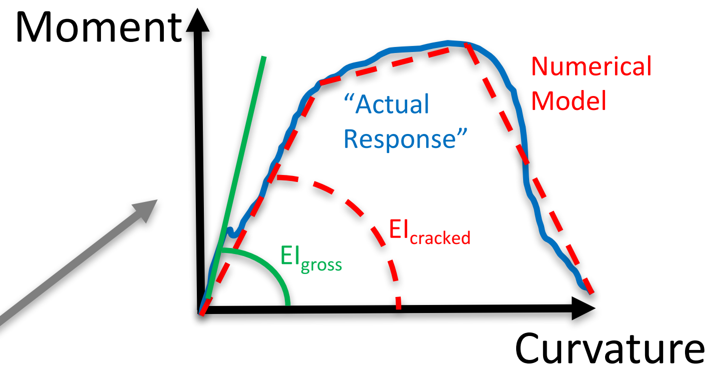

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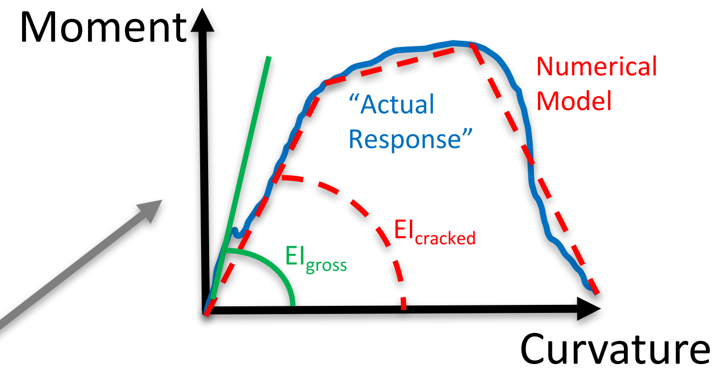
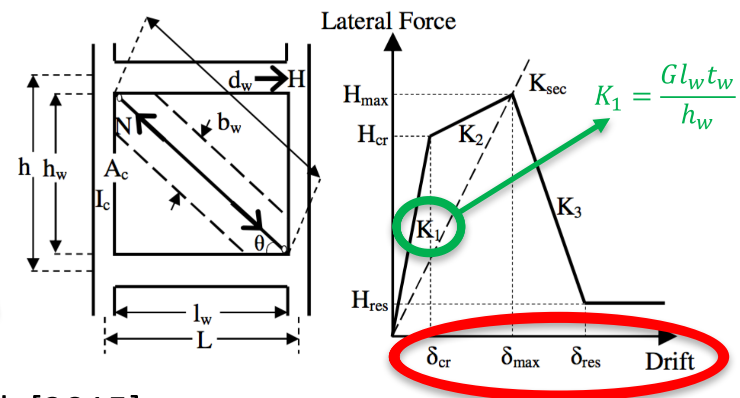
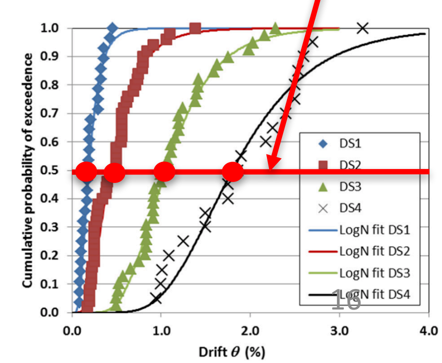



Sassun et al. [2015] proposed the drift values of the infill model correspond to the median of the damage states from test data collected



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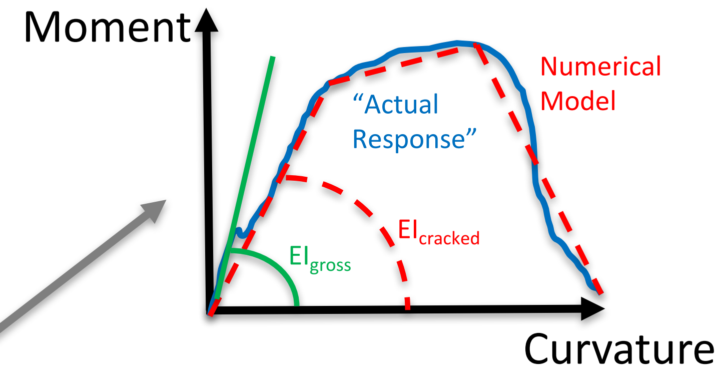


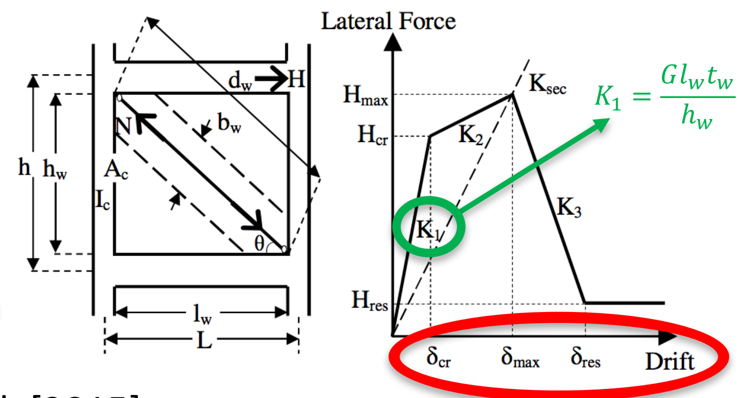


Loading = Dead Load + ~~0.33 x Live Load~~

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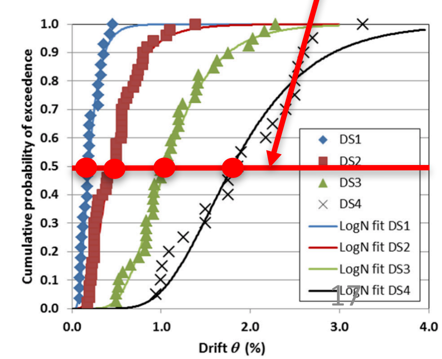
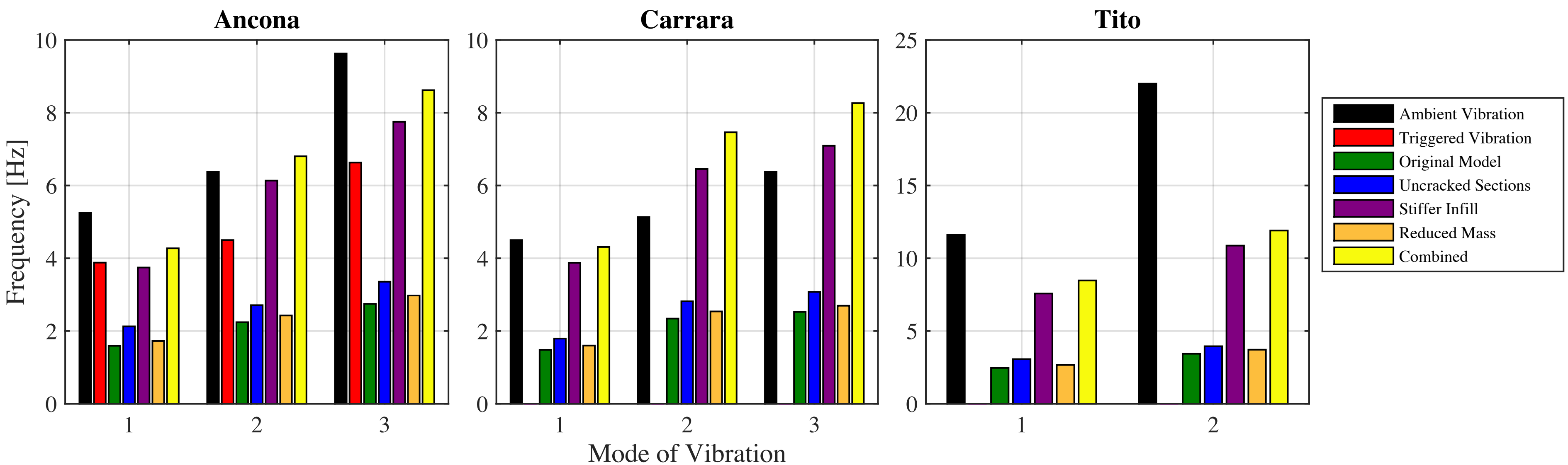


