Use of anti-seismic devices

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30th March 2022

Anti-seismic devices

- **Rigid Connection Device**
  (shock transmission units, guide and restraint bearings, mechanical fuses)

Section 6.8 of EN1998-1-1 covers the GENERAL ASPECTS for all type of anti-seismic devices and structures (buildings, bridges, tanks…)

ENERGY DISSIPATION DEVICES

- **Displacement-Dependent Device**
  (friction, hysteretic…)
- **Velocity-Dependent Device**
  (fluid viscous $F=Cv\uparrow\alpha\downarrow ve$, viscoelastic $F=Kd+Cv$...)

+ AUXILIARY ELEMENS OF ENERGY DISSIPATION SYSTEM + MAIN STRUCTURE = STRUCTURE EQUIPPED WITH ENERGY DISSIPATION SYSTEMS

- **Seismic Isolator**
  (elastomeric isolators, sliders…)

+ ENERGY DISSIPATION DEVICES + SUPERSTRUCTURE AND SUBSTRUCTURE = BASE ISOLATED STRUCTURE

BASIS OF DESIGN

- Increased reliability is required to **anti-seismic devices** and their **connections** (i.e. displacements, velocities increased by γ_X).
- Auxiliary elements of the energy dissipation system should remain elastic.
- The isolation system should present re-centring capability in both horizontal directions
- The isolation system should provide sufficient lateral restraint at the isolation interface to satisfy limitation of displacements/deformations.

MODELLING

- Multiple analysis should be conducted to bound the effects of varying properties of anti-seismic devices.

ANALYSIS METHODS

STRUCTURES WITH **FULL** ISOLATION

STRUCTURES WITH **PARTIAL** ISOLATION

STRUCTURES WITH ENERGY DISSIPATION SYSTEMS

- Fundamental-mode equivalent linear response-spectrum
- Multi-mode equivalent linear response-spectrum
- Response-history
- Multi-mode non-linear response-spectrum
- Energy-balance based

Fundamental-mode equivalent linear response-spectrum analysis*

STRUCTURES WITH FULL ISOLATION

- Superstructure and substructure in case of buildings, or the deck in case of bridges, are assumed rigid (rigid masses)
- The higher modes of superstructure/substructure are neglected
- The structure is assumed to respond predominantly as a SDOF system in each horizontal direction, but the torsional effects about a vertical axis are accounted for.
- The isolation system is modelled as an equivalent linear SDOF system with K_{eff} and $\xi_{eff} = 1/2\pi \left[\sum E_{D,i} / K_{eff} d_{Ed}^2 \right]$. Here, K_{eff} is obtained from the secant stiffness $k_{eff,i}$ of isolators in case of buildings, and also from the displacement stiffness of piers and translation/rotational stiffness of foundations in case of bridges. $E_{D,i}$ is the dissipated energy of each anti-seismic devices (isolator and EDDs). K_{eff} and ξ_{eff} depend on design displacement d_{bd} (iterations required).

*≈ simplified linear analysis in current EN1998-1

Multi-mode equivalent linear response-spectrum analysis*

STRUCTURES WITH FULL ISOLATION

- Superstructure/substructure represented by flexible elastic 3D model
- The higher modes of superstructure/substructure considered
- The response in the first modes involving deformations of the isolation system (i.e. affected by anti-seismic devices) is obtained representing the structure as an equivalent SDOF system with an effective period T_{eff}, and with an effective damping ξ_{eff} calculated with the $E_{D,i}$ dissipated by each anti-seismic device.
- The response in the higher modes not involving deformations of the isolation system (i.e. not affected by anti-seismic devices) are obtained with the ξ of a non-isolated structure.
- The response in each mode through response spectrum analysis.

