# ROBUSTNESS OF MULTI-STOREY TIMBER BUILDINGS IN SEISMIC REGIONS

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# Topics

1. Introduction
2. Objectives
3. Framework for robustness assessment
4. Progressive collapse assessment procedures
5. Numerical models for progressive collapse assessment of timber structures
6. Robustness assessment of multi-storey timber structures

# Introduction

## Seismic design provisions

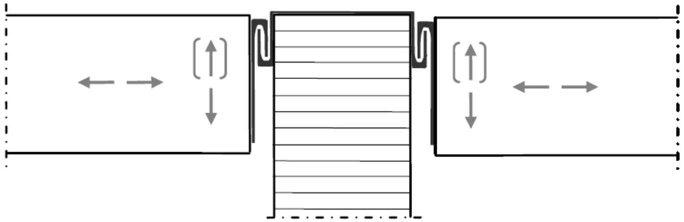
- Simplicity
- Uniformity
- Symmetry
- Redundancy
- Bi-directional strength and stiffness
- Torsional resistance and stiffness
- Diaphragmatic behaviour at the storey level
- Adequate foundations

## Robustness design recommendations

- Alternate load paths
- Effective horizontal ties
- Vertical ties to ensure stability
- Effective anchorage of suspended floors to walls
- Ductility
- Redundancy

- Compartimentalisation;

# Introduction



**Compartmentalisation**

- Reduction of the costs of failure
- Avoid load redistribution
- Cut of alternate load paths

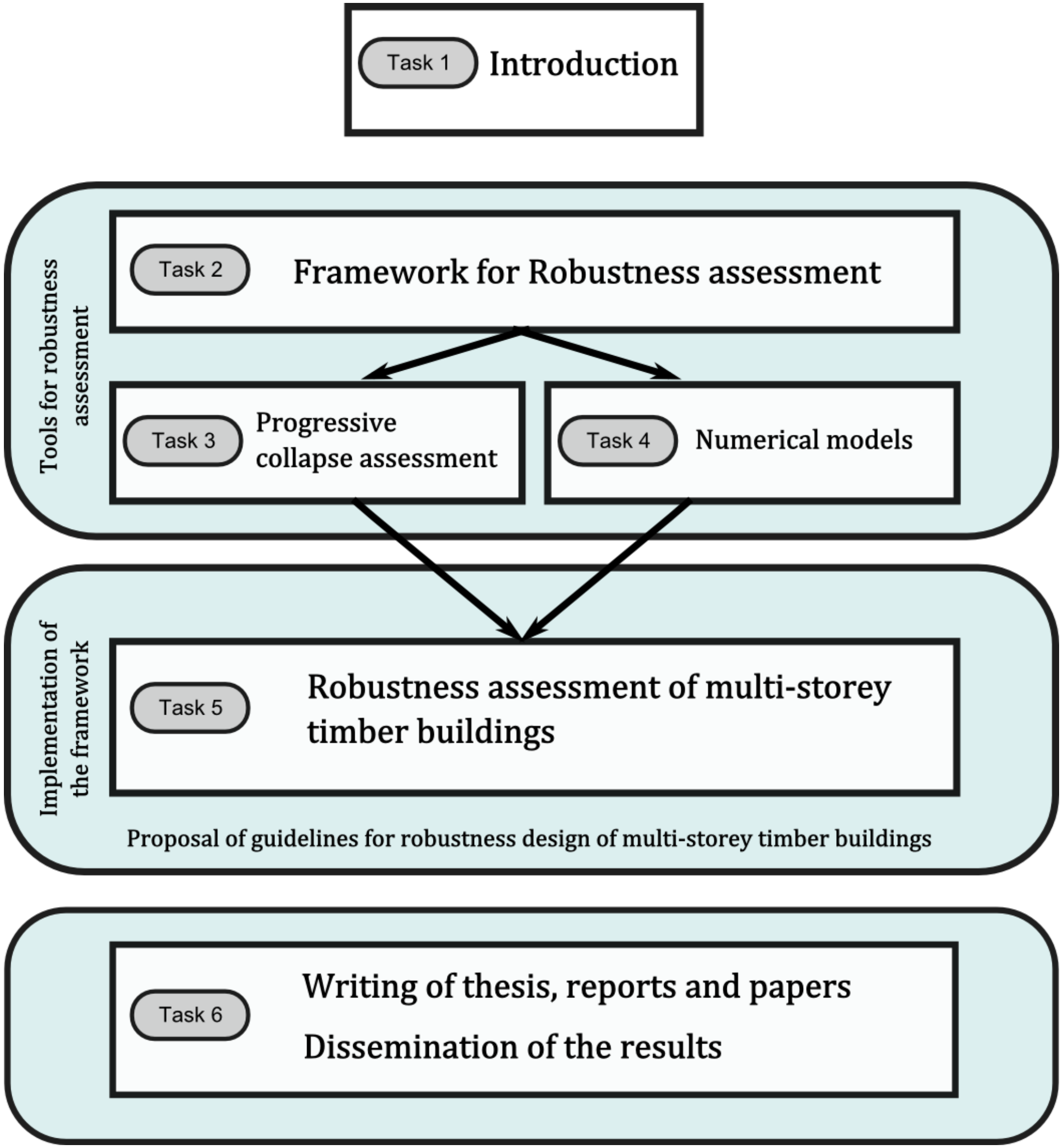
# Introduction

**Alternate load paths**

- Redundancy to distribute loads to undamaged elements
- Reserve of resistance to withstand the load increment
- Ductility to achieve large deformations

