# **Second Generation of Eurocode 8**

# Webinar 1-1.3: Modelling, analysis and verification rules

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    - 6.4 Linear elastic analysis for force-based approach
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    - 6.7 Verification to limit states

# 6.1 General

- EC8 defines two (three) approaches for earthquake-resistant design
- Force-based approach
  - Linear elastic analysis (Lateral force method, Response spectrum method)
  - Approximately accounts for the overstrength and the non-linear response through a behaviour factor q
  - May be used for (also historically) verification to significant damage (SD) limit state
  - May be used for the verification to DL and OP limit states, using q=1
  - Design displacement obtained from the seismic analysis, but multiplied by q<sub>disp</sub>

# 6.1 General

- Displacement-based approach (usually termed as performance-based approach)
  - Implemented through a non-linear static analysis (pushover analysis)
  - Explicitly accounts for the structural non-linear behaviour
  - The design displacements are directly obtained from the analysis based on:
    - R-µ-T relationship (Fajfar, 2000)
    - Non-linear response history analysis of SDOF model (Annex E)
- Verification rule:
  - Action effects should not exceed the resistance
  - Force-based approach: generalised forces at the member level
  - Displacement-based approach: generalised deformation or forces

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# 6.2 Modelling

#### Modelling rules are mainly descriptive

- It is expected that engineer has adequate knowledge on modelling (challenging in the case of nonlinear analysis)
- General:
  - The model of the structure should be adequate (stiffness, mass, damping, strength, deformation capacity)
    - Details are provided in relevant parts of EN 1998 or other ENs
  - Member properties should be based on the mean values of the properties of material
  - Ancillary elements which may influence the seismic response should be accounted in the model for seismic analysis (AE: not considered as load carrying element but causes risk to person or structure in the case of earthquake)
  - Influence of adjacent structures should be considered

# 6.2 Modelling

#### Additional rules for linear analysis

- Elastic stiffness should be equal to secant effective stiffness that correspond to the elastic limits of the structural member
- SSI should be taken into account in the case of adverse effect (EN1998-5)
- Additional rules for non-linear analysis
  - Minimum: a bilinear force-deformation (also elasto-plastic) relationship at the member level
  - Trilinear force-deformation relationships may be used (RC, RM structures)
  - Deformation capacity: Cyclic degradation should be considered. Strength deterioration should be included if expected.
  - Bending: Consider axial and shear forces for force-deformation relationship
  - Consider hysteretic behaviour in the case of response history analysis

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#### 6.4 Seismic analysis: Force-based approach

- Reduced (design) spectrum
  - Ductility classes
    - DC1 accounts only for overstrength
    - DC2 accounts for local overstrength capacity, deformation capacity and energy dissipation capacity.
    - DC3 in addition to above, accounts for the ability to form global plastic mechanism at SD limit state
  - Behaviour factor:  $q=q_Rq_Sq_D$ 
    - R: overstrength due to the redistribution of seismic action effects in redundant structures (1.0)
    - S: overstrength due to all other sources (1.5)
    - D: deformation capacity and energy dissipation capacity (>1 for DC2)
  - One ductility class per building but  $q_D$  can be different in horizontal directions



#### 6.4 Seismic analysis: Force-based approach

- Reduced spectrum
  - The concept is the same as in the current EC8, but formulas are different
  - For horizontal components:

$$S_{\mathrm{r}}(T) = \frac{S_{\mathrm{e}}(T)}{R_{\mathrm{q}}(T)} \ge \beta S_{\alpha,475}(T)$$

- *β*=0.08
- The reduction factor for PGA is  $q_R q_S$ , while for  $S_e(T>T_B)$  the  $R_q(T)=q$
- For vertical components:

$$S_{\rm vr}(T) = \frac{S_{\rm ve}(T)}{q_{\rm v}}$$

•  $q_v = q_s = 1.5$ . Greater values should be justified based on analysis



#### 6.4 Seismic analysis: Force-based approach

#### Lateral force method

- Basically the same as in the case of current EC8
- Rayleigh formula for period of the fundamental mode (EC8-1-2)
- Response spectrum method
  - Residual mode is introduced
  - Combination of modal responses is explicitly defined by formulas (SRSS, CQC)
- Displacements
  - Based on displacement from analysis and behaviour factor for displacements
- Combination of the effects of the components of the seismic action
  - SRSS rule
  - 100–30 rules

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# 6.5 Seismic analysis: Non-linear static analysis

- Theoretical background of pushover-based method
- EC8: 6.5 Nonlinear-static analysis
  - General
  - Lateral loads
  - Capacity diagram
  - Equivalent SDOF model
  - Target displacement
  - Annex E



Theoretical background of nonlinear-static seismic analysis (pushover-based seismic analysis)

- General description of the problem:
  - Equation of motion at level of structure (for relative kinematic quantities)
  - System of *n* dependent non-homogeneous second-order differential equations with nonlinear coefficients

```
\mathbf{M}\,\ddot{\mathbf{U}} + \mathbf{C}\,\dot{\mathbf{U}} + \mathbf{K}\,\mathbf{U} = -\mathbf{M}\,\ddot{\mathbf{U}}_{\mathbf{g}}
```

