New methods for the seismic safety assessment of existing buildings in the context of Eurocode 8 – Part 3

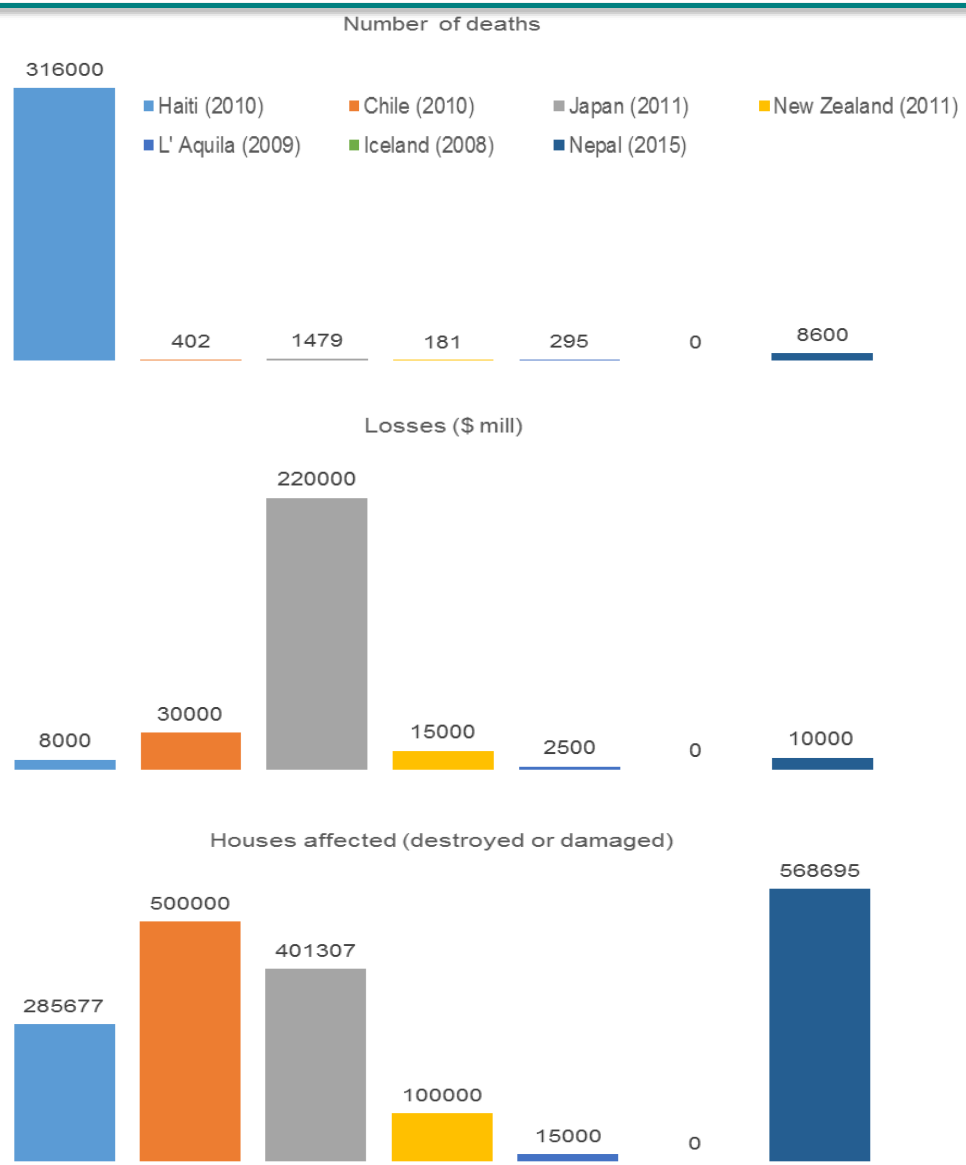
Analysis of the critical angle of seismic excitation

Author:
Despoina Skoulidou, F.E.U.P

Supervisor:
Xavier Romão, F.E.U.P

Thessaloniki, 1978

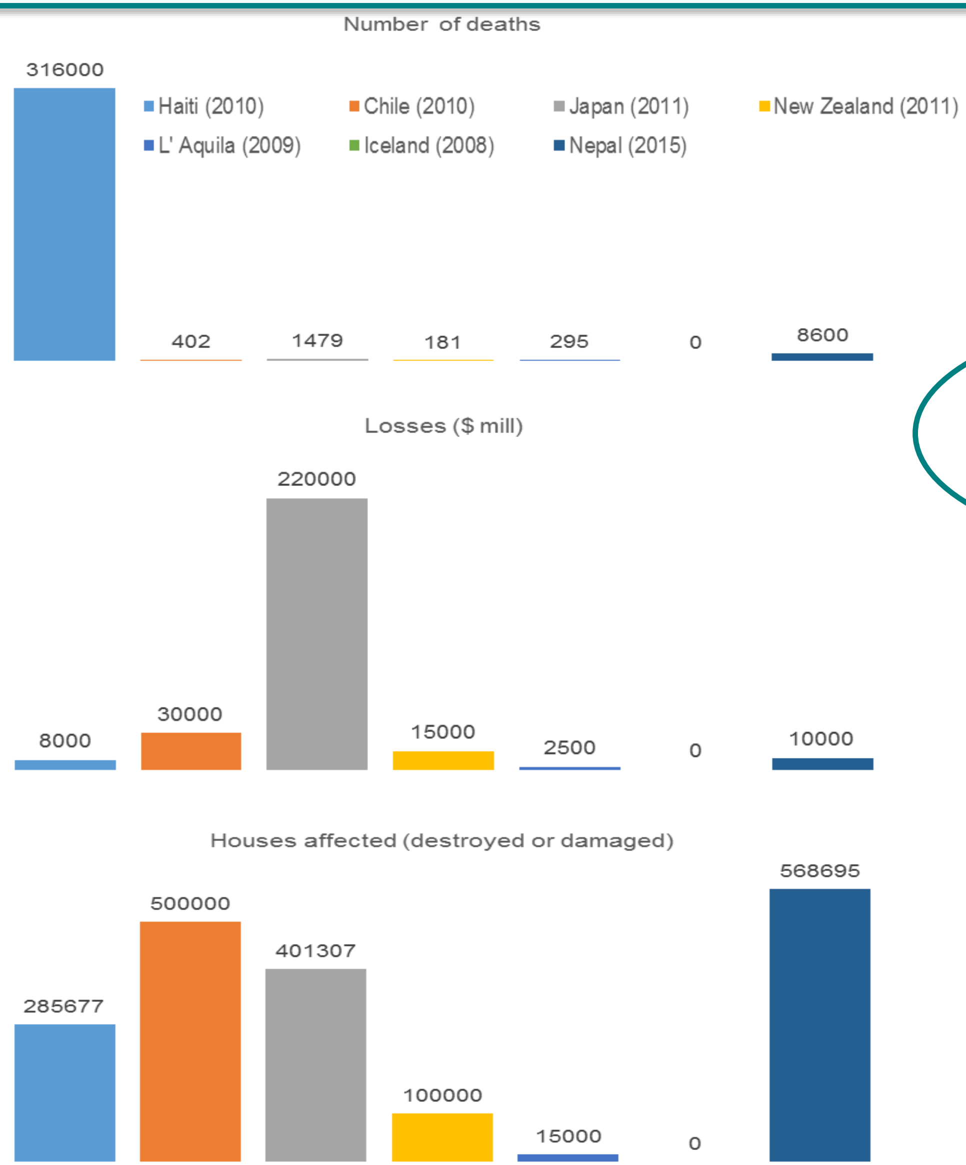
Scope



Consequences caused by different hazards depend on:

- Characteristics of the hazard
- Location
- Exposed assets

Scope



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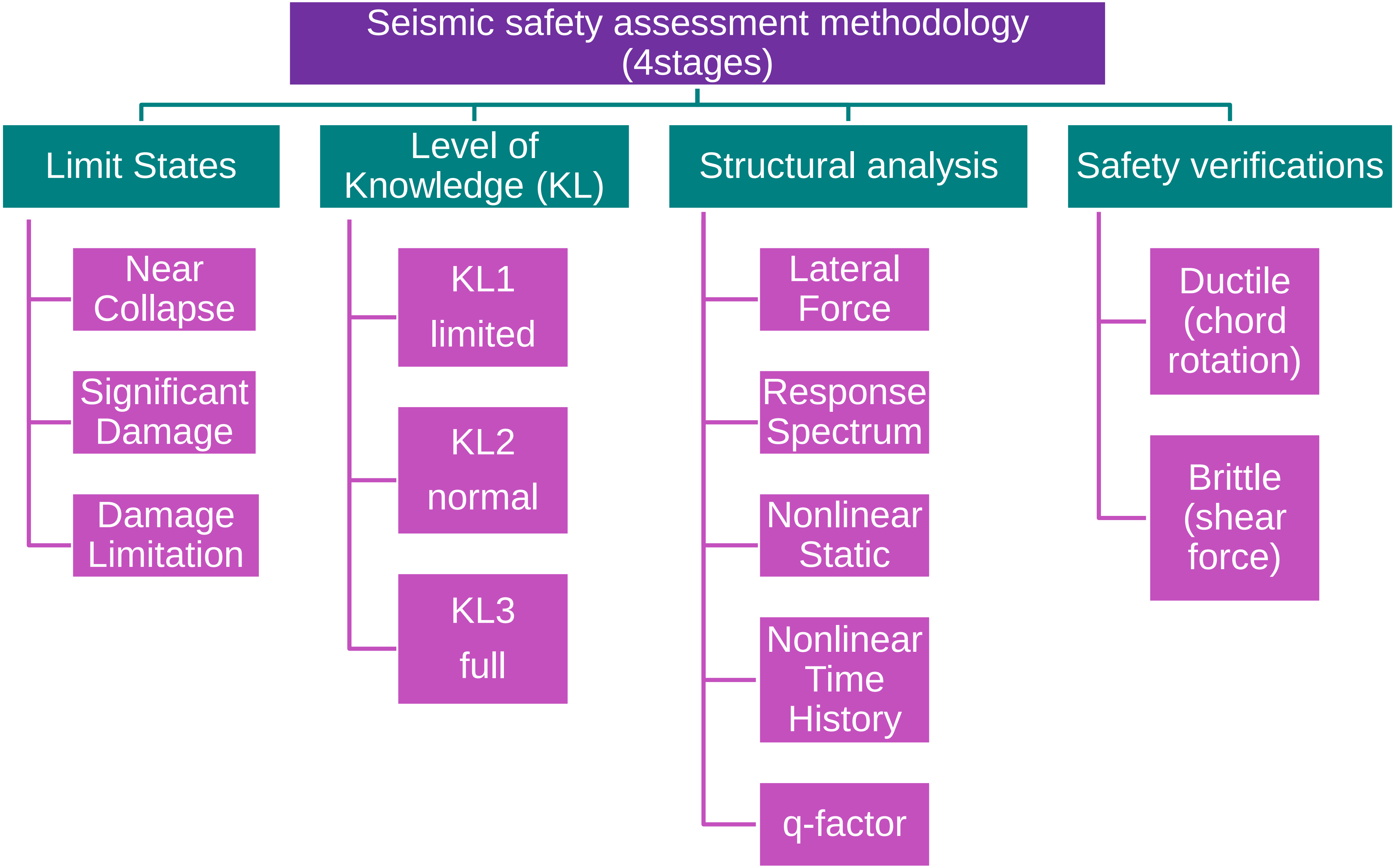
Standards for seismic safety assessment and retrofit of structures started being drafted

Safety Assessment Procedure according to EC8 part 3



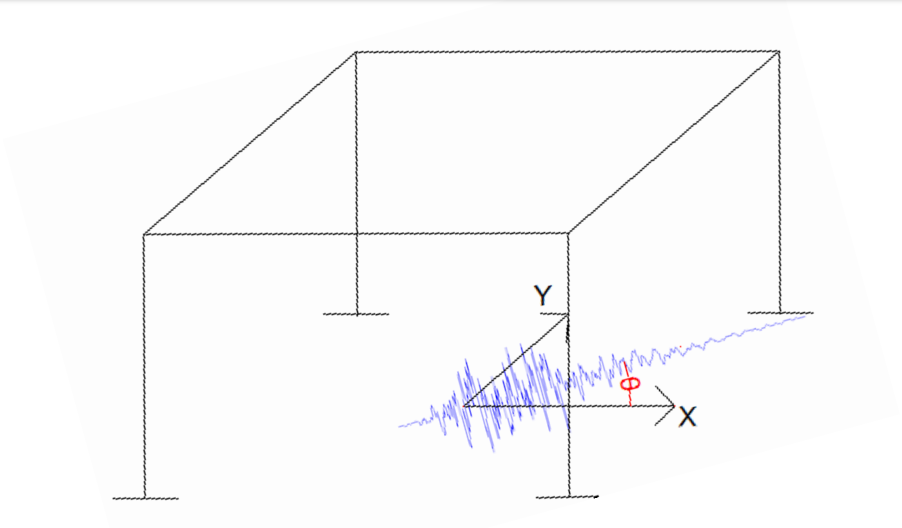
Safety Assessment Procedure according to EC8 part 3

Seismic safety assessment methodology (4stages)

- **Limit States**
  - Near Collapse
  - Significant Damage
  - Damage Limitation
- **Level of Knowledge (KL)**
  - KL1 limited
  - KL2 normal
  - KL3 full
- **Structural analysis**
  - Lateral Force
  - Response Spectrum
  - Nonlinear Static
  - Nonlinear Time History
  - q-factor
- **Safety verifications**
  - Ductile (chord rotation)
  - Brittle (shear force)