# Objectives

- Methodology for assessment of robustness
- Numerical models for robustness analysis of timber structures
- Robustness assessment of multi-storey timber buildings
- Propose guidelines to robustness design of timber structures



# Robustness measures for timber structures

## How to quantify robustness?

Deterministic robustness index

$$I_{rob} = \frac{P_{(damaged,i)}}{P_{(intact)}}$$

Reliability based robustness index

$$RI = \frac{P_{f(damaged)} - P_{f(intact)}}{P_{f(intact)}} \qquad \beta_R = \frac{\beta_{(intact)}}{\beta_{(intact)} - \beta_{(damaged)}} \qquad I_{Rob} = \frac{\beta_{(damaaged)}}{\beta_{(intact)}}$$

Risk-based robustness index

$$I_{Rob} = \frac{R_{dir}}{R_{dir} + R_{ind}} \qquad I_{Rob|exposure} = \frac{R_{dir|exposure}}{R_{dir|exposure} + R_{ind|exposure}}$$

# Framework for robustness assessment

$\boxed{\text{Exposures}}$

Mechanical properties

Expected loads

Damage

Failure

Consequences

**Impacts and explosions**

- Notional removal of primary load-bearing members

**Human Errors**

- Local and global reduction of mechanical characteristics of timber elements and connections

# Framework for robustness assessment

Exposures

Mechanical properties

Expected loads

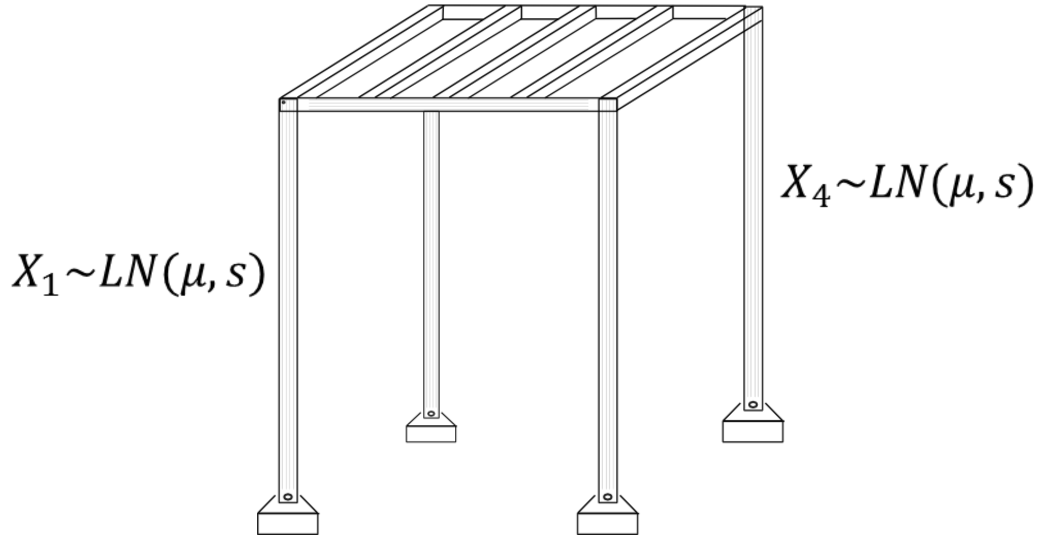
Damage

Failure

Consequences

**Timber elements**

-Modelled according to JCSS PMC
-Spatial variability between elements (correlated variables)




**Connections**
-Stiffness and strength dependent of metal connectors and timber density
-Spatial variability between connections