# Natural Frequency Comparison




- The original models considering cracked section tend to under predict the natural frequencies.
- Considering elastic section properties of RC members and masonry infill tend to align better with recorded values.
- Results suggest a disparity between current state-of-the-art models to examine non-linear behaviour collapse and nonlinearity and the response of the buildings to low amplitude vibration.

| School | Mode | Ambient/ Numerical | Triggered/ Numerical |
|---|---|---|---|
| Ancona | 1 | 1.23 | 0.91 |
| | 2 | 0.94 | 0.66 |
| | 3 | 1.11 | 0.78 |
| Carrara | 1 | 1.04 | |
| | 2 | 0.68 | |
| | 3 | 0.77 | |
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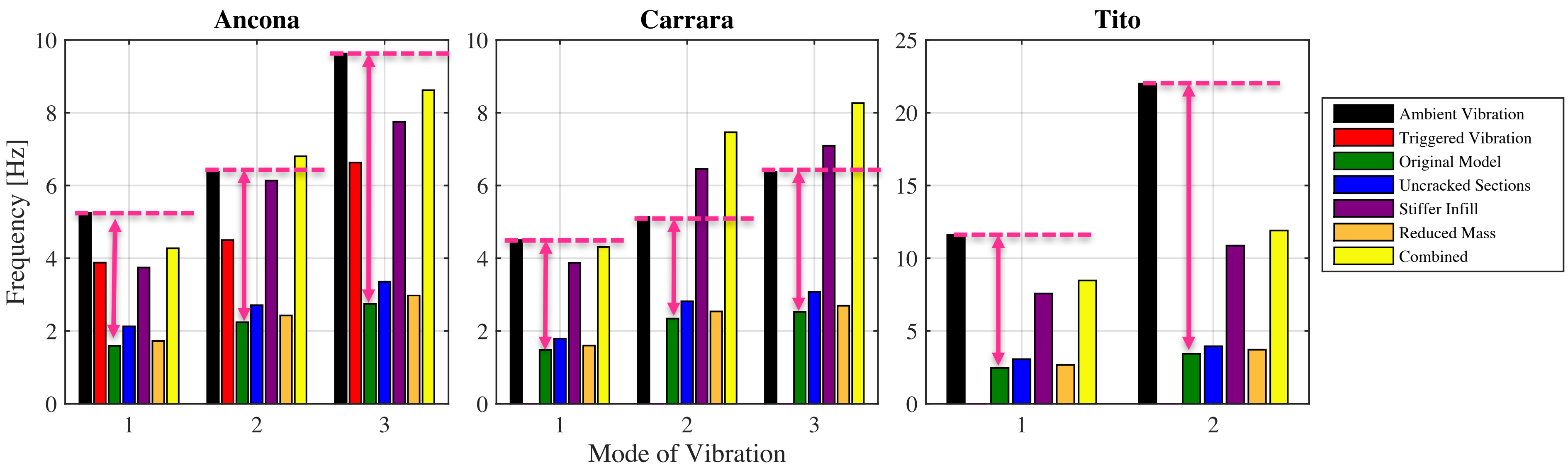


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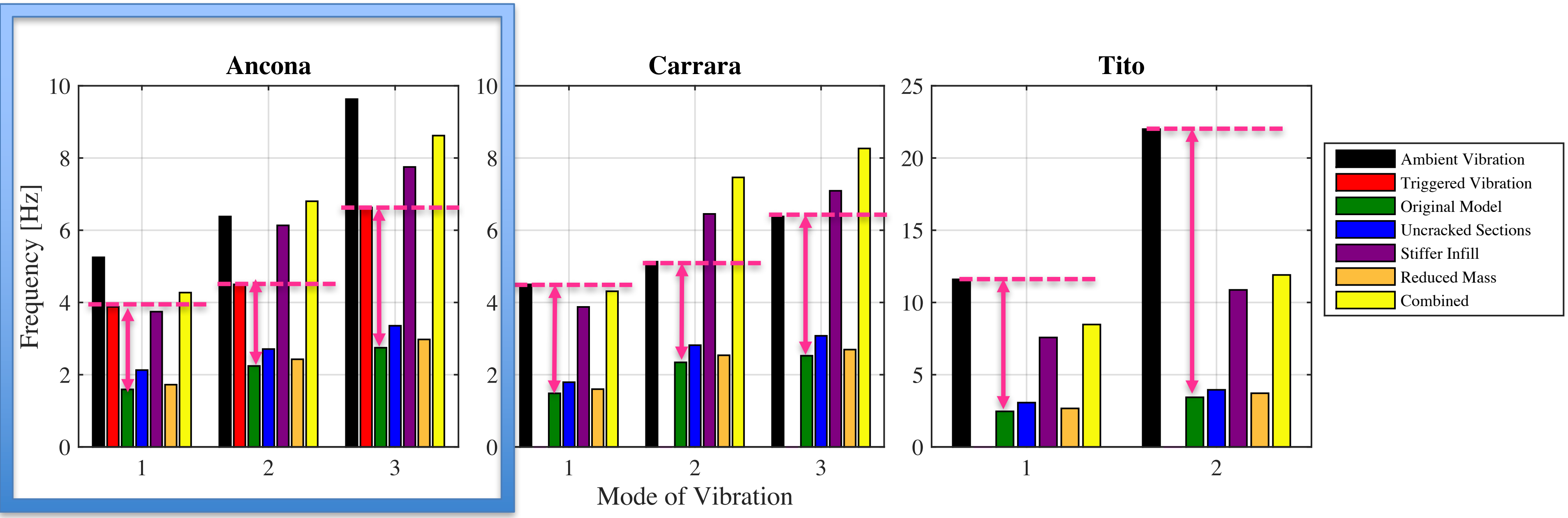