3rd Stage - Structural Analysis: Angle of Seismic Incidence

3D model when the structure is non conforming with the in-plan regularity criteria
(EC8-1 (§ 4.2.3.2))



Angle of incidence, θ

3rd Stage - Structural Analysis: Angle of Seismic Incidence

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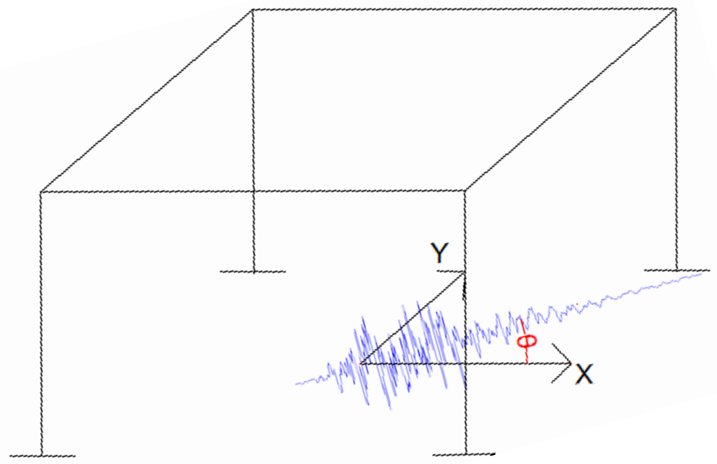

Angle of incidence, θ

EC8 provisions:

- Angle that leads to the highest demand (critical angle of incidence)

  How to calculate ?

- Structures with force resisting elements along two perpendicular directions (X and Y), loading along those directions.

  Highest demand ?

3rd Stage - Structural Analysis: Angle of Seismic Incidence

Critical Angle of Incidence?

- No provisions exist on how to calculate the critical angle
- Each structure has different critical angles
- The demand parameters do not obtain their maximum values simultaneously
- Different ground motions lead to different critical angles
- In NL analysis the critical angle depends on intensity and design
- The orientation of the ground motion affects the critical angle

3rd Stage - Structural Analysis: Angle of Seismic Incidence

Application along the structural axes?

- For all methods of analysis the structural demand in underestimated
- Unconservative results

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- For all methods of analysis the structural demand in underestimated
- Unconservative results

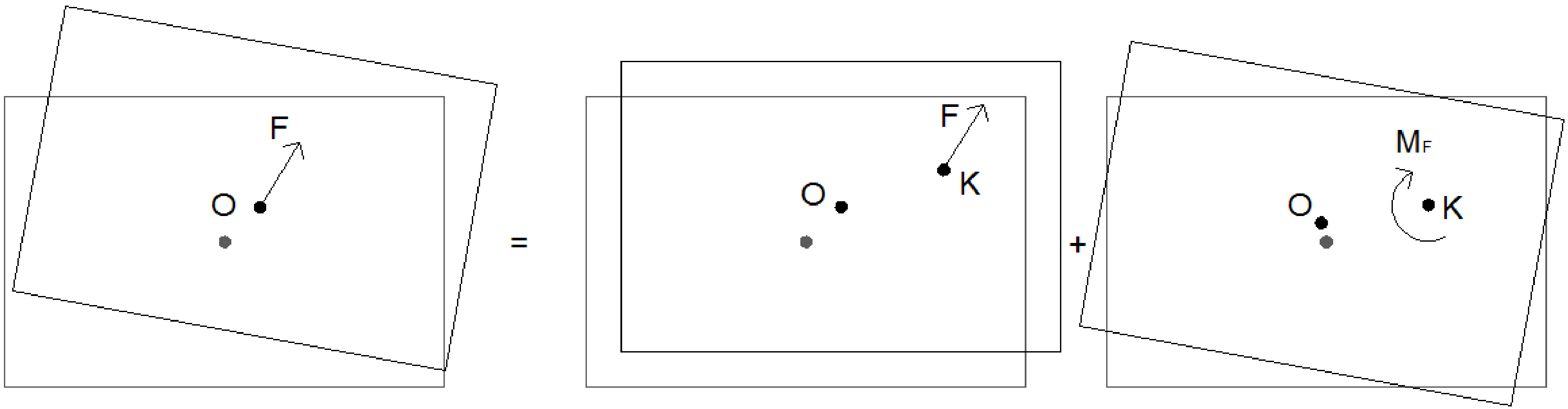
!! As a result..

Necessary to define methods to take into consideration the critical angle of incidence in a robust way

Static behaviour of single storey buildings

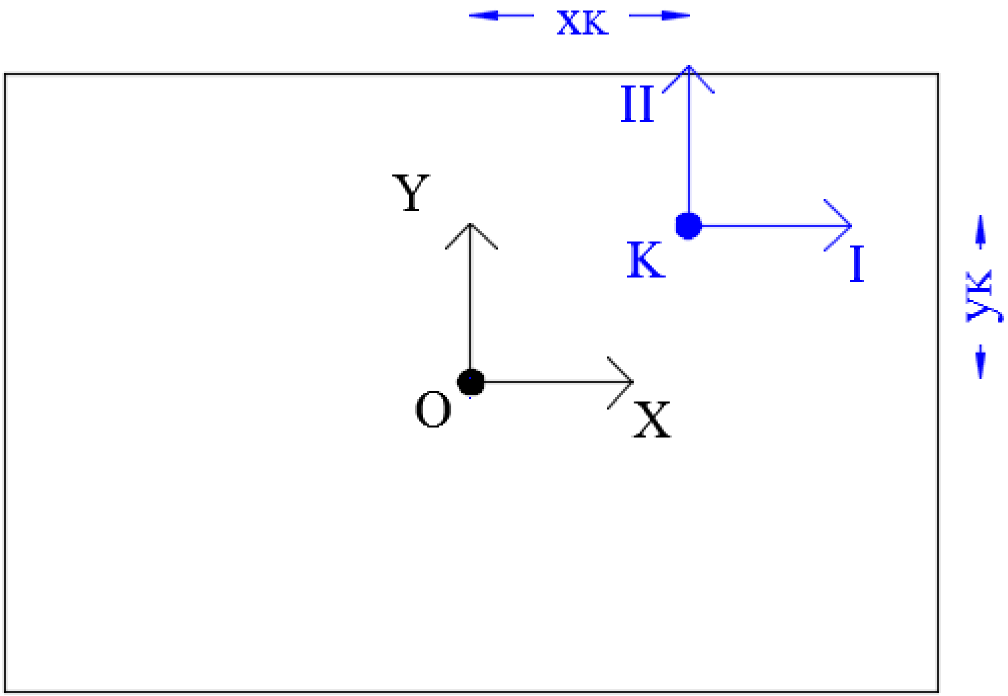
Structural characteristics:

- Material mechanical behaviour: Linear elastic
- Floor in-plane rigid and out-of-plane flexible
- Vertical elements are axially rigid