# Framework for robustness assessment

Exposures

Mechanical properties

Expected loads

Damage

Failure

Consequences

**Self-weigth** (JCSS PMC)
-Normal distribution

**Live-Loads**
-Sustained loads (type I extreme value distribution)
-Transient loads (Exponential distribution)

**Wind loads**
-Gumbel distribution
-Considering characteristic values given by Design Codes (e.g EN-1991-1-4)

**Snow loads**
-Gumbel distribution
-Considering characteristic values given by Design Codes (e.g EN-1991-1-3)

# Framework for robustness assessment

Exposures

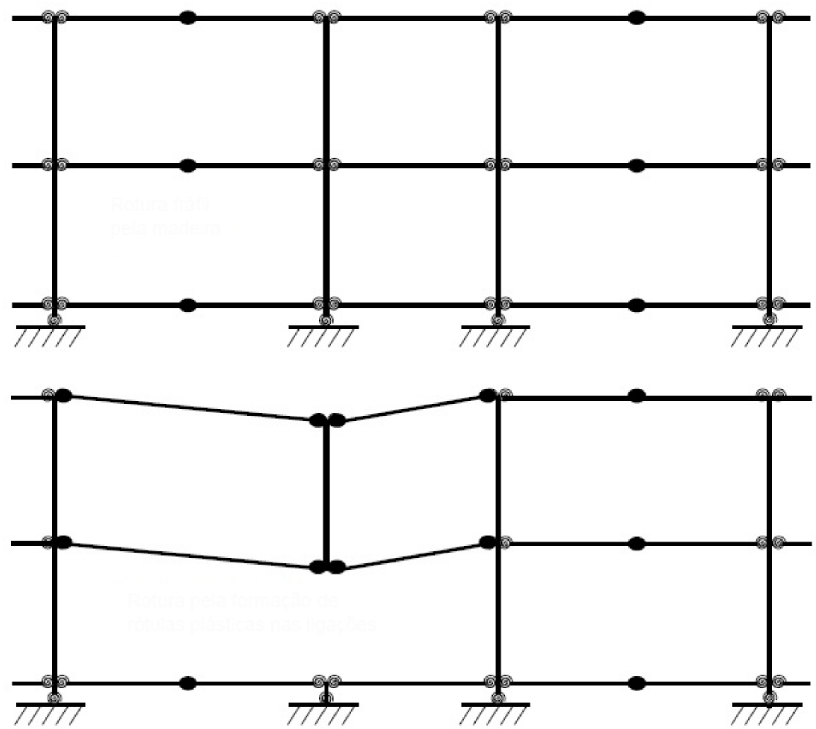
Mechanical properties

Expected loads

Damage

Failure

Consequences



Related to loss of capacity of individual components of the system.

# Framework for robustness assessment

Exposures

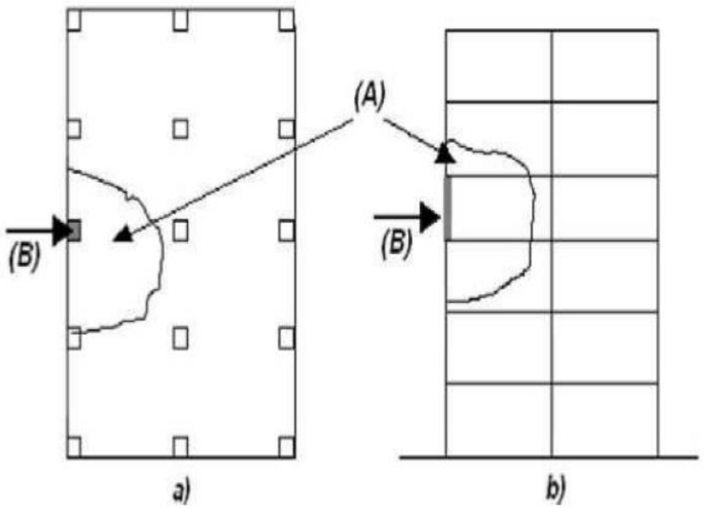
Mechanical properties

Expected loads

Damage

Failure

Consequences




Failure occurs when the extension of damage reaches 15% of the area of floor or it is higher than $100m^2$

- **Partial collapse**
- **Progressive collapse**

# Framework for robustness assessment

Exposures

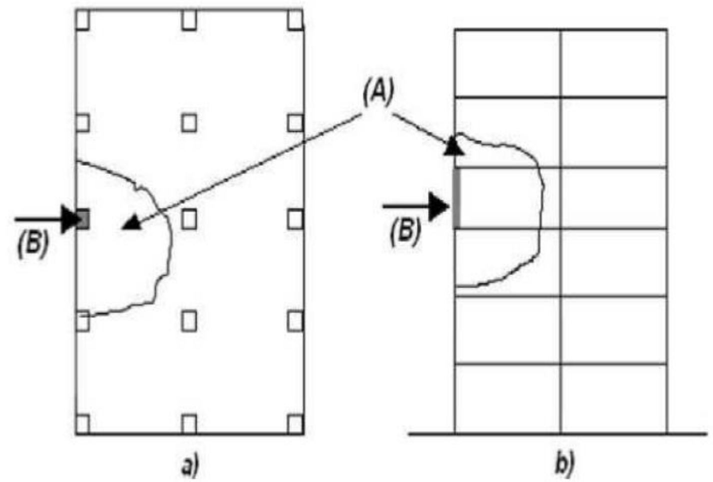
Mechanical properties

Expected loads

Damage

Failure

Consequences



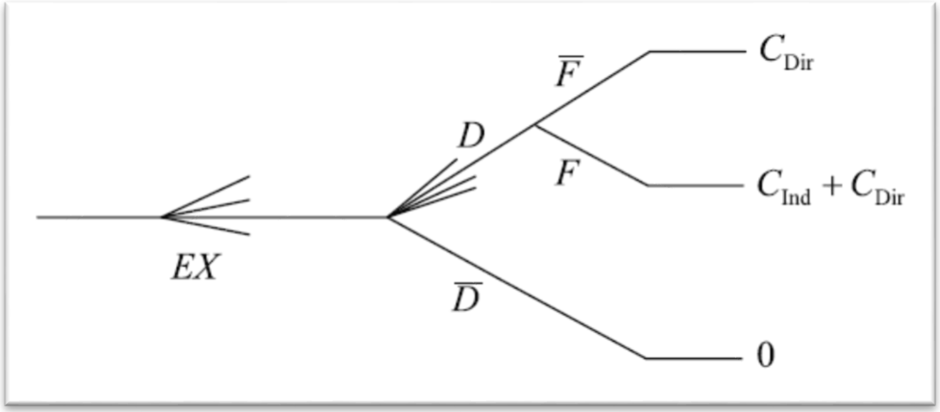

Consequences of damage and failure :