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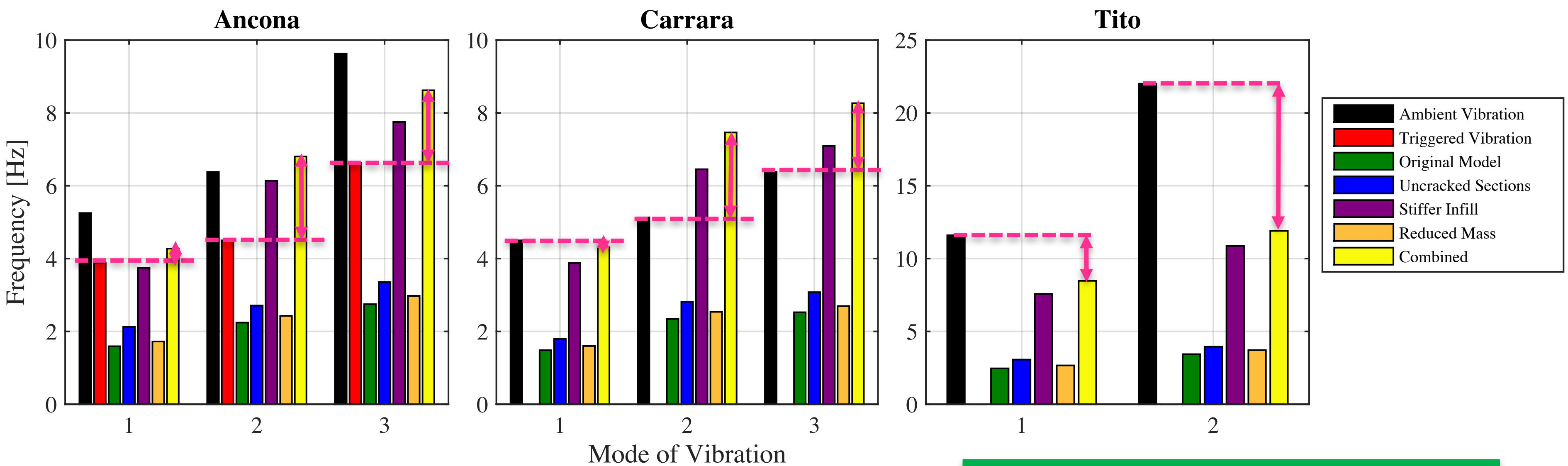


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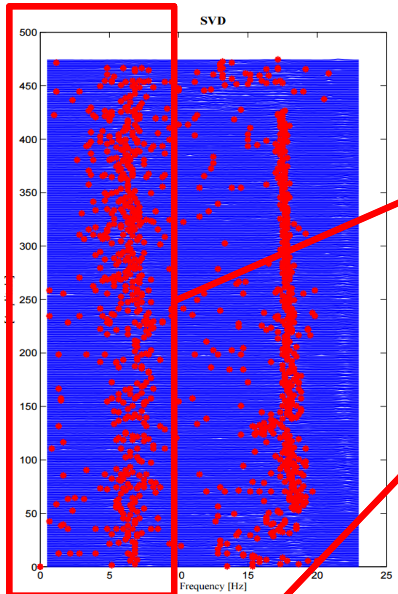
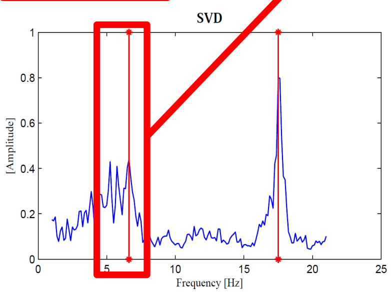
# URM School Buildings

| School | Region | Typology | No. of Floors | Year |
|---|---|---|---|---|
| Ancona | Marche | RC | 3 | 1960’s |
| Avola | Sicilia | URM | 2 | 1900’s |
| Carrara | Toscana | RC | 2 | 1960’s |
| Cassino | Lazio | PC | 2 | 1980’s |
| Ghedi | Lombardia | URM | 2 | 1960’s |
| Tito | Basilicata | RC | 3 | 1970’s |

# System Identification from Ambient Vibration

## AVOLA




High dispersion has been observed in this range of frequencies.

The range of frequencies between the three peaks could be considered representative for the first mode

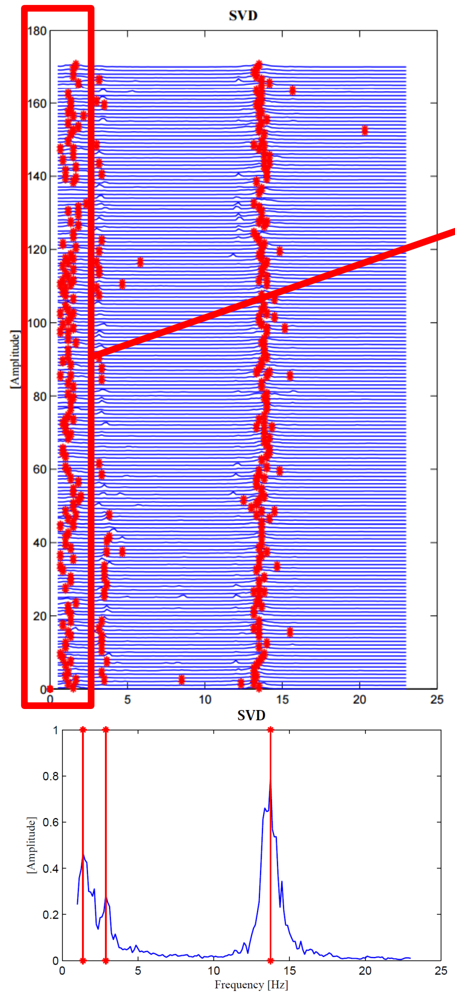
Varying the Young Modulus of the masonry (in the range available in the literature for the typology of masonry available in the school of Avola), the ratio Measured/Predicted decreases.

| First Mode | | | | |
|---|---|---|---|---|
| Young Modulus Masonry (Mpa) | Measured Freq (Hz) | Predicted Freq (Hz) | Measured/Predicted | Measured (mod)/Predicted |
| 1080 | 6,625 | 2,865 | 2,31 | 1,82 |
| 2000 | 6,625 | 4,184 | 1,58 | 1,24 |
| 3000 | 6,625 | 5,128 | 1,29 | 1,01 |

If we assume that the measured frequency of the first mode is equal to 5.2 Hz (first peak) the ratio improves significantly.