- Simultaneously addressing interaction between seismic demand and seismic capacity
- Too complex for practical applications



Theoretical background of nonlinear-static seismic analysis (pushover-based seismic analysis)

- Assumptions:
  - the shape of displacement vector  $\, U \,$  is independent of time
  - ground motion in one direction only
- Consequence: the equation of motion is simplified to a SDOF model

$$m_* \ddot{u}_* + c_* \dot{u}_* + k_* u_* = -m_* \ddot{u}_g$$

- 1 non-homogeneous second-order differential equations with nonlinear coefficients
- often solved indirectly by R-μ-T relationship (classic N2 method, Fajfar, 2000)
- can be solved directly by numerical integration (e.g. Dolšek, 2015)
- both options are foreseen in Eurocode 8



Theoretical background of nonlinear-static seismic analysis (pushover-based seismic analysis)





### 6.5 Seismic analysis: Non-linear static analysis

- Theoretical background of pushover-based method
- Eurocode 8-1-1: Section 6.5
  - General
  - Lateral loads
  - Capacity diagram
  - Equivalent SDOF model
  - Target displacement
  - Annex E

# 6.5 Nonlinear-static analysis: General

Use of the non-linear static analysis method

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 Lateral loads
 Capacity diagram
 Equivalent SDOF model
 Target displacement
 Annex E

- to verify the structural performance of newly designed structures
- to assess the structural performance of existing or retrofitted structures as specified in EN 1998-3 for buildings and bridges
- to verify the structural performance of newly designed bridges as specified in EN 1998-2
- In conjunction with EN 1998-5
- NOTE 2 The method is not meaningful for structures not exhibiting a globally ductile behaviour (e.g. tanks).
- NOTE 3 Multi-mode methods exist, where multiple pushover analyses are carried with different force distributions and multiple equivalent SDOF models are established.



• Treatment of the assumptions



- Seismic action effects in the structure and structural members should be for defined structures corrected by factors, which take into account:
  - the effects of higher modes, torsion, minimum eccentricity (correction factors  $C_P$ ,  $C_E$ )
  - and the combination of the horizontal components of the seismic action
- When pushover analysis is carried out for assessing an existing structure, the model for the deformation capacity should account for cyclic degradation of structural members.

# 6.5 Nonlinear-static analysis: Lateral loads and capacity curve

Lateral forces for pushover analysis should be defined for each horizontal direction seismic action

(2) At least a "modal" pattern of lateral forces should be applied

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$$\overline{F}_{i} = m_{i}\phi_{i}$$

$$F_{\rm b} = \sum F_{\rm i} = \alpha \sum \overline{F}_{\rm i}$$

(4) The control displacement  $d_n$ 

• EC8: Section 6.5



Capacity diagram
Equivalent SDOF model
Target displacement
Annex E

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(5) The capacity curve, the  $F_B - d_n$  relationship for multi-degree-of-freedom (MDOF) structure, should be determined by a pushover analysis.

(6) Pushover analysis should continue to  $d_{\nu}$ , i.e. until the ultimate local deformation in a ductile post-elastic mechanism, or to brittle failure or instability when this occurs first.

NOTE Procedures to calculate the deformation at yield, the ultimate deformations and the resistance to brittle failure or instabilities in members are given in 7 and in the relevant parts of EN 1998.

#### 6.5 Nonlinear-static analysis: Equivalent SDOF model

SDOF (R-
$$\mu$$
-T)  $u_* = d_t^* = f(S_e(T^*), S_y, d_{et}^*, T^*)$   $\mathcal{M}_* i$ 

$$m_* \ddot{u}_* + c_* \dot{u}_* + k_* u_* = -m_* \ddot{u}_g$$

• Equivalent mass

 $m^* = \sum m_i \phi_i$ 

• Force-displacement relationship

$$F^* = \frac{F_{\rm b}}{\Gamma} \quad d^* = \frac{d_{\rm n}}{\Gamma \phi_{\rm n}} \qquad \Gamma = \frac{m^*}{\sum m_{\rm i} \phi_{\rm i}^2}$$

• Bilinear (also elasto-plastic) idealisation



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# 6.5 Nonlinear-static analysis: Target displacement

**SDOF (R-µ-T)** 
$$u_* \equiv d_t^* = f(S_e(T^*), S_y, d_{et}^*, T^*)$$

- EC8: Section 6.5
  - General
  - Lateral loads
  - Capacity diagram
  - Equivalent SDOF model

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- Target displacement
- Annex E