*≈ full modal analysis in current EN1998-1

Response-history analysis

STRUCTURES WITH FULL OR PARTIAL ISOLATION

STRUCTURES WITH ENERGY DISSIPATION SYSTEMS

- Constitutive relationships of anti-seismic devices must adequately reproduce their behaviour in the range of deformations and velocities of the design seismic situation
- In structures on near-fault sites, each pair of horizontal input motion component should be rotated to the fault-normal and fault-parallel directions of the causative fault and applied to the model in such orientation
- The inherent damping ratio of the structure (i.e. before yielding) $\leq 3\,\%$

BUILDINGS WITH BASE ISOLATION- Chapter 8 of EN1998-1-2

- Chapter 8 provides additional (few) provisions for buildings with **full** base isolation
- **Additional conditions** are set for applying the **fundamental-mode equivalent linear response-spectrum analysis** in buildings, e.g.

$3T_f \leq T_{eff} \leq 3$; $K_V / K_{eff} \geq 150$; $T_V = 2\pi\sqrt{M/K_V} \leq 0.1 s$

- Seismic action effects on superstructure and substructure are calculated with *q=1.5*.

BRIDGES WITH ISOLATION- Chapter 8 of EN1998-2

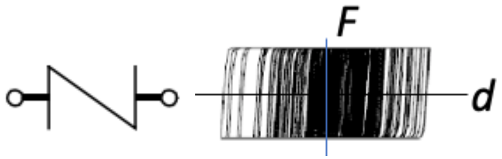
- Chapter 8 provides additional (few) provisions for bridges with full or partial isolation
- The superstructure (deck) should remain always elastic
- In case of full isolation, the substructure should be designed as non-dissipative (DC1; global and local ductility conditions neglected). Exception: for heavy piers in moderate or high seismicity regions DC2 is required.

BUILDINGS WITH ENERGY DISSIPATION SYSTEMS - Chapter 9 of EN1998-1-2

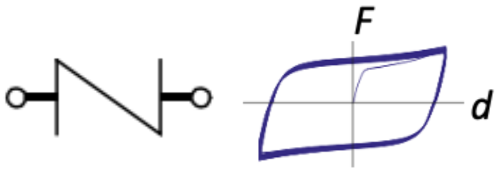
Two types of energy dissipation devices are considered:

- **Displacement-Dependent Devices with response controlled only by displacements**

  (a) devices with rigid-plastic behaviour (e.g. friction dampers)



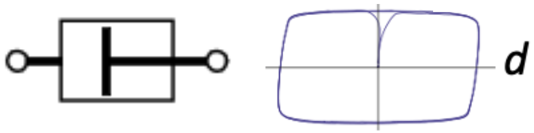
  (b) multilinear hysteresis (e.g. metallic dampers)