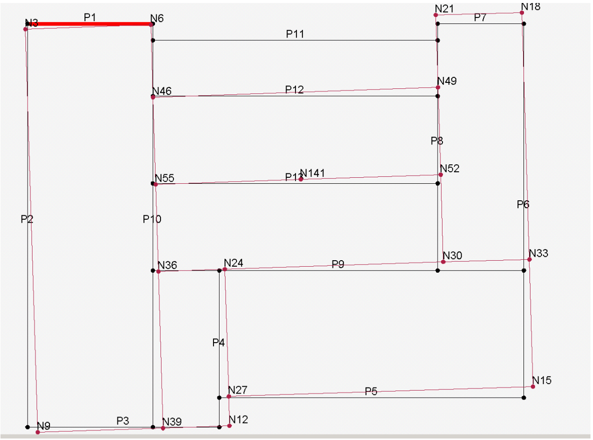
# System Identification from Ambient Vibration

## GHEDI




These measurements could be not related with the modal frequencies. A period equal to 0.74 sec is not representative for a two story masonry building

| Mode | Measured Freq (Hz) | Predicted Freq (Hz) | Measured/Predicted | Measured (mod)/Predicted |
|---|---|---|---|---|
| 1 | 1,375 | 3,086 | 0,45 | 0,93 |
| 2 | 2,875 | 3,35 | 0,86 | |
| | | | | |




A good correlation between experimental and numerical results has been observed if the first measured frequency is not taken into account (both in terms of frequency and modal shape).

# PC School Buildings

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| Avola | Sicilia | URM | 2 | 1900’s |
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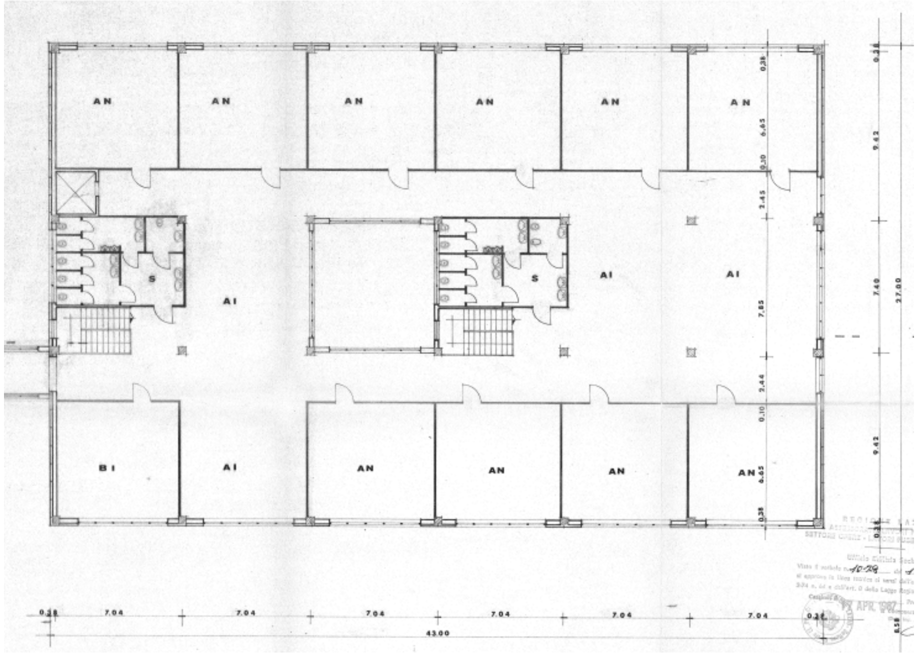
| Ghedi | Lombardia | URM | 2 | 1960’s |
| Tito | Basilicata | RC | 3 | 1970’s |

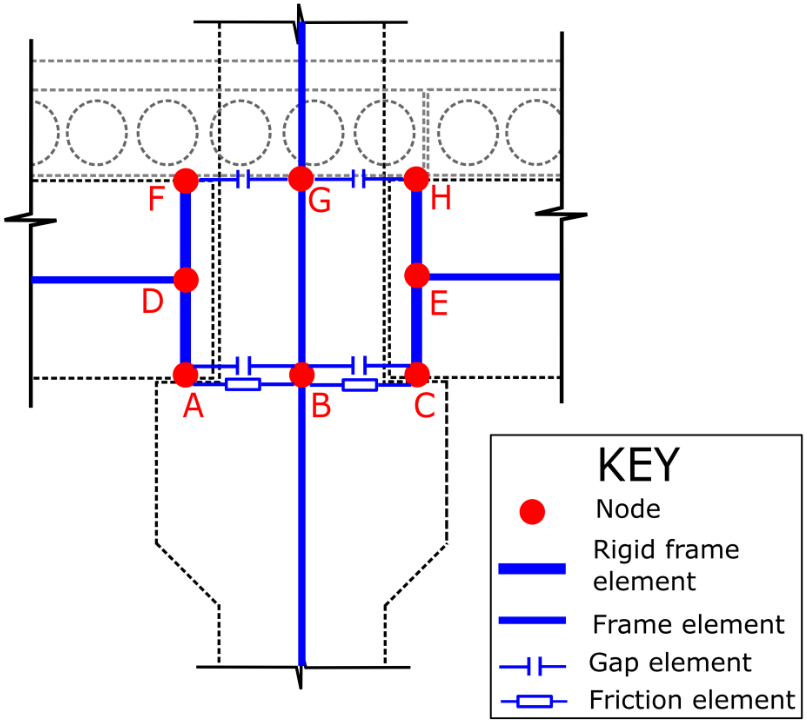
# Building Configuration

- Precast beams seated on corbels of precast columns.
- Precast hollowcore floor and roof system.
- Exterior concrete cladding panels and interior masonry partitions.
- High level of symmetry in both NS and EW directions.

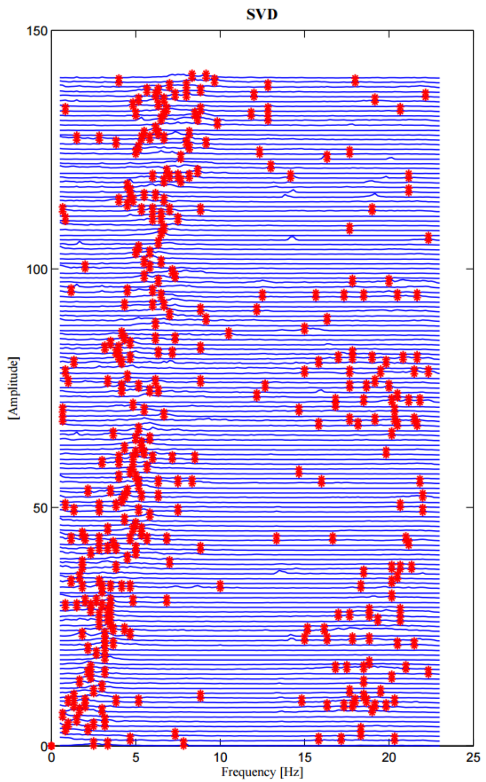



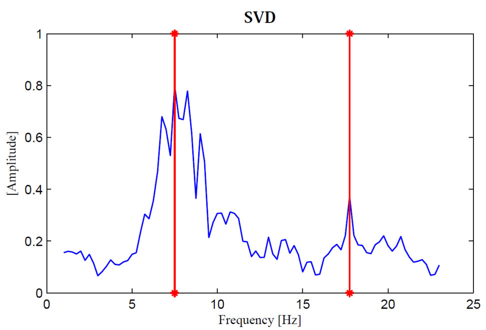
# Simple Geometry, Complex Joints

- Beams seated on columns corbels without any additional fixings.
- Closing of joints as building displaces. Variable gap sizes due to construction tolerances.
- Modelled through combinations of gap and friction elements.