- **Damaged area**
- **Structural system**
- **Repair, re-qualification and demolishing**

# Quantification of robustness

## Risk-based robustness index

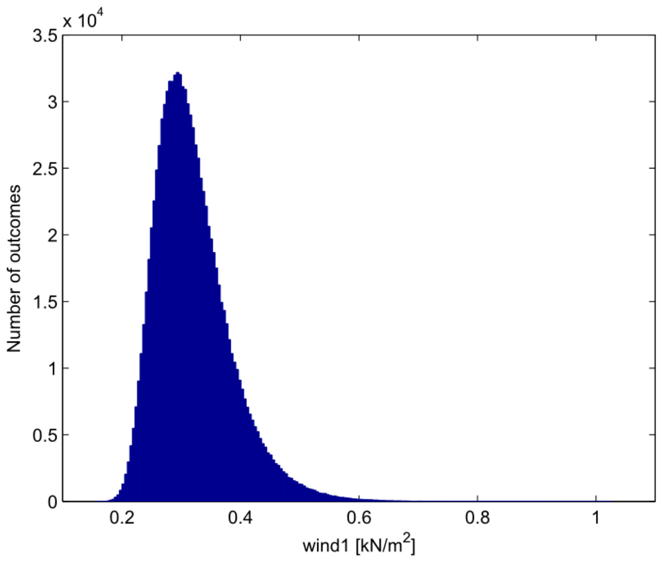
$$I_{Rob} = \frac{R_{dir}}{R_{dir} + R_{ind}}$$




$$R_{dir} = \sum_i \sum_j C_{dir,ij} P\left(D_j \middle| EX_i\right) P(EX_i)$$

$$R_{ind} = \sum_k \sum_i \sum_j C_{ind,ijk} P\left(S_k \middle| D_j \cap EX_i\right) P\left(D_j \middle| EX_i\right) P(EX_i)$$

# Quantification of robustness




$$RI = \frac{P_{f(damaged)} - P_{f(intact)}}{P_{f(intact)}}$$

$$\beta_R = \frac{\beta_{(intact)}}{\beta_{(intact)} - \beta_{(damaged)}}$$

$$I_{Rob} = \frac{\beta_{(damaaged)}}{\beta_{(intact)}}$$

**Reliability based robustness index**

**Damage scenarios**
-Failure of connections
-Failure of timber elements

**Probabilistic assessment**
-Monte Carlo simulations

Variability of typical loads
Variability of mechanical characteristics

**Non-linear static analysis**

**How prone a structure is to disproportionate collapse given a local failure?**

**Identify key elements**

# Quantification of robustness

**Deterministic robustness index**

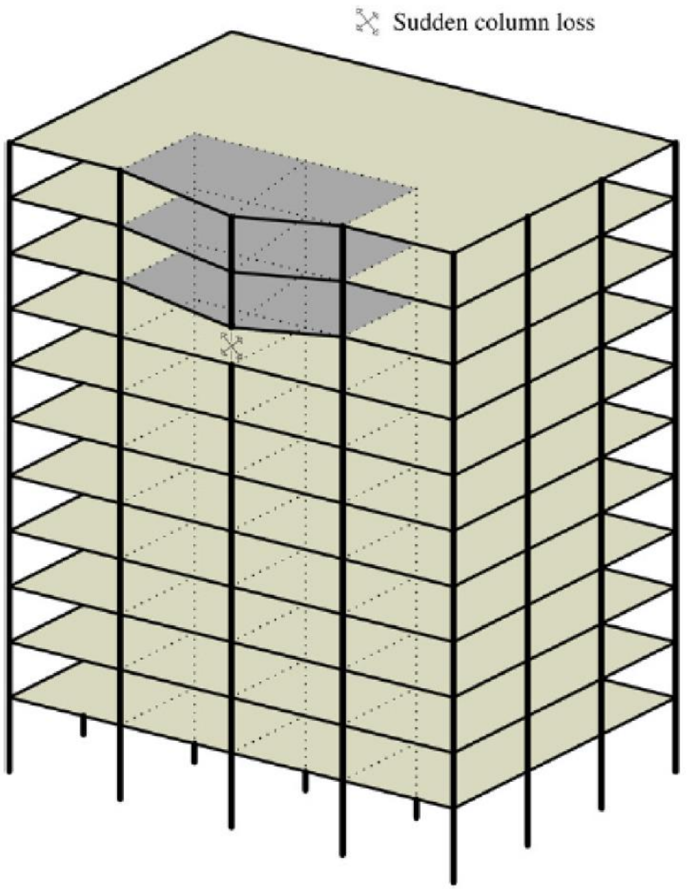
- Characteristic values for timber elements and connections