- **Velocity-Dependent Devices with response influenced by velocity**

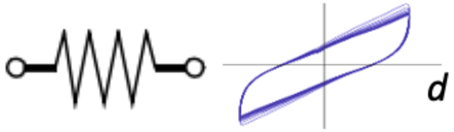
  (a) viscous (fluid) devices

$F = Cv^{\alpha_{ve}}$

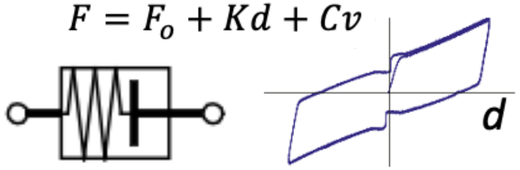


  (b) viscoelastic (solid or fluid) devices

$F = Kd + Cv$



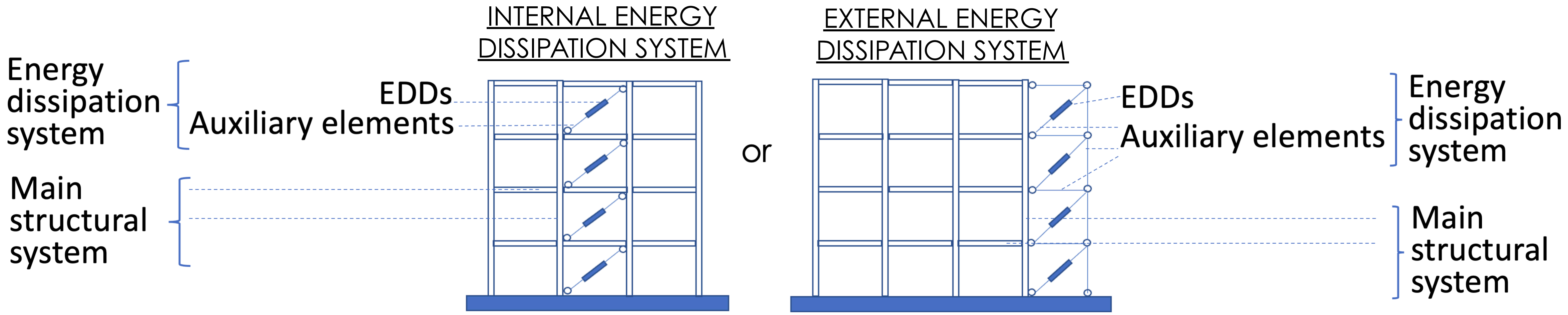
$F = F_o + Kd + Cv$



BASIS OF DESIGN

A building with energy dissipation systems is composed of two systems in parallel:

- **Main structural system** = primary + secondary structural elements
  Primary role: sustain gravity loading when subjected to lateral displacements
  Secondary (optional) role: contribute to energy dissipation through plastic strains
- **Energy dissipation system** = energy dissipation devices (EDD) + auxiliary elements
  Primary role: dissipate most of the energy input by the earthquake
  Secondary (compulsory) role: transfer the forces from EDDs to main structural system



MAIN REQUIREMENTS / VERIFICATIONS

Main structural system:

The energy that the primary seismic members of the main structural system at the k-th storey **can** dissipate before reaching the SD limit state	≥	The maximum energy dissipation **demand** on the primary seismic members of the main structural system at the k-th storey under the design seismic action.

Energy dissipation system:

The energy that the dampers at the k-th storey **can** dissipate before one of them reaches the SD limit state	≥	The maximum energy dissipation **demand** on the dampers at the k-th storey under the reference seismic action

These main verifications are done using TWO DIFFERENT ANALYSIS METHODS:

BUILDINGS WITH VELOCITY-DEPENDENT EDDs

- with floor diafragms that are rigid in their plane
- with ≥2 EDDs in each direcction and each story arranged to provide torsional sitffness/resistance
- same type of EDD, α_{ve} , η_{loss} in all stories

→ **NON-LINEAR RESPONSE SPECTRUM ANALYSIS**

BUILDINGS WITH DISPLACEMENT-DEPENDENT EDDs

- with floor diafragms that are rigid in their plane
- with ≥2 EDDs in each direcction and each story arranged to provide torsional sitffness/resistance

→ **ENERGY-BALANCE BASED ANALYSIS**

COMMON ASPECTS OF BOTH ANALYSIS METHODS:

- The overall system (main structure and energy dissipation devices) is assumed to dissipate energy through plastic deformations only in the first mode (i.e. the vibration mode with largest effective modal mass in the direction under consideration).
- In the higher modes, the overall system is assumed to remain elastic and the response is obtained through conventional response spectrum analysis.

NON LINEAR RESPONSE SPECTRUM ANALYSIS FOR BUILDINGS WITH **VELOCITY-DEPENDENT EDDs**

NON LINEAR RESPONSE SPECTRUM ANALYSIS for buildings with VELOCITY-DEPENDENT EDDs

- Combines non-linear static analysis and response spectrum analysis
- Largely based on the capacity spectrum method (Freeman, 1975)
- Response in 1st mode is obtained idealizing the overall structure with an equivalent SDOF system with effective stiffness T_{eff1} and effective **viscous** damping ratio ξ_{eff1} .
- This method is appropriate for structures with velocity-dependent EDDs since their main source of energy dissipation is of the viscous type (i.e. of the same nature as the effective viscous damping used to represent the EDDs).
- This method is questionable for structures with displacement-dependent EDDs since their main source of energy dissipation is of the hysteretic type and *there is no physical principle that justifies the existence of a stable relationship between the hysteretic energy dissipation of the maximum excursion and equivalent viscous damping, particularly for highly inelastic systems* (Fajfar, 1999; Krawinkler, 1995).