# System Identification from Ambient Vibration



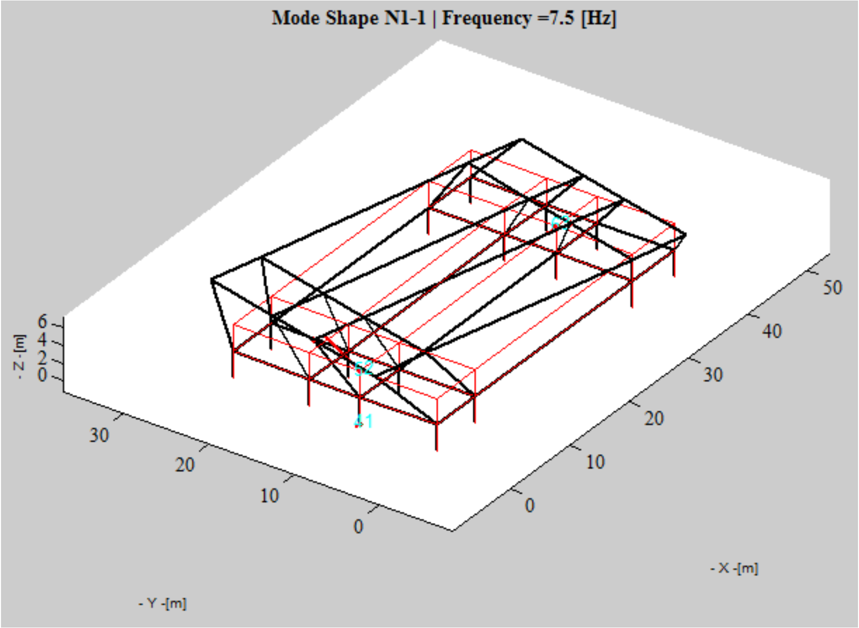




## CASSINO

High dispersion has been observed in this range of frequencies.

First mode identified as torsional. Unlikely given symmetric configuration.

Measured frequency significantly higher than model. Potentially a result of beam column joints locking up.

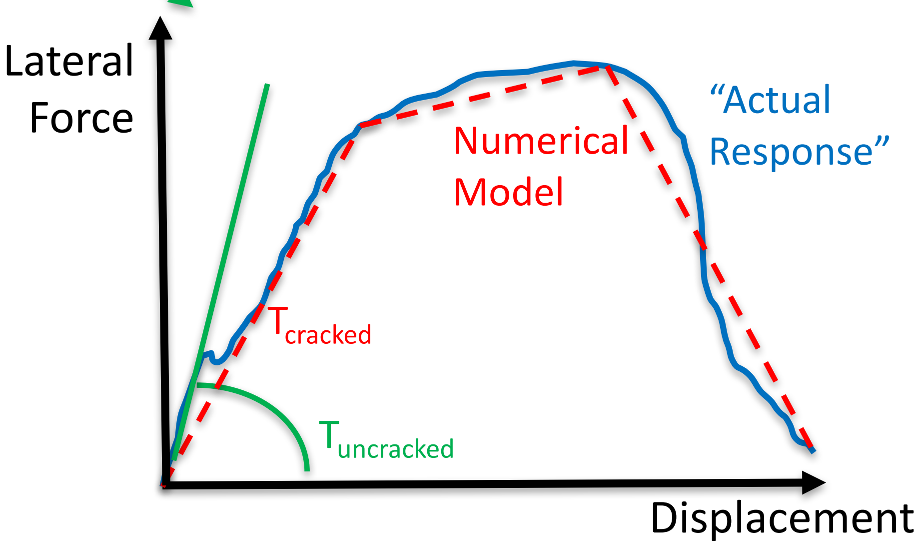


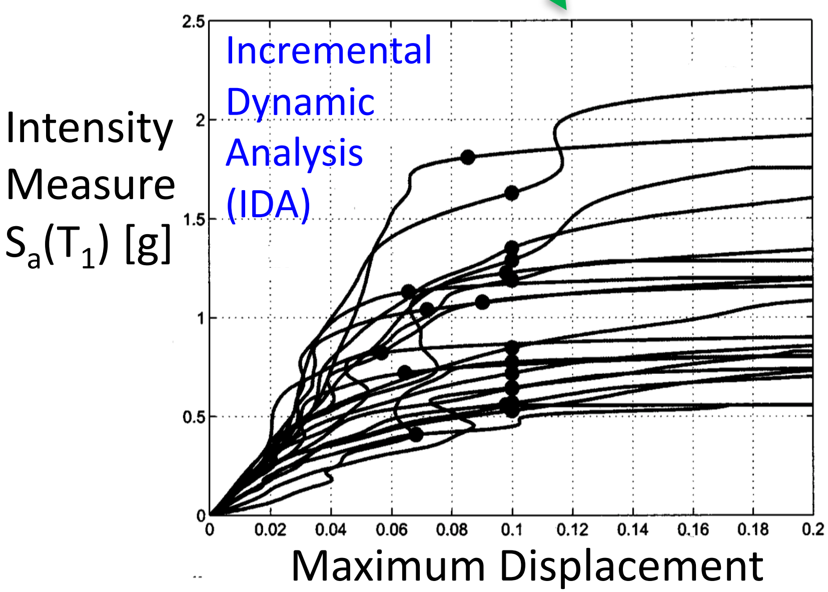
# Summary and Conclusions

- Comparative study has been conducted between the measured modal information of the instrumented school buildings and numerical models.
- Initial comparisons showed that overall modes of vibrations to be correctly predicted but the natural frequencies to be underestimated.
- This is attributed to both the lack of modelling of the non-structural and consideration of cracked section stiffness.
- A parameter study on the different numerical modelling parameters showed the initial stiffness of the masonry infill to be very influential, a finding that agrees with previous empirical work by Ricci et al. [2011].
- Comparisons with the triggered response measurements in the case of school in Ancona show an overall reduction in natural frequencies to be more aligned with the numerical model's – an expected consequence of the increased amplitude of the input vibration.

# Summary and Conclusions

- Overall, the implications of the different modelling decisions on the modal analysis of the existing school buildings has been illustrated to highlight the importance of proper consideration of the various structural and non-structural elements in seismic assessment of existing structure.
- Two main points can be drawn going forward in the are of seismic assessment of existing structures:
  - Using cracked section models for assessing all intensity levels?
  - Using spectral acceleration at fundamental period ($S_a(T_1)$) as intensity measure?