- Equal displacement rule:  $T^* \ge T_{\rm C}$   $d^*_{\rm t} = d^*_{\rm et} = S_{\rm De}(T^*)$
- Proxy for inelastic  $T^* < T_C$   $d_t^* = \min\left\{3; \frac{1}{u}\left[1 + (u-1)\frac{T_C}{T^*}\right]\right\} d_{et}^*, \quad u = \frac{S_e(T^*)}{S_y}$  displacement:
- Amplification of the target displacement:

$$c_{\rm dt} = \sqrt{1 + \left(\frac{\Gamma'}{\Gamma}\right)^2}$$





- Annex E gives procedure for the determination of the target displacement using non-linear response-history analysis
  - Generalised SDOF model based on multi-linear force-displacement relationship
  - Target displacement using non-linear response history analysis
  - Limit-state spectral acceleration using non-linear response history analysis

# 6.5 Nonlinear-static analysis: Target displacement (Annex E)

SDOF (non-linear, dynamic)  
$$m_* \ddot{u}_* + c_* \dot{u}_* + k_* u_* = -m_* \ddot{u}_g$$

Generalised SDOF model:

- Multi-linear force-displacement relationship
- Rules for the idealisation of the pushover curve
- The damping coefficient is defined (not the model)
- Hysteretic behaviour should reflect the response of the entire structure (no cyclic strength deterioration)



- General
- Lateral loads
- Capacity diagram
- Equivalent SDOF model

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- Target displacement
- Annex E





# 6.5 Nonlinear-static analysis: Target displacement (Annex E)

SDOF (non-linear, dynamic)  
$$m_* \ddot{u}_* + c_* \dot{u}_* + k_* u_* = -m_* \ddot{u}_g$$

Determination of target displacement:

- Accelerograms should be selected according to Annex D
- Not less than 15 accelerograms
- Target displacement is the mean of log values of max. displacements

$$u_* \equiv d_{t}^* = \exp\left(\frac{1}{N_a}\sum_{i=1}^{N_a} ln(d_{t,i}^*)\right)$$

• EC8: Section 6.5

- General
- Lateral loads
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- Equivalent SDOF model

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- Target displacement
- Annex E



Limit-state spectral acceleration:

- It can be obtained by IDA
- $S_{e,LS}$  is calculated as the mean of log values of limit-state spectral accelerations
- The S<sub>e,LS</sub> can be increased due to inconsistency between target spectrum for selection of accelerograms and conditional spectrum

$$S_{e,LS} = \exp\left(\frac{1}{N_a}\sum_{i=1}^{N_a} ln(S_{e,LS,i})\right)$$

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6.5 Non-linear static analysis for displacement-based approach (performancebased)

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- 6.7 Verification to limit states



# 6.7 Verification to limit states

- General:
  - The action effects shall not exceed the corresponding resistance for all structural members including connections and ancillary elements



- Force-based approach: may be used for verification of SD limit state, DL and OP limit state (using q=1)
- Overall stability: overturning, sliding



# 6.7 Verification to limit states

#### • Displacement-based approach, SD limit state

- $E_d$  from nonlinear static method (corrected due to irregularity in elevation and torsion, effect of both components of seismic action)
- R<sub>d</sub> based on model of ultimate deformations (Section 7 of EC8), verification of mechanisms based on forces

$$\delta_{\rm SD} = \frac{1}{\gamma_{\rm Rd,SD,\theta}} \left( \delta_{\rm y} + \alpha_{\rm SD,\theta} \delta_{\rm u}^{pl} \right) \qquad V_{\rm R,SD} = \frac{V_{\rm R}}{\gamma_{\rm Rd,SD,V}}$$

•  $R_d$  based on displacement of the equivalent SDOF model

$$d_{\mathrm{SD}}^* = \frac{1}{\gamma_{\mathrm{Rd},\mathrm{SD},\mathrm{d}}} \left[ d_{\mathrm{y}}^* + \alpha_{\mathrm{SD},\mathrm{d}} (d_{\mathrm{u}}^* - d_{\mathrm{y}}^*) \right]$$

• Foundation and soil are able to resists the  $E_d$  without substantial permanent deformation (EN1998-5)



# 6.7 Verification to limit states (Annex F)

- Annex F (Informative): Simplified reliability-based verification format
  - Provides a basis for measuring performance of structures in probabilistic terms



$$P_{\rm LS} = \int_0^\infty P(LS|S_{\rm e}) \left| \frac{\mathrm{d}H(S_{\rm e})}{\mathrm{d}S_{\rm e}} \right| \mathrm{d}S_{\rm e}$$
$$P_{\rm LS} = H(S_{\rm e,LS}) exp(0.5k^2\beta_{S_{\rm e,LS}}^2)$$

For CC2,  $P_{t,NC,CC2} = 2 \times 10^{-4}$  or defined in National Annex



#### Conclusions

- Modelling:
  - Not much changes
- Analysis:
  - Force-based design approach is similar as in the current EC8, ductility classes and behaviour factors are redefined
  - Displacement-based design (Performance-based design)
    - Correction factors for pushover-based method (elevation, plan, 2 components of horizontal actions)
    - Target displacement (Annex E)
- Verification rules:
  - New for displacement-based approach
  - Informative reliability-based verification format (Annex F)