NON LINEAR RESPONSE SPECTRUM ANALYSIS for buildings with VELOCITY-DEPENDENT EDDs

MAIN VERIFICATION of the Main Structural System

The energy that the primary seismic members at the k-th storey **can** dissipate before reaching the SD limit state	≥	The maximum energy dissipation **demand** on the primary seismic members at the k-th storey under the design seismic action.

Indirect verification:

1. The main structural system is classified as DC1 or DC2 or DC3 depending on the compliance of the conditions in 6.2.7 EN1998 1-1 and **10** to **15** in EN1998 1-2. This determines the maximum allowable $\boldsymbol{q_D}$
2. Calculate the displacement ductility demand d_{roof1} is the maximum roof displacement in the first mode in the direction considered;

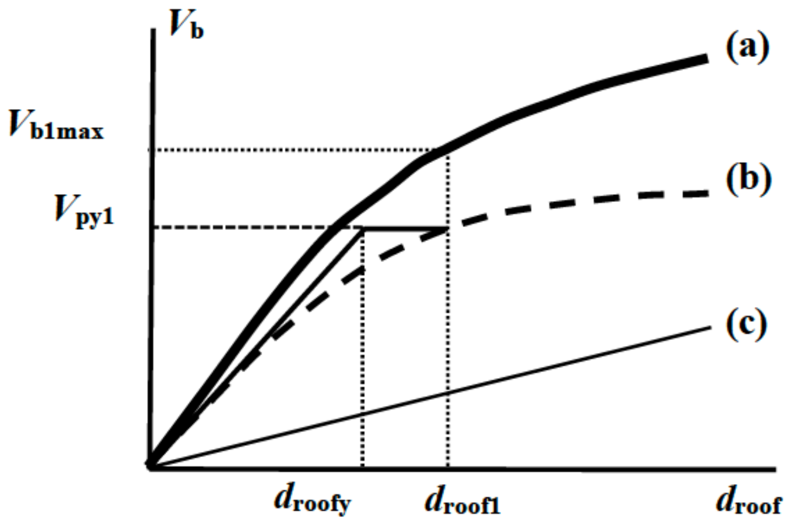
$$d_{\mathrm{roofy}} = \frac{V_{\mathrm{py,1}}\, T_{\mathrm{p1}}^2 \Gamma_{\mathrm{p1}}}{4\pi^2 m_{\mathrm{peff1}}}$$

3. Check: $\mu_f \leq q_D$.

NON LINEAR RESPONSE SPECTRUM ANALYSIS for buildings with VELOCITY-DEPENDENT EDDs

d_{roof1} is obtained idealizing the structure with equivalent SDOF system T_{eff1} and ξ_{eff1}

1. Obtain the capacity curve of the main structural system – curve (b)
2. Adopt a tentative d_{roof1} and obtain the corresponding μ_f, T_{eff1} and ξ_{eff1}.
3. Calculate total base shear V_{b1} by summing up the V_{py1} corresponding to d_{roof1} and the base shear sustained by the the elastic part of EDDs (in case of viscoelastic EDDs).
4. Obtain $V_{b1\,max} = m_{eff\,1} S_e(T_{eff\,1}, 5\%)\, \eta(T_{eff\,1}, \xi_{eff\,1})$ ➔ Is $0.95 V_{b1max} \leq V_{b1} \leq 1.05 V_{b1max}$?
   - YES: d_{roof1} is OK
   - NO: goto step 2



$$T_{eff\,1} = T_1 \sqrt{\frac{\mu_f}{1+(\mu_f-1)(2\xi_{V1}/\eta_{loss})}}$$

$$\xi_{eff1} = \xi_I \frac{\left(\frac{T_1}{T_{p1}}\right)}{\sqrt{1+(\mu_f-1)\left(\frac{2\xi_{V1}}{\eta_{loss}}\right)}} + \xi_{V1}\left[\frac{\mu_f}{1+(\mu_f-1)\left(\frac{2\xi_{V1}}{\eta_{loss}}\right)}\right]^{1-0,5a} + \xi_H$$