**Nonlinear static analysis**

$$I_{rob} = \frac{P_{(damaged,i)}}{P_{(intact)}}$$

**Redundancy assessment**

**Identify key elements**

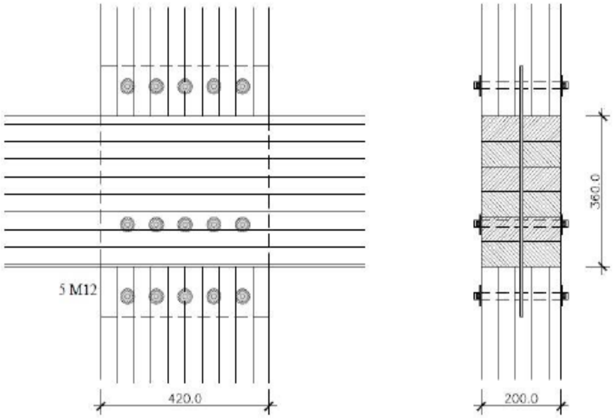


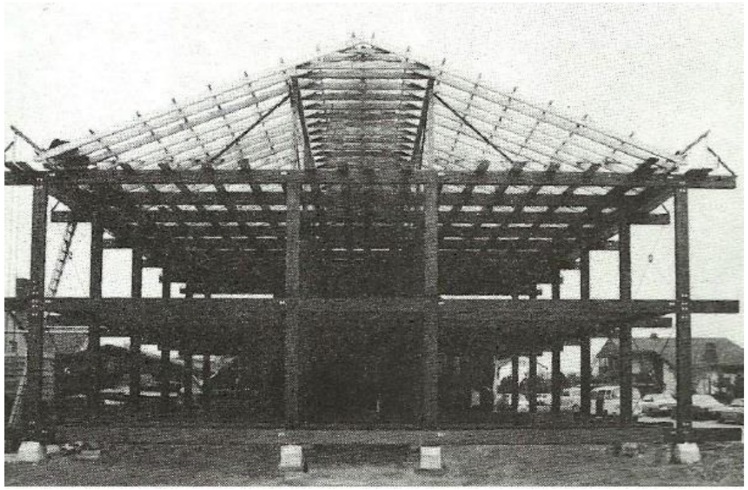
# Application of deterministic methods

## Post and Beam structure

Continuous beams

Tie cables as bracing system

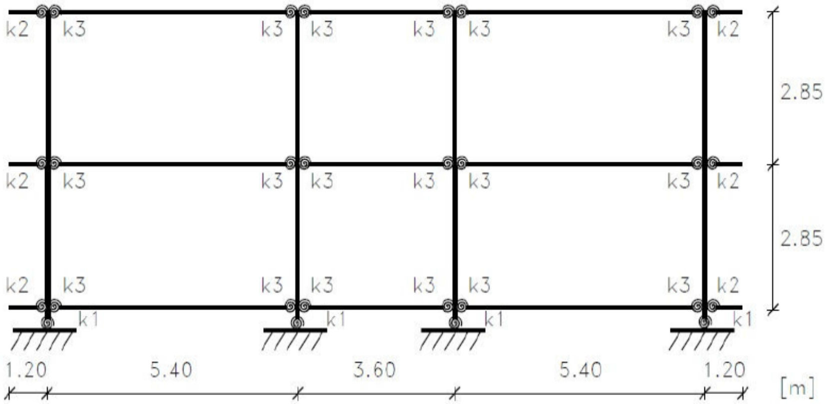


## Alternative design

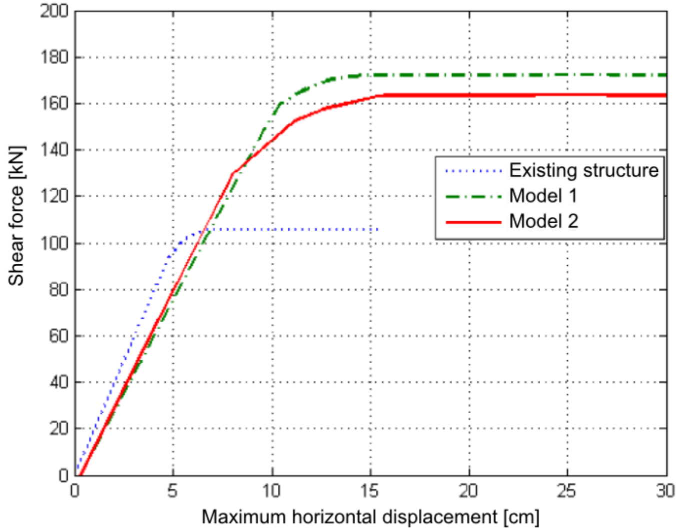
Continuous columns

Tie cables as bracing system



# Application of deterministic methods

## 2D pushover analysis




## Deterministic robustness index

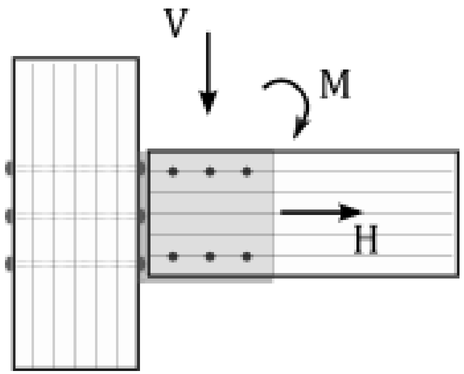
| Model | $P_{int}$ [kN] | $P_{dam}$ [kN] | $I_{rob}$ |
|---|---|---|---|
| Existing | 1683.6 | 883.4 | 0.525 |
| Model 1 | 2170.1 | 210.7 | 0.097 |
| Model 2 | 2105.9 | 285.8 | 0.136 |

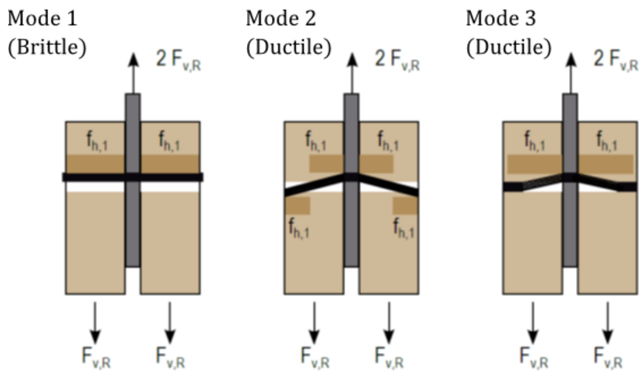