Overall displacement | Purely translational | Purely rotational

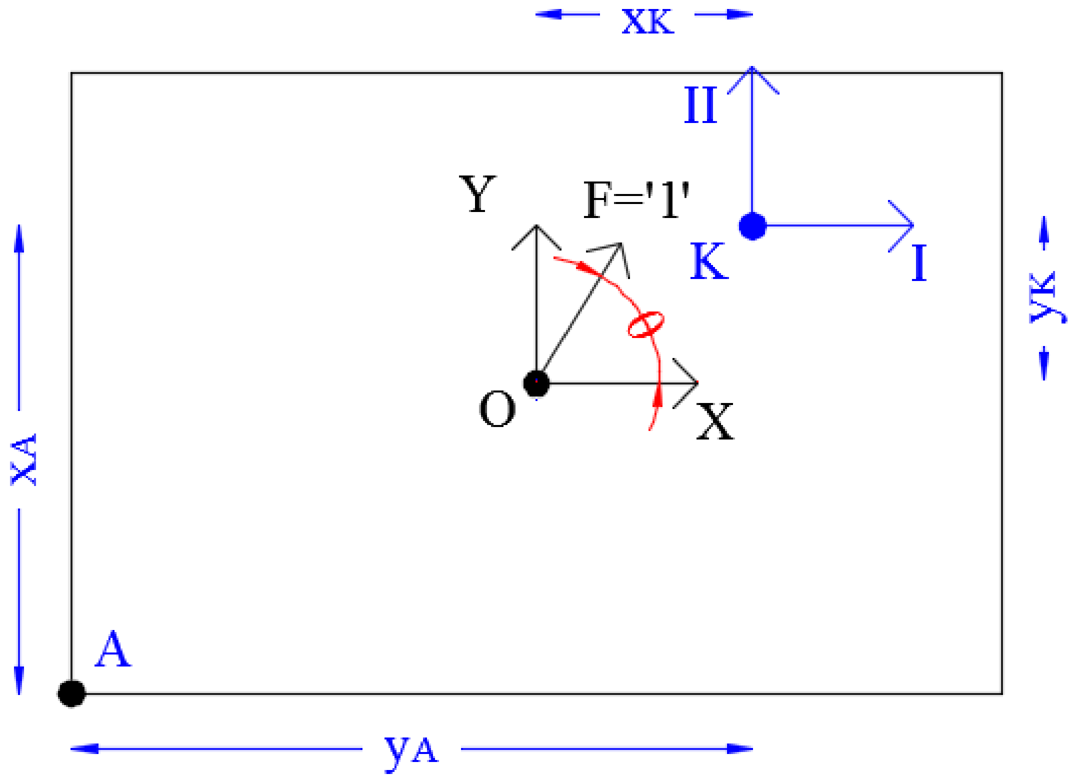
Critical angle of incidence in single storey buildings



$$\underline{K}_{I,II,III} = \begin{bmatrix} K_I & 0 & 0 \\ 0 & K_{II} & 0 \\ 0 & 0 & K_{III} \end{bmatrix}$$

- Elastic centre K
- Principal axes I, II, III

Critical angle of incidence in single storey buildings



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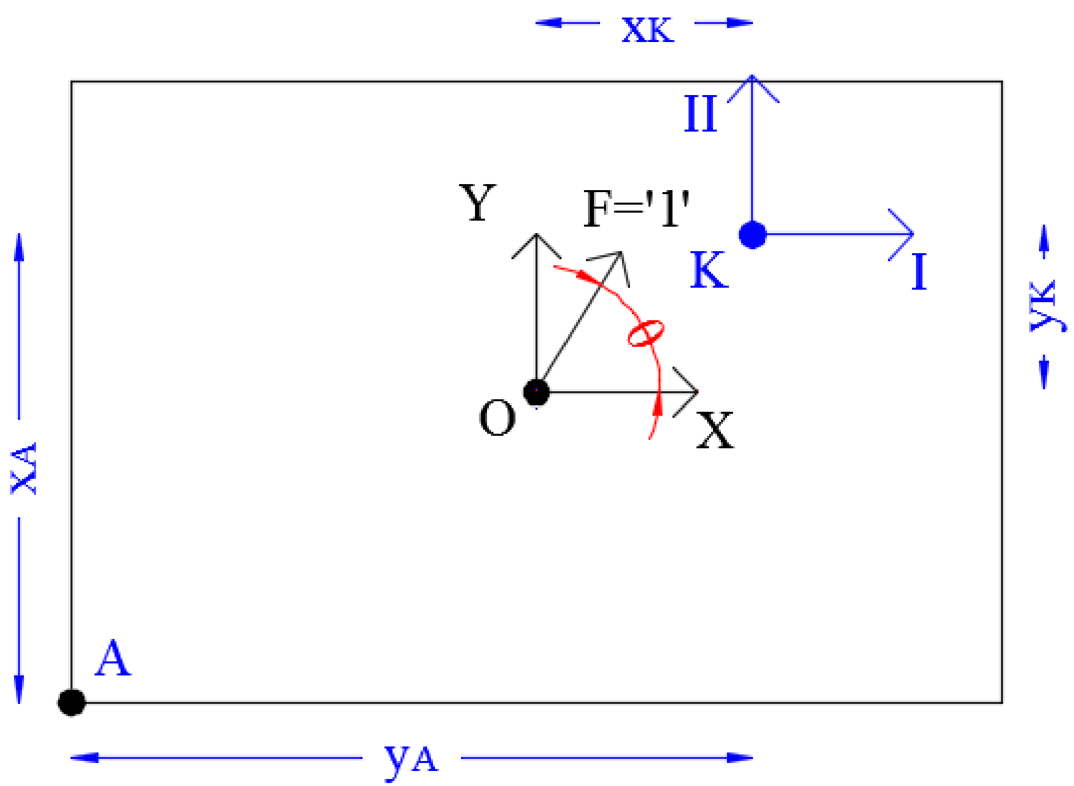
$$u_A = \sqrt{\left(\frac{\cos(\theta)}{K_I} - y_A \frac{(\cos(\theta)\cdot y_K - \sin(\theta)\cdot x_K)}{K_{III}}\right)^2 + \left(\frac{\sin(\theta)}{K_{II}} + x_A \frac{(\cos(\theta)\cdot y_K - \sin(\theta)\cdot x_K)}{K_{III}}\right)^2}$$