$$\xi_{V1} = \frac{\sum_j (2\pi)^a T_1^{2-a} c_j (2{,}1+1{,}9\, e^{-0{,}6a})(\cos\theta_j\, \phi_{rj1})^{1+a} d_{roof\,1e}^{a-1}}{8\pi^3 \sum_i (m_i \phi_{i1}^2)}$$

$$\xi_H = \frac{2F_H}{\pi}\left(\frac{1}{1+(\mu_f-1)(2\xi_{V1}/\eta_{loss})} - \frac{1}{\mu_f}\right)$$

NON LINEAR RESPONSE SPECTRUM ANALYSIS for buildings with VELOCITY-DEPENDENT EDDs

MAIN VERIFICATION on the Energy Dissipation Devices (EDDs):

The energy that the dampers at the k-th storey can dissipate before one of them reaches the SD limit state

≥

The maximum energy dissipation demand on the dampers at the k-th storey under the reference seismic action

Direct verification:

the energy dissipation capacity of the energy dissipation devices installed on each storey k in the direction under consideration when any EDD on the same storey attains its SD limit state (evaluated with EN15129)

≥

$$\frac{1}{2} m \left[\frac{T_{s1}}{2\pi} S_e(T_{s1}, 5\%)\, \eta(T_{s1}, \xi_I) \right]^2$$

Assumes the worst case scenario: all the energy input by the earthquake (except that dissipated by inherent damping) concentrates in a single story k.

NON LINEAR RESPONSE SPECTRUM ANALYSIS for buildings with VELOCITY-DEPENDENT EDDs

ADDITIONAL VERIFICATIONS on the Main Structural System and Auxiliary elements of Energy Dissipation System ($E_d \leq R_d$)

The design value of seismic action effects E_d are calculated in three stages:

(i) maximum displacement

$E_{Emax,disp} = \text{SRSS@CQC}\{E_{Emax,disp,m}\}$

(ii) maximum velocity

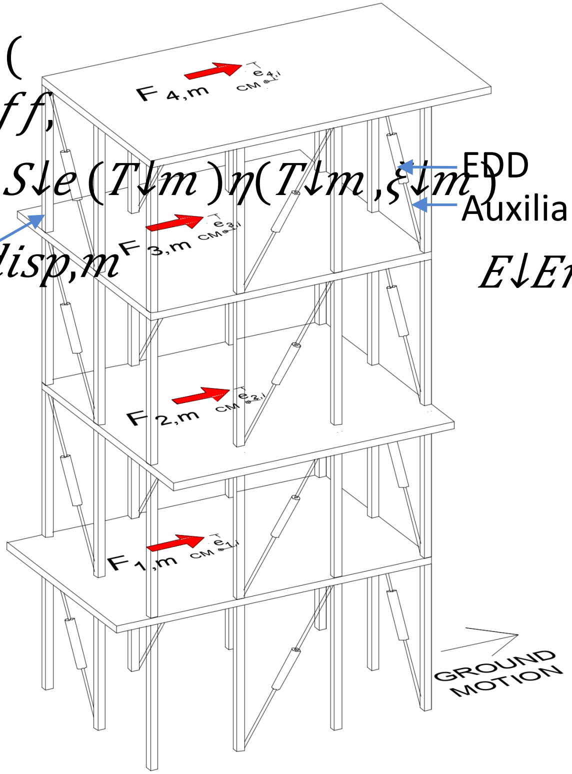
$E_{Emax,vel} = \text{SRSS@CQC}\{E_{Emax,vel,m}\}$

(iii) maximum acceleration

$E_{Emax,accel} = \text{SRSS@CQC}\{E \ldots$

$F_{i1} = m_i \phi_{i1} \Gamma_1 S_e(T_{eff,1})\eta(T_{eff,1}, \xi_{eff,1})/q_R q_S$