# Thank you for your attention


References:

- Sassun, K., Sullivan, T. J., Morandi, P., Cardone, D. [2015] "Characterising the In-Plane Seismic Performance of Infill Masonry," *Bulletin of the New Zealand Society for Earthquake Engineering*, Vol. 49, No.1.
- O'Reilly, G. J. [2016] "Performance-Based Seismic Assessment and Retrofit of Existing RC Frame Buildings in Italy," PhD Thesis, IUSS Pavia, Italy.
- Ricci, P., Verderame, G. M., Manfredi, G. [2011] "Analytical investigation of elastic period of infilled RC MRF buildings," *Engineering Structures*, Vol. 33, No.2, pp. 308–319.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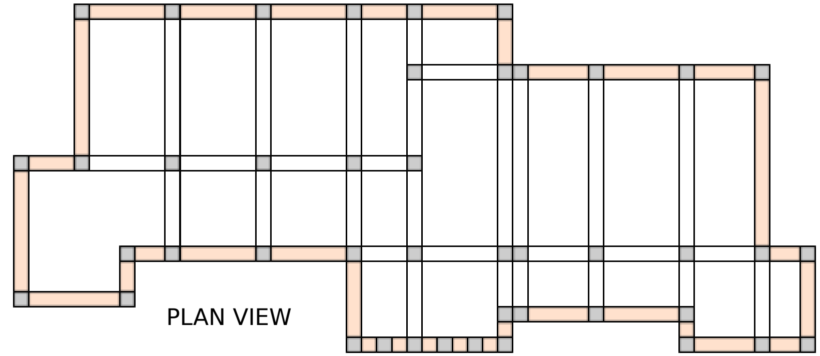
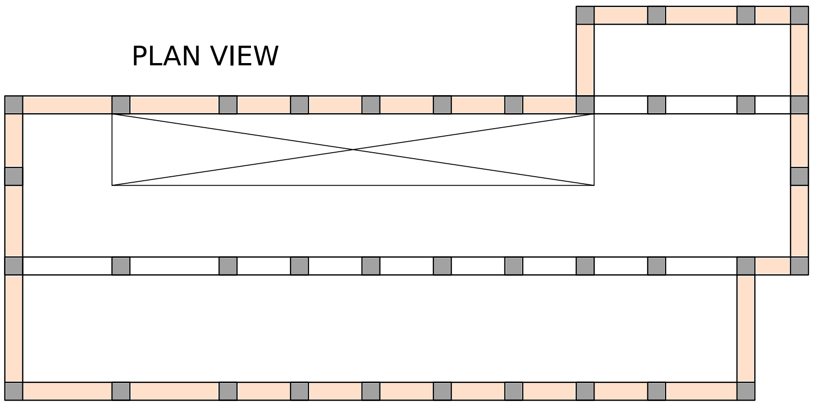
# RC Frame School Buildings