Critical angle of incidence in single storey buildings



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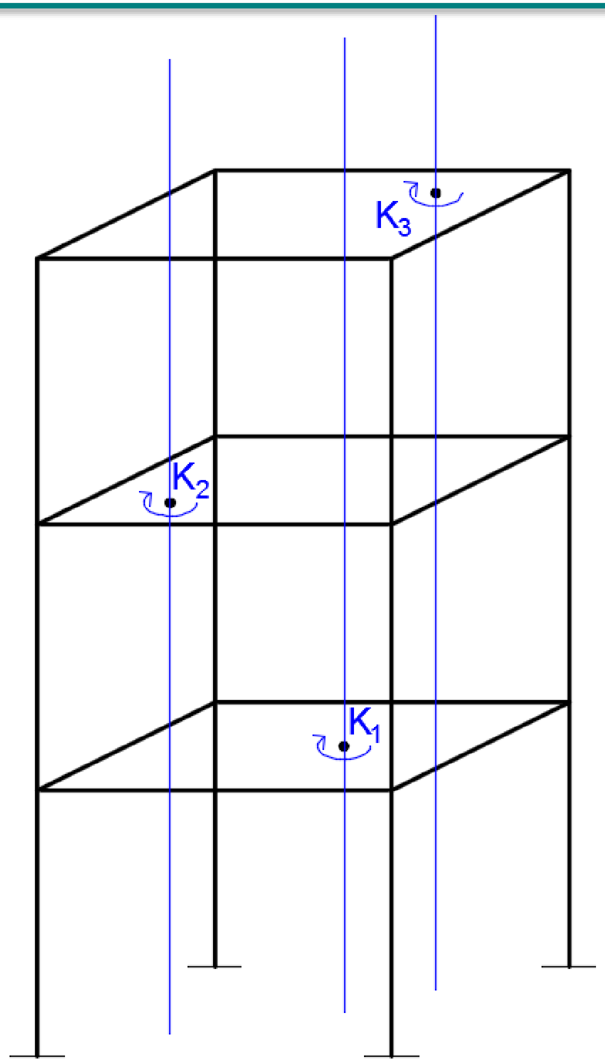
$$\frac{du_A}{d\theta} = 0 \rightarrow \theta_{crit}$$

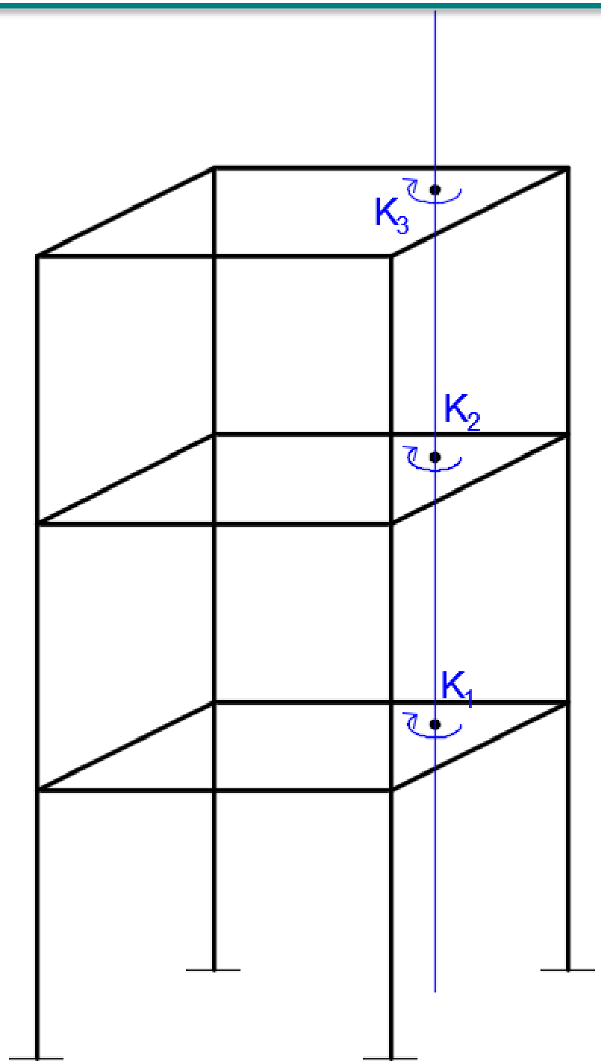
Static behaviour of multi-storey buildings



Building without an elastic axis

Multi-storey buildings generally do not possess an elastic axis or principal bending directions

Static behaviour of multi-storey buildings



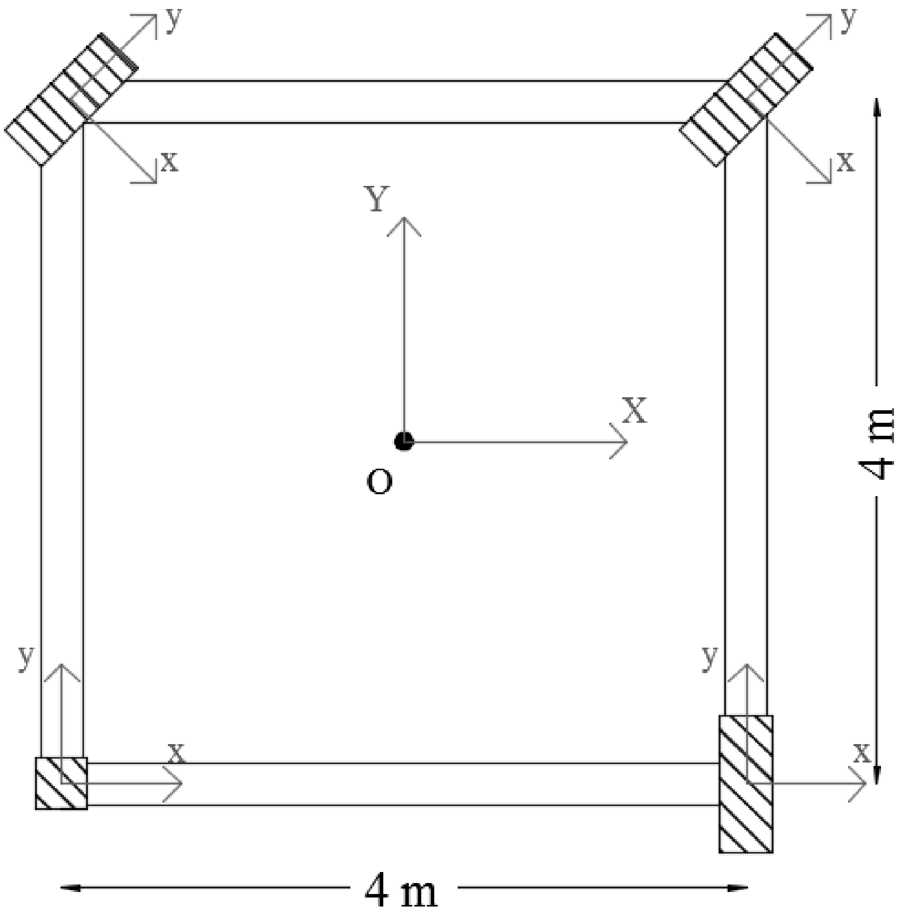
Building with an elastic axis

Multi-storey buildings generally do not possess an elastic axis or principal bending directions

Multi-storey buildings for which an elastic axis and principal bending directions can be defined are:

- Doubly symmetric
- Isotropic
- Ortho-isotropic
- Complex-isotropic (coaxial)