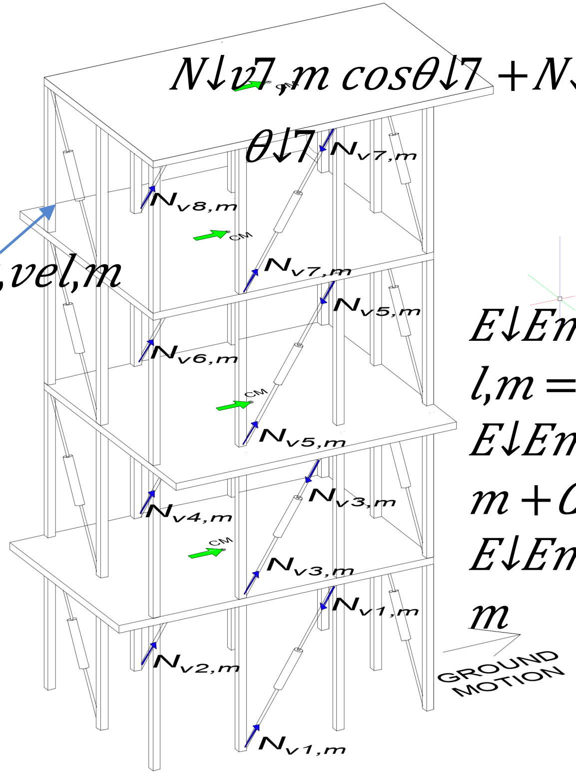
$F_{i,m} = m_i \phi_{i1} \Gamma_m S_e(T_m)\eta(T_m, \xi_m)$



$E_{Emax,disp,m}$

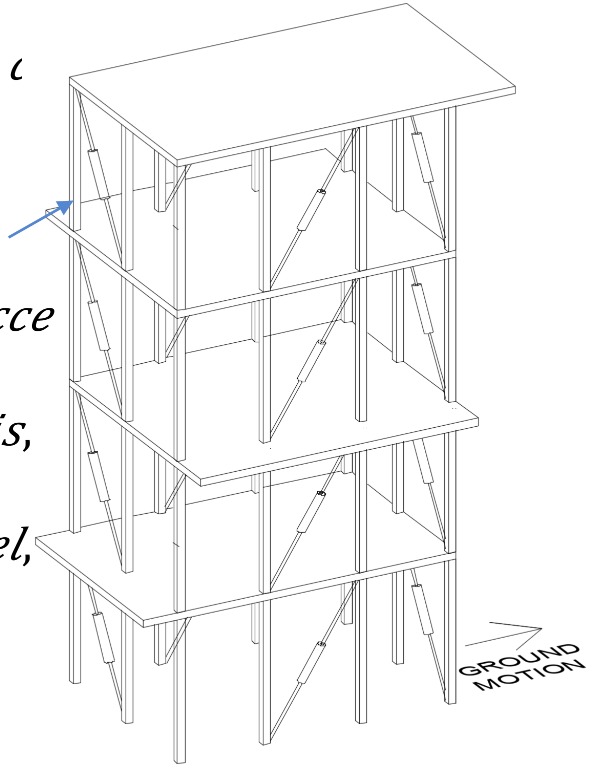
$N_{v7,m}\cos\theta_7 + N_{v8,m} \ldots$

θ_7



$E_{Emax,vel,m}$

$E_{Emax,accel,m} = CF_1 E_{Emax,dis,m} + CF_2 E_{Emax,vel,m}$



For calculating seismic actions in auxiliary elements of the Energy Dissipation System, $F_{i,1}$ is multiplied by $q_R q_S$.