## Main conclusion:

Simple models without propagation of damage restrains the conclusions since they do not consider the total effects of ductility and redundancy.

# Structural modeling for robustness analysis

$$\left(\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right)^2 + \frac{\sigma_{m,y,d}}{f_{m,y,d}} + k_m \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1$$




**Failure Modes assessment**

**Timber elements**

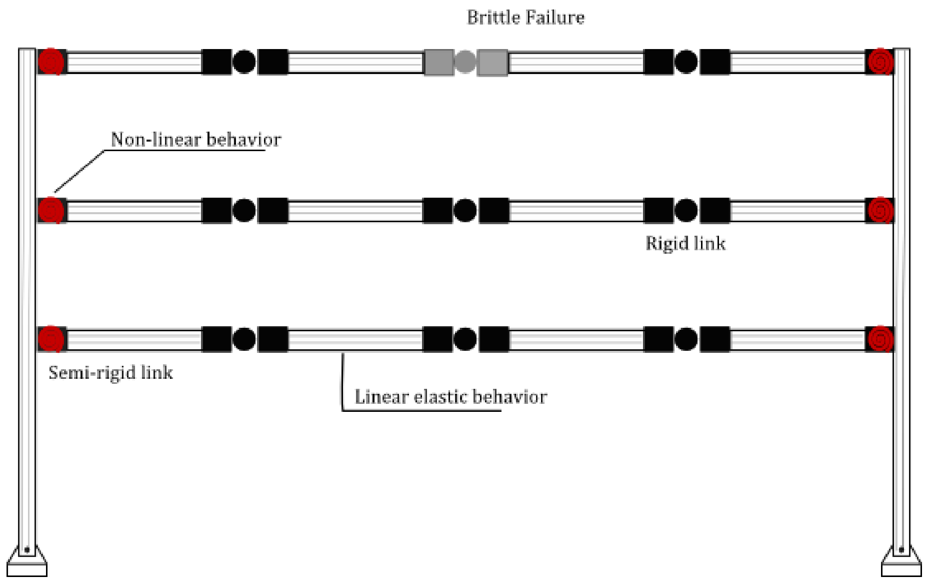
Brittle failure for bending, shear and axial forces

**Connections**

Brittle and ductile failure modes

Opensees finite element framework allows user defined computations and changes in the structural model after each analysis step

# Procedures for progressive collapse assessment




1) load increment

2) structural analysis

3) Assessment of failed components

4) Removal of failed components

5) load updating

6) mechanical properties updating

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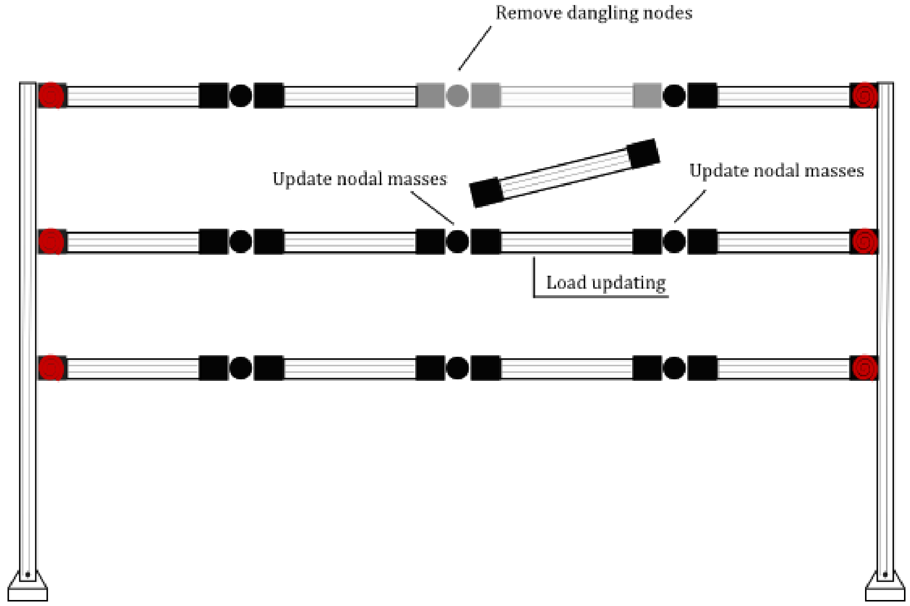