Numerical example of a single storey building



Plan view

Structural characteristics

- Height = 4 m
- E = 25 Gpa
- Material behaviour: linear elastic
- Rigid diaphragm
- Columns axially rigid

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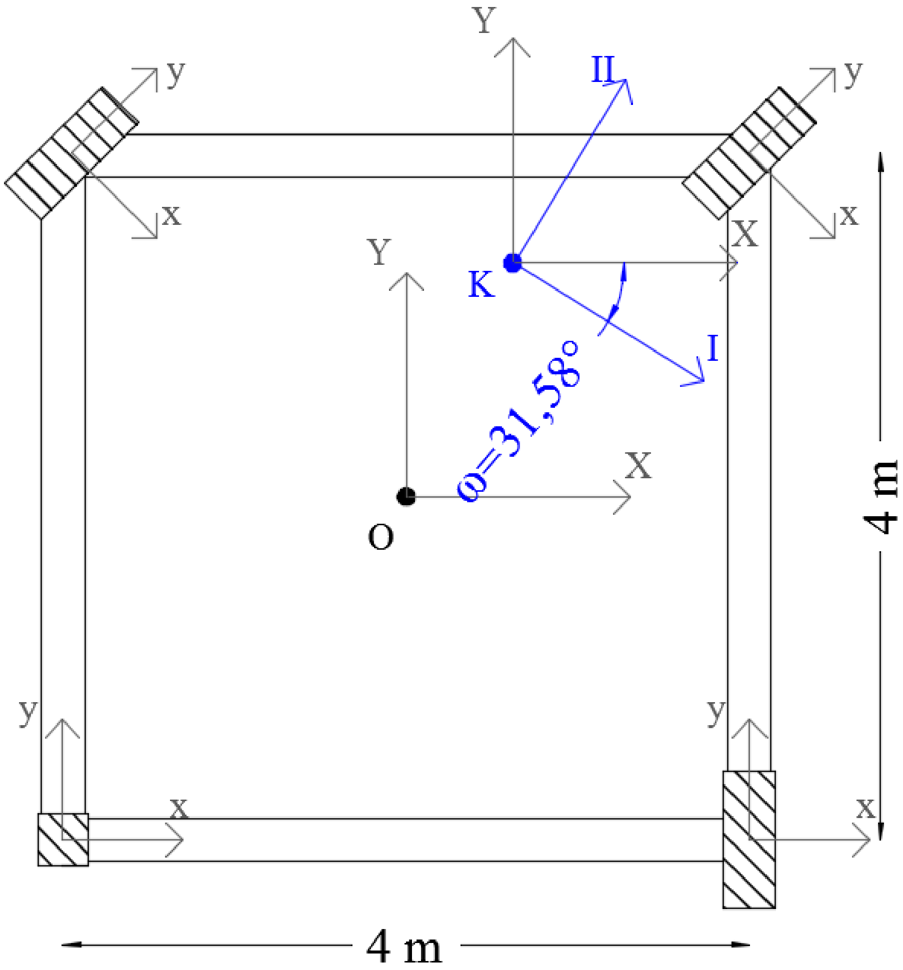

Plan view

Structural characteristics

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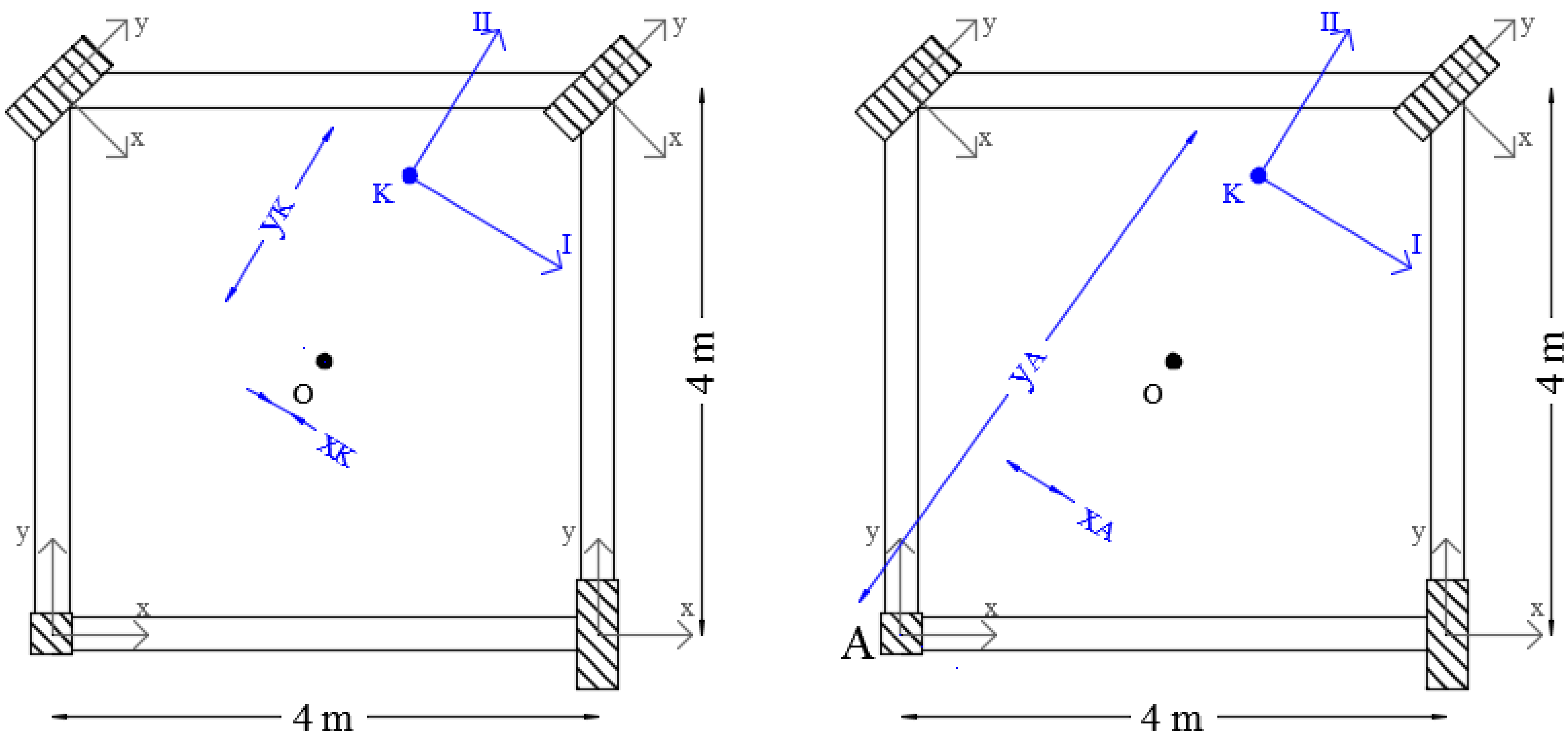
Principal system

- Elastic centre K
- Principal axes not parallel to global, but rotated by an angle ω