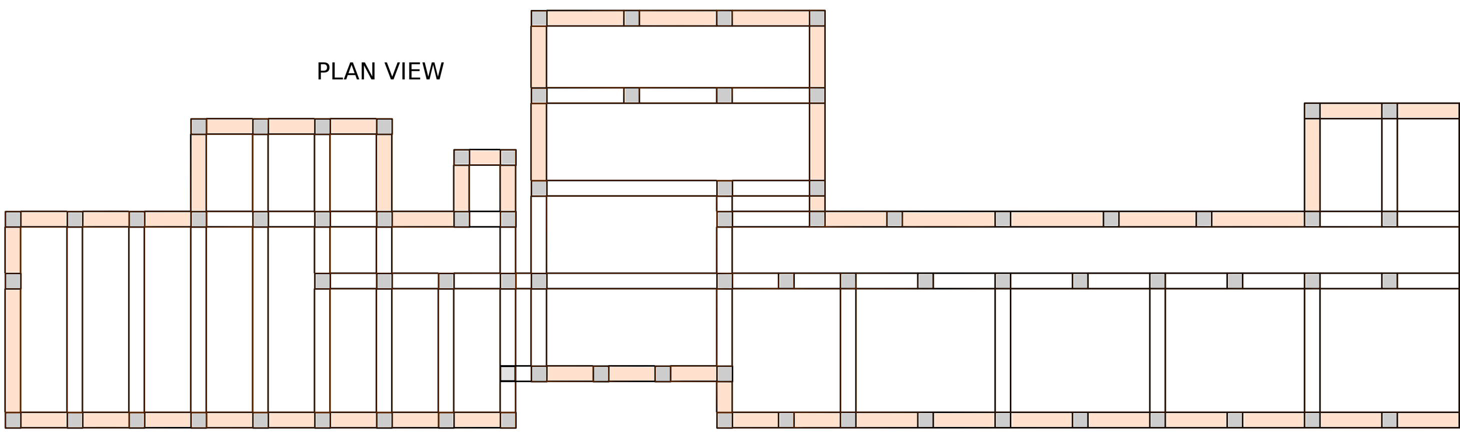
ANCONA




PLAN VIEW



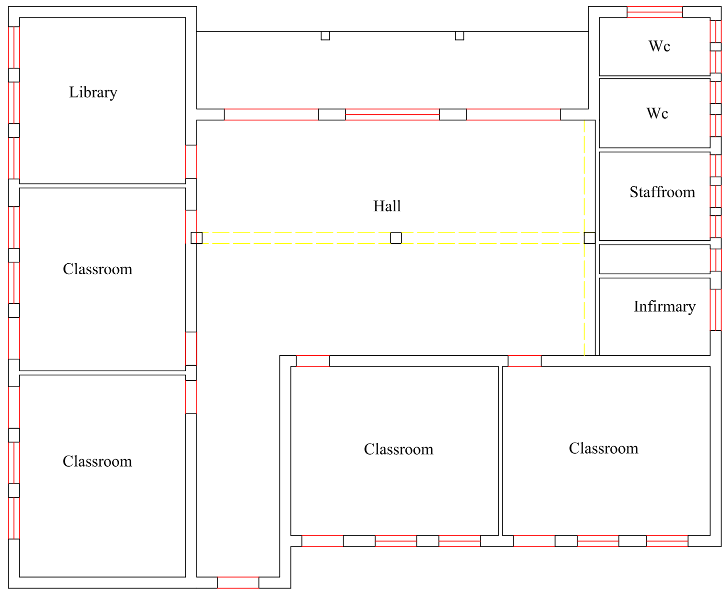
CARRARA



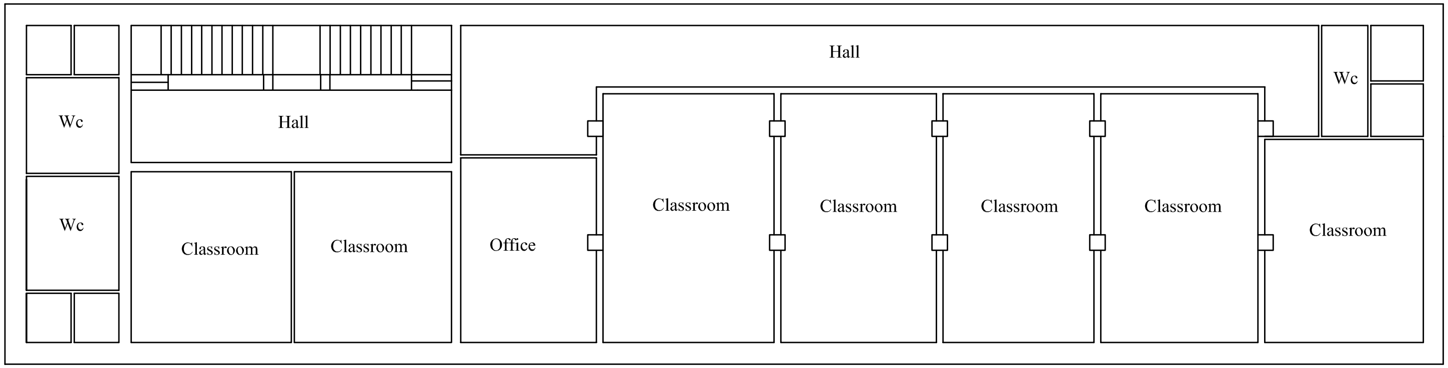

TITO

# Masonry School Buildings

GHEDI

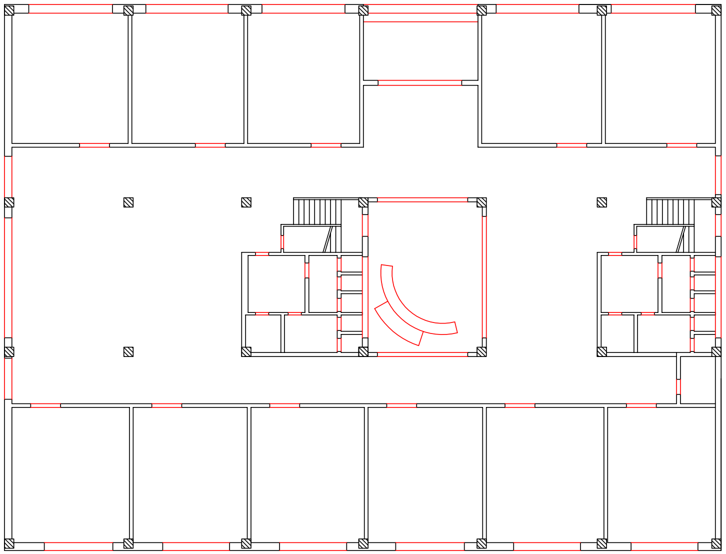



AVOLA

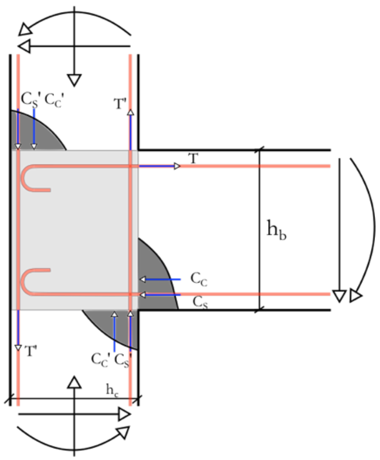


# Precast School Building

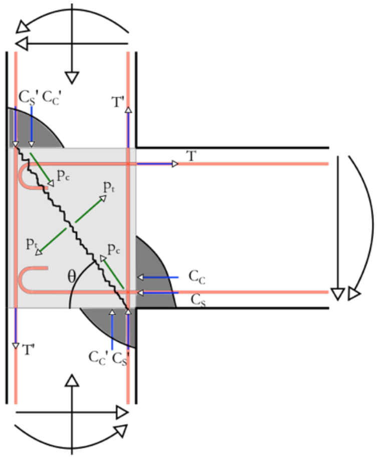
CASSINO



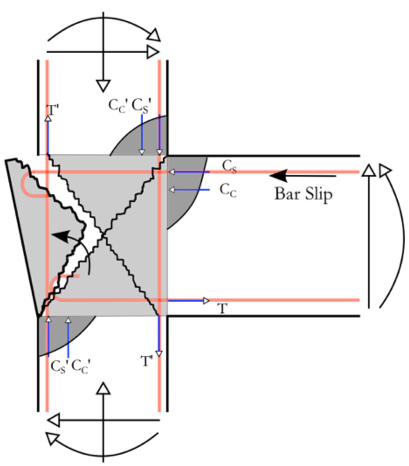
# Modelling of RC Beam-Column Joints




(a) Joint Force Distribution.




(b) Diagonal cracking in joint.

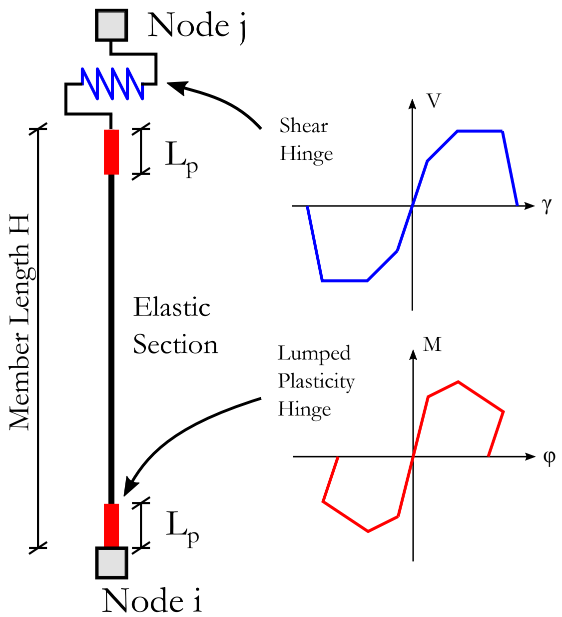



(c) Diagonal cracking on load reversal and ejection of concrete wedge

(d) Experimental observation from Pampanin et al. [2002]

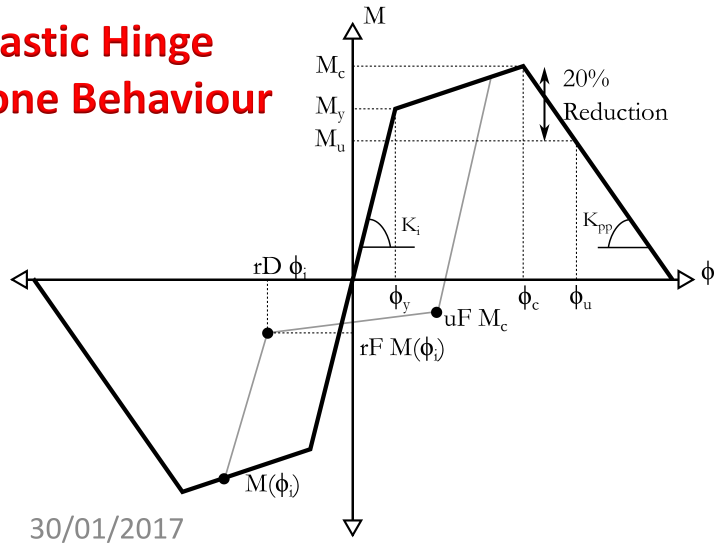
- Surveys show bars were smooth bars and given the age of the structure, end-hooks with no joint reinforcement is expected.
- Modelling of poor joint behaviour observed in past experiments **<u>AND</u>** damage reported in past earthquakes.