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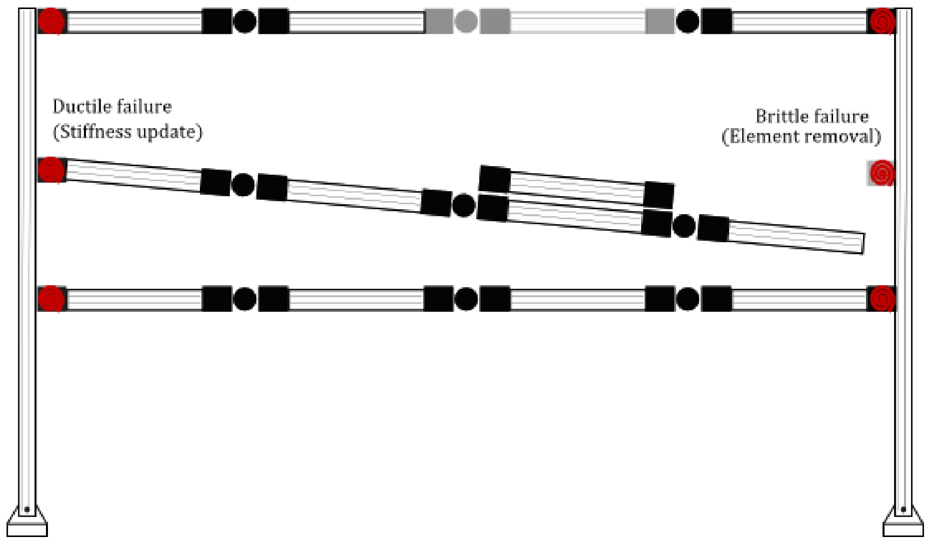


1) load increment
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3) Assessment of failed components
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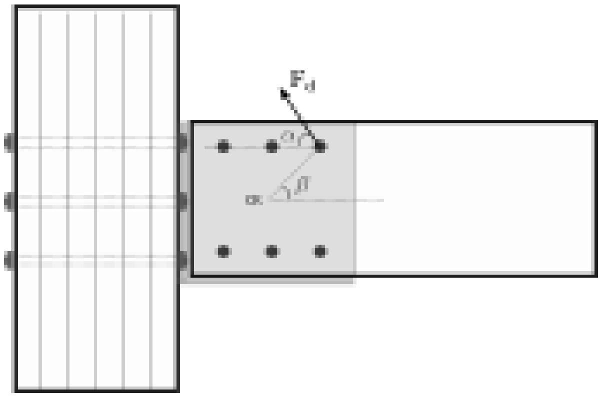
# Numerical analysis for robustness