Parameters determined from the structure. Selection of A



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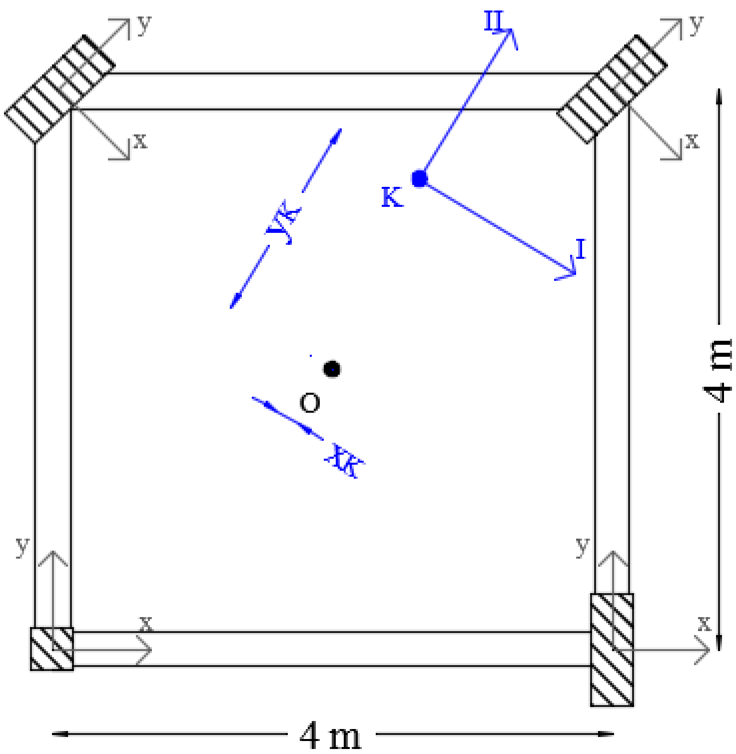
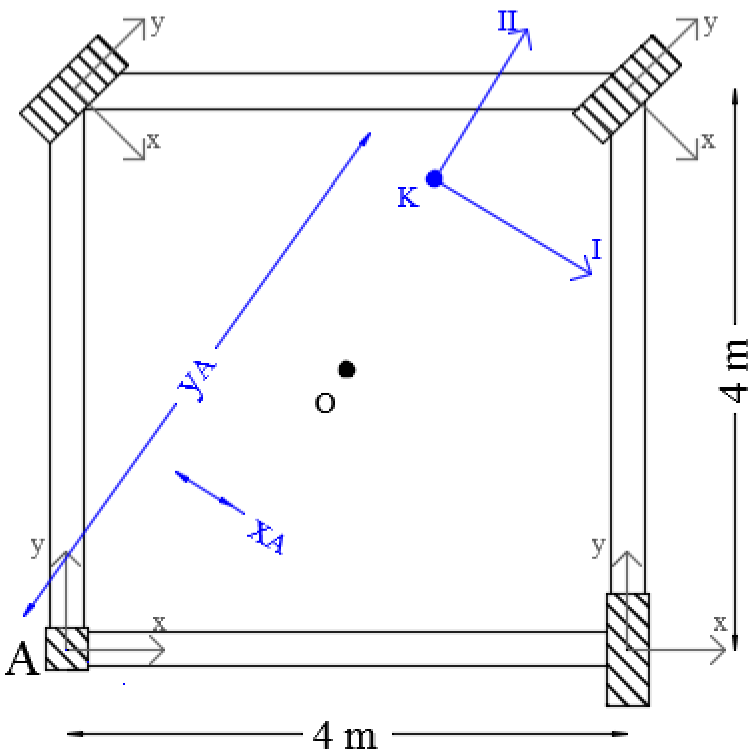
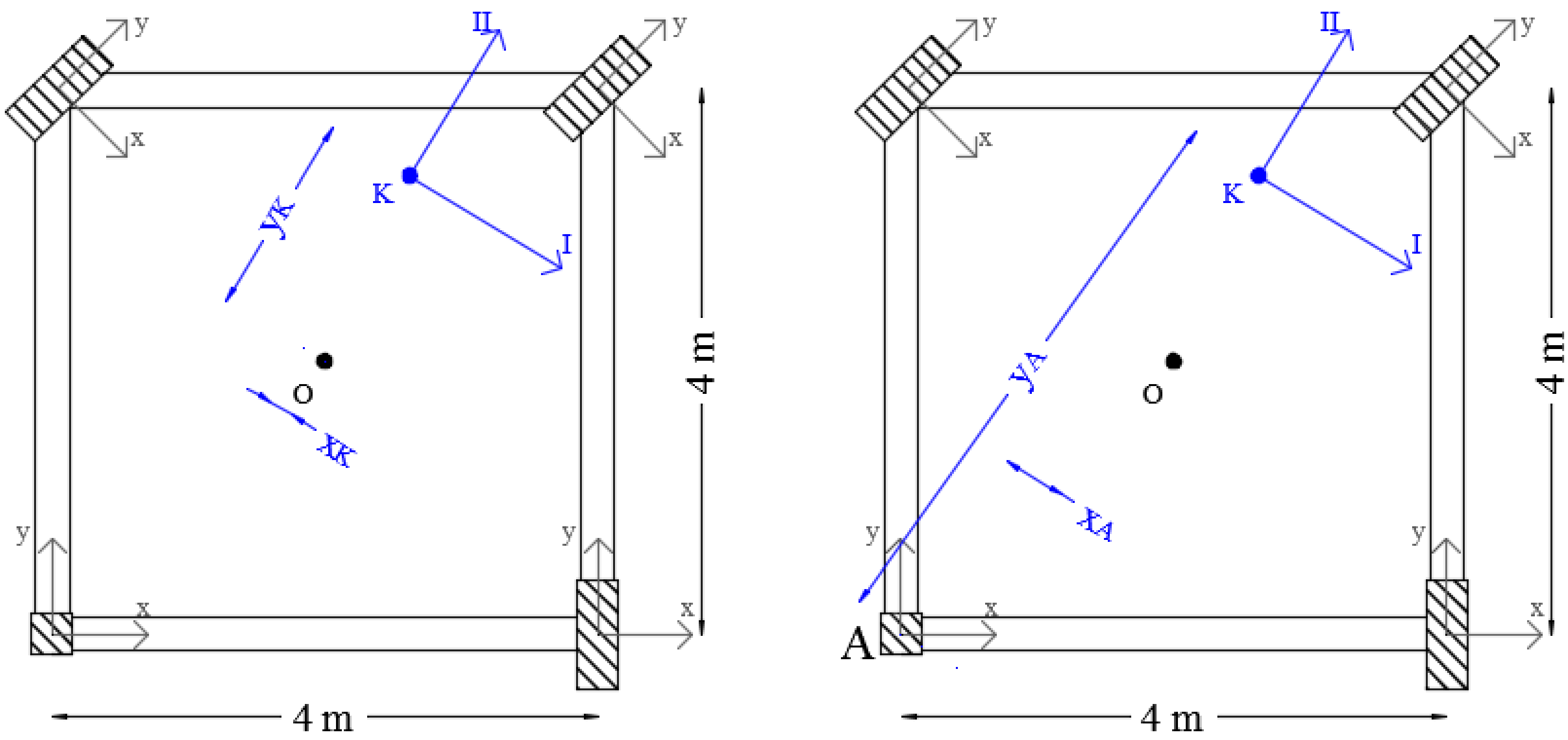