# Modelling of RC Beam-Column Elements

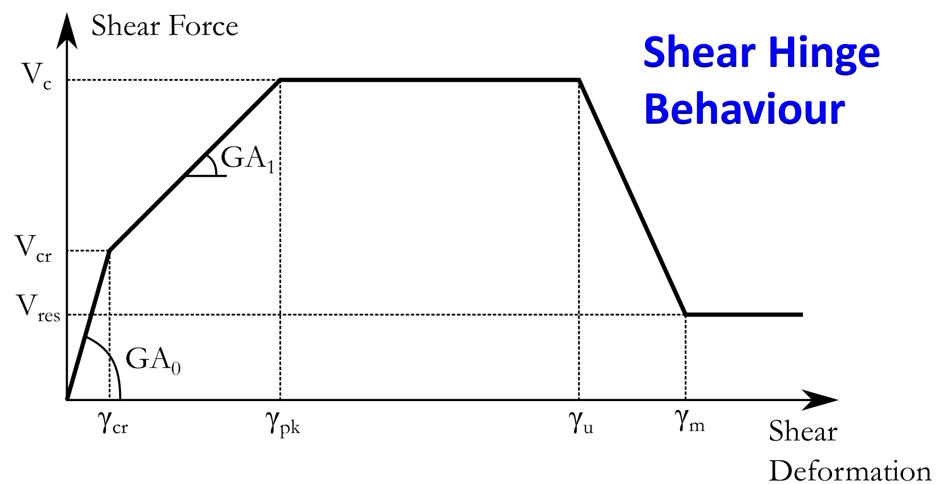



- Beam-Column Elements modelled using a lumped plasticity approach.
- Hysteretic behaviour of plastic hinge zones calibrated using numerous experimental tests reported in another document
- Additional shear hinge aggregated into section (uncoupled) to capture shear deformation in element.

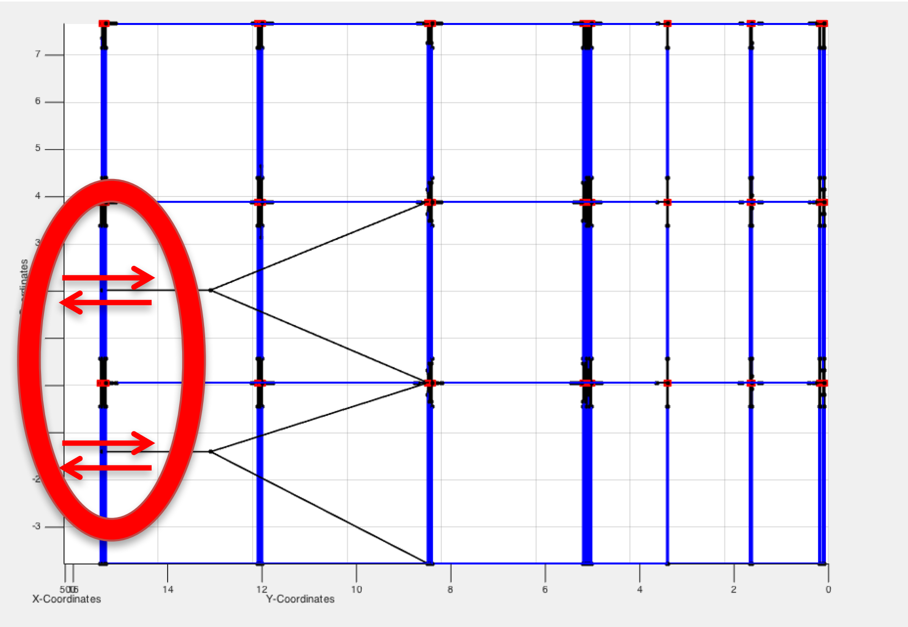
**Plastic Hinge Zone Behaviour**




**Shear Hinge Behaviour**



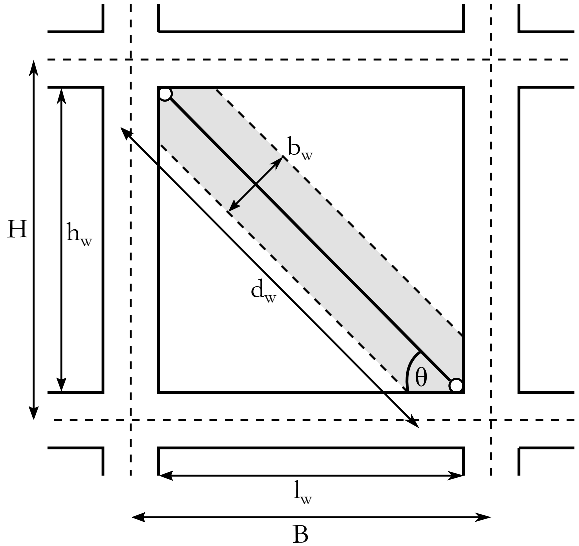
# Modelling of Staircase in RC Frames

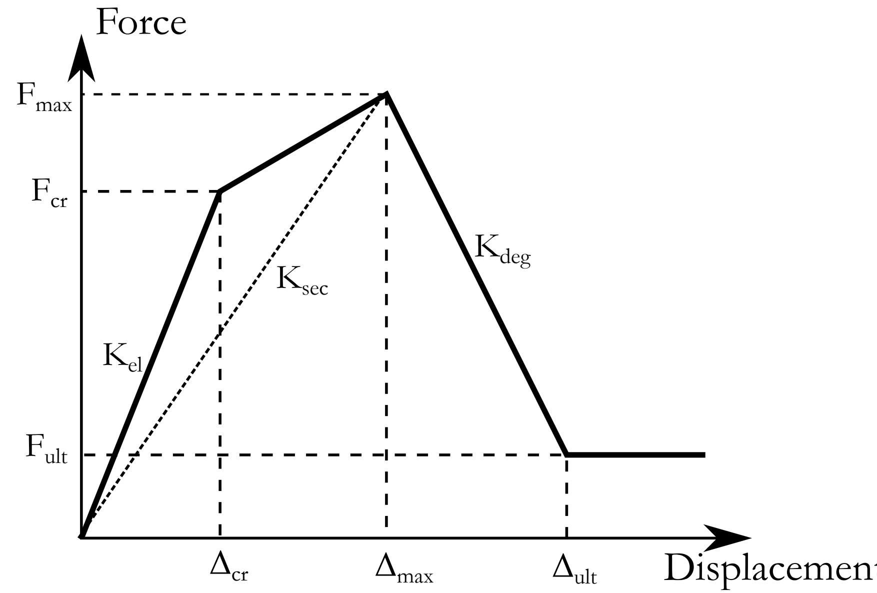




- Staircase modelled using a series of elastic elements.
- This captures the transfer of high shear forces to the columns, which was **reported** to cause failures of column members in past earthquakes.
- The modelling of the beam-column elements with uncoupled shear allows for this to be captured in the model.

# Modelling of Masonry Infill in RC Frames




- Masonry infill modelled to account for their addition strength and stiffness on overall structural response.
- Equivalent diagonal compression-only strut elements used to model the maosnry infill.
- Infill strut backbone computed from masonry brick properties.
- Displacement values taken from median damage state values in experimental database compiled by Sassun et al. [2015].