Seismic actions in auxiliary elements of the energy dissipation system amplified by $\boldsymbol{\gamma}_x$

ENERGY-BALANCE BASED ANALYSIS for buildings **DISPLACEMENT-DEPENDENT EDDs**

ENERGY-BALANCE BASED ANALYSIS for buildings with DISPLACEMENT-DEPENDENT EDDs

- The hysteretic energy is NOT represented by an equivalent viscous damping ratio: the problem is addressed directly in terms of hysteretic energy.
- Based on the conservation of energy (Housner 1956, Akiyama 1985, Fardis, 2018).
- Ideally suited for application to structures employing energy dissipation devices, since for these systems proper energy management is a key to successful design (Soong and Dargush, 1997).
- The designer is concerned not so much with the resistance to lateral forces (forced-based approach) or with the lateral displacements (displacement-based approach) but with the product of both, that is, with energy.
- The designer directly and explicitly controls and decides how the energy input into the structure from the earthquake is distributed between the Main Structural System and the Energy Dissipation System.
- Allows a quantitative control of damage.

ENERGY-BALANCE BASED ANALYSIS for buildings with DISPLACEMENT-DEPENDENT EDDs

MAIN VERIFICATION of the Main Structural System

The energy that the primary seismic members at the k-th storey can dissipate before reaching the SD limit state	≥	The maximum energy dissipation demand on the primary seismic members at the k-th storey under the design seismic action
$E_{pH,k,SD}$	≥	$E_{pH,k,max}$

This verification can be made in two alternative ways:

- **Direct verification**
- **Indirect verification**

ENERGY-BALANCE BASED ANALYSIS for buildings with DISPLACEMENT-DEPENDENT EDDs

Direct verification

A- Estimate $E\downarrow pH,k,max$

$$E_{H,k} = \frac{s_k (p_k\, p_{t,k})^{-n}}{\sum_{j=1}^{N} s_j (p_j\, p_{t,j})^{-n}} \left[\frac{1}{2} M \left(\frac{T_{s1}}{2\pi} S_e(T_{s1}, 5\%)\, \eta(T_{s1}, \xi_1) \right)^2 - \sum_{j=1}^{N} \left(\alpha_j \bar{m}_j M g d_{py,j}/2 \right) \right]$$

$$s_k = \left\{ \bar{m}_k + \frac{2T_1}{1+3T_1} \left(\sqrt{\bar{m}_k} - \bar{m}_k^2 \right) \right\}^2 \frac{d_{py,k}(V_{py,1}+V_{dy,1})}{d_{py,1}(V_{py,k}+V_{dy,k})}$$

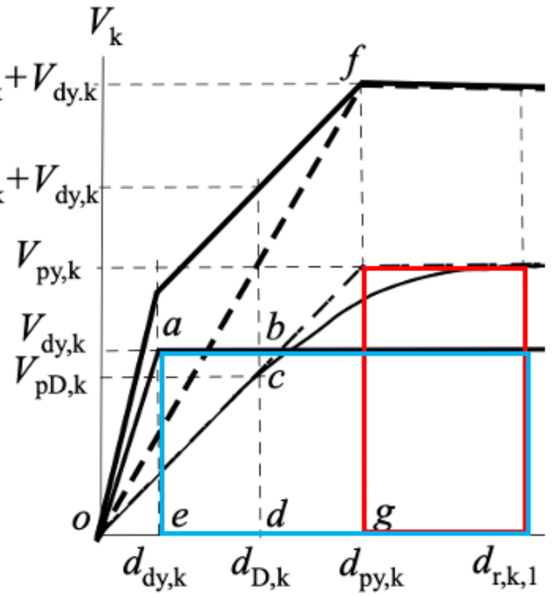
$$p_k = \frac{(V_{py,k}+V_{dy,k})}{(V_{py,1}+V_{dy,1})} \left\{ \bar{m}_k + \frac{2T_1}{1+3T_1} \left(\sqrt{\bar{m}_k} - \bar{m}_k^2 \right) \right\}^{-1}$$

$$p_{t,k} = \begin{cases} 1{,}0 & for \quad (e_{0x}/r_x) < 0{,}15 \\ 1{,}15 - \frac{e_{0x}}{r_x} & for \quad 0{,}15 < (e_{0x}/r_x) < 0{,}30 \\ 0{,}85 & for \quad (e_{0x}/r_x) > 0{,}30 \end{cases}$$

distance between center of mass and center of stiffness

$\sqrt{K\downarrow torsion} / K\downarrow lateral$

$$E_{pH,k,max} = E_{H,k} \left[\frac{\boxed{V_{py,k}(d_{r,k,1}-d_{py,k})}}{\boxed{V_{py,k}(d_{r,k,1}-d_{py,k})} + \boxed{V_{dy,k}(d_{r,k,1}-d_{dy,k})}} \right]$$