Critical angle of incidence in the principal reference system: θ’ = 182,3º

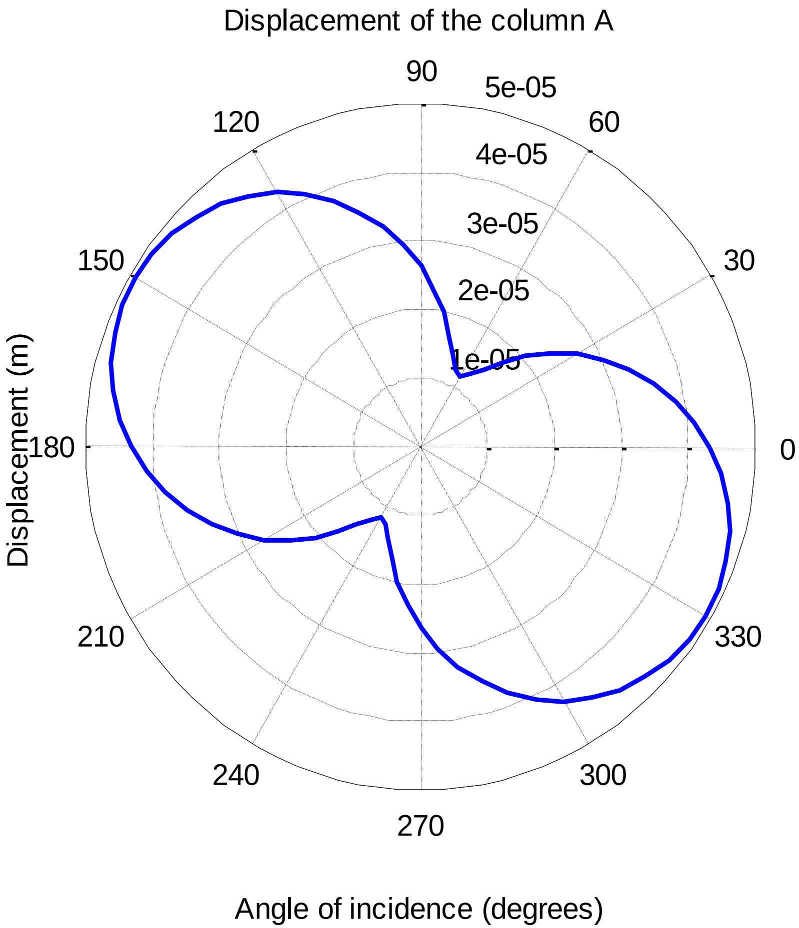
Parameters determined from the structure. Selection of A



Critical angle of incidence in the principal reference system: θ’ = 182,3º

Critical angle of incidence in the **global reference system**: θ = θ’ + ω = **150,7º**

Verification using parametric analysis



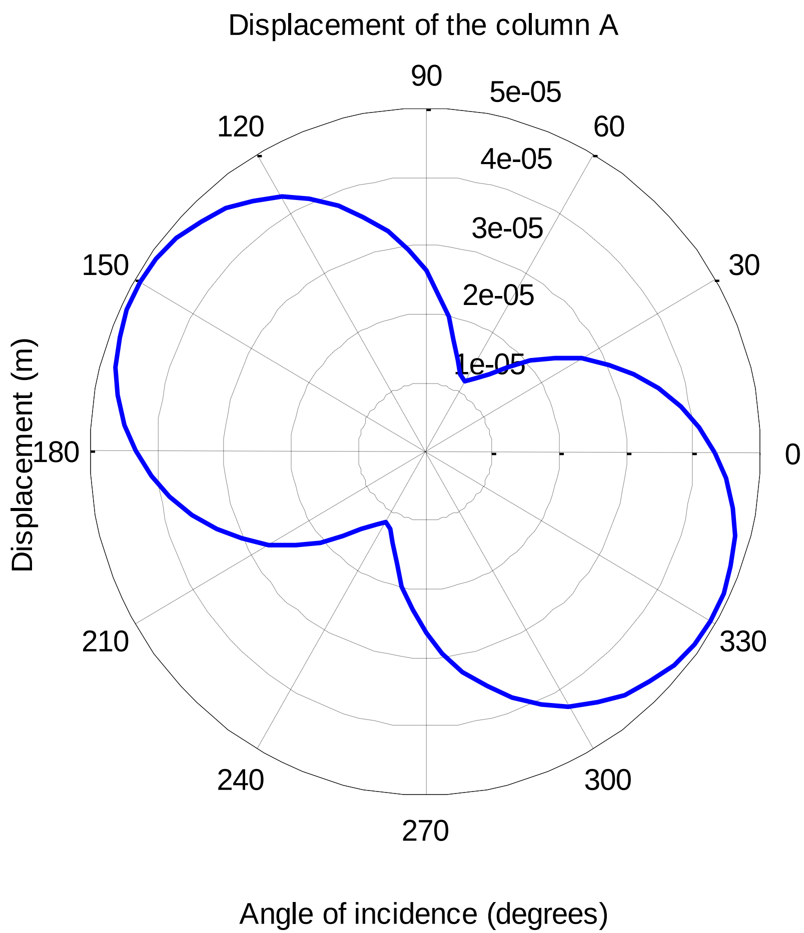
Parametric analysis (OpenSees)

Angle of incidence varies from 0º to 360º

Steps of 0.5º

Critical angle $\theta_{param.}$ = 150.5º

Verification using parametric analysis



Parametric analysis (OpenSees)

Angle of incidence varies from 0º to 360º

Steps of 0.5º

Critical angle $\theta_{param.} = 150.5^o$

Comparison:

$\theta_{anal.} = 150,7^o$

Results:

Very good approximation using analytical expression

Conclusions

- The angle of incidence is important, but difficult to take into account in a robust way
- Existing methods rely on preliminary analyses, parametric analysis, simulation techniques
- Standard provisions should be established both for design and assessment of structures

Conclusions

- It is possible to calculate the critical angle of incidence of the displacement in single storey and isotropic multi-storey buildings using analytical expressions

- The proposed expressions depend only on the mechanical and geometrical characteristics of the structure. Independent of the external static loads

- Similar expressions should be defined for other methods of analysis and material behaviour…

Research plans

- Determination of Global EDPs for 3D analysis
- Critical angle of incidence for various analysis methods (static, dynamic)..
- ..and material behaviour (linear, nonlinear)
- Methods to implement the procedures in guidelines