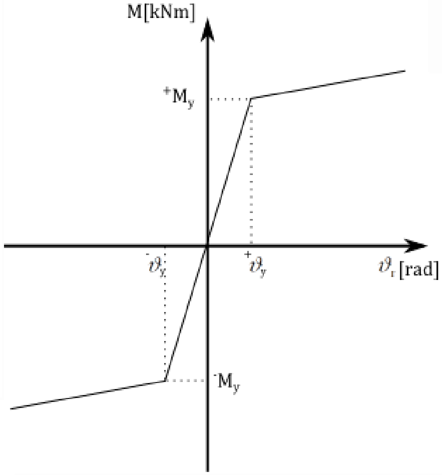


**Nonlinear static analysis**

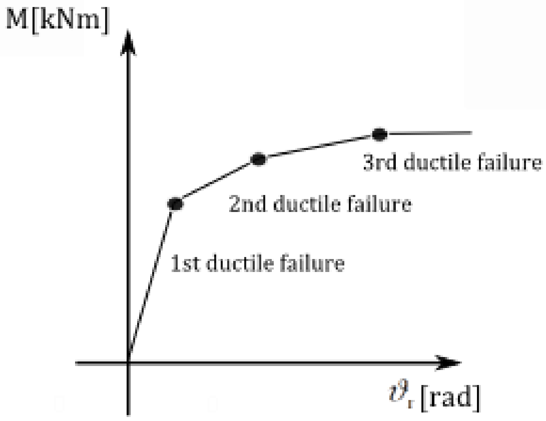
Timber elements - Linear elastic

Material nonlinearities
•Bi-linear curves
•Stiffness updating

Geometric nonlinearities
•P-Delta effects
•Corotational transformation

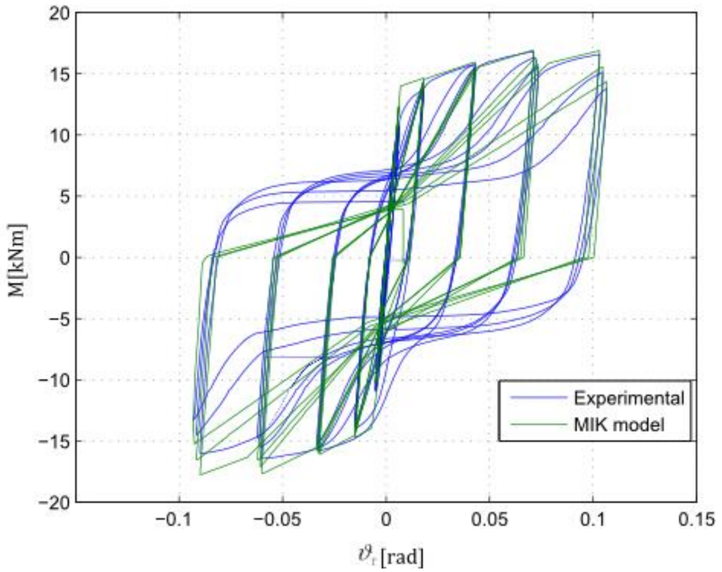



Bi-linear curve




Stiffness updating

# Numerical models for earthquakes




**Nonlinear dynamic analysis**

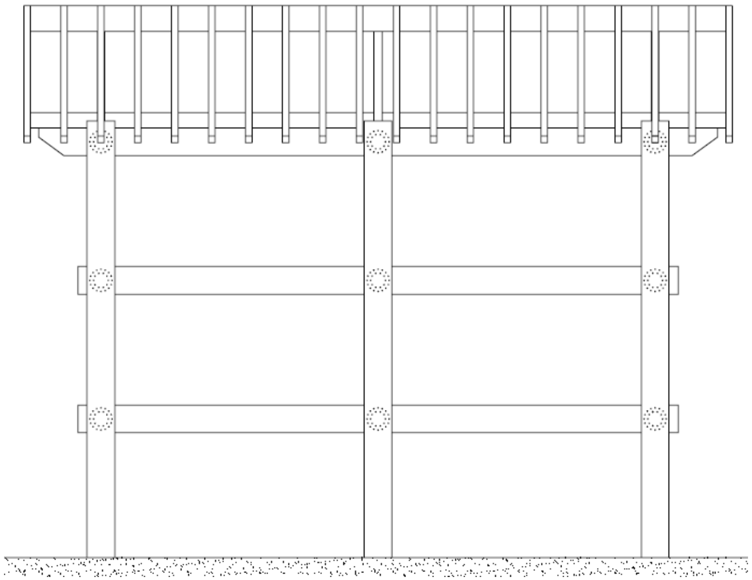
Timber elements - Linear elastic

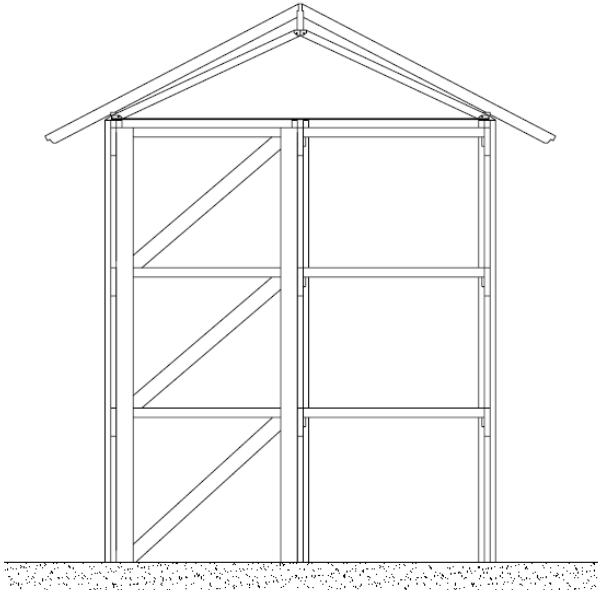
Material nonlinearities (connections)
•bi-linear curves
•Modified Ibarra Krawinkler models
•Bouc – Wen – Baber - Noori

**(FP1101 – Short term scientific mission – University of Trento)**

**Objective:**
Evaluate the influence of sophisticated models on vulnerability assessment

# Numerical models for earthquakes





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Evaluate the influence of sophisticated models on vulnerability assessment

# Robustness assessment of multi-storey timber structures

**Design of different structural typologies**

Post and beam

Portal frames

CLT structures

**Analysis methods:**

Linear static analysis

Linear dynamic analysis

# Robustness assessment of multi-storey timber structures

**Application of the robustness framework**

Compare redundancy and ductility levels of different systems.

Which structural topologies lead to high robustness?

Which exposures have more influence on this classification?

Evaluate the correlation between seismic behaviour and robustness.

**Propose guidelines to design robust timber buildings.**