B- Estimate $E\downarrow pH,k,SD$

- $E\downarrow pH,k,SD$ is the plastic strain energy dissipation capacity under cyclic (not monotonic) loading
- $E\downarrow pH,k,SD$ is determined from the cyclic response of structural members or subassemblies obtained experimentally –EN1998 1-1 clause 7.1.(9). The deformation and strength models of EN 1998 1-1 clause 7 can be useful to have a lower bound of $E\downarrow pH,k,SD$.

ENERGY-BALANCE BASED ANALYSIS for buildings with **DISPLACEMENT-DEPENDENT EDDs**

Indirect verification

1. The main structural system is classified as DC1 or DC2 or DC3 depending on the compliance of the conditions in 6.2.7 EN1998 1-1 and **10** to **15** in EN1998 1-2. This determines the maximum allowable q_D

2. Calculate the displacement ductility demand d_{roof1} is the maximum roof displacement in the first mode in the direction considered, and

$$d_{roofy} = \frac{T_1^2 (V_{py,1} + V_{dy,1}) \Gamma_1}{4\pi^2 m_{eff1}}$$

   Here, d_{roof1} is obtained from the plastic energy dissipation dem... ,
   k, $E_{H,k}$, assuming that $E_{H,k}$ is dissipated in one cycle of amplitude equal to the maximum interstory drift:

$$d_{roof,1} = \sum_{k=1}^{N} \left\{ d_{py,k} + E_{H,k} / 4(V_{py,k} + V_{dy,k}) \right\}$$

(assumes that $E_{H,k}$ is dissipated in one cycle of maximum interstory drift)

3. Check: $\mu_f \leq q_D$.

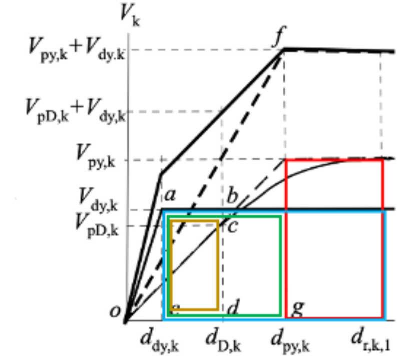
ENERGY-BALANCE BASED ANALYSIS for buildings with DISPLACEMENT-DEPENDENT EDDs

MAIN VERIFICATION on the Energy Dissipation Devices (EDDs):

The energy that the energy dissipation system at the k-th storey can dissipate before it reaches the SD limit state	≥	The maximum energy dissipation demand on the energy dissipation system at the k-th storey under the reference seismic action

Direct verification: $E_{dH,k,SD} \geqq E_{dH,k,SD}$

The energy dissipation capacity of the EDDs installed on each storey k when any EDD on the same storey attains SD limit state $\boldsymbol{E_{dH,k,SD}}$ (evaluated with EN15129)	≥	$E_{dH,k,max} = E_{H,k}\left[\frac{\boxed{V_{dy,k}(d_{r,k,1}-d_{dy,k})}}{\boxed{V_{py,k}(d_{r,k,1}-d_{py,k})}+\boxed{V_{dy,k}(d_{r,k,1}-d_{dy,k})}}\right] + \boxed{40V_{dy,k}[d_{py,k}-d_{dy,k}]} + \boxed{100V_{dy,k}[d_{D,k}-d_{dy,k}]}$



Energy corresponding to 5 low intensity earthquakes, each one introducing the energy corresponding to 5 cycles of amplitude $d_{D,k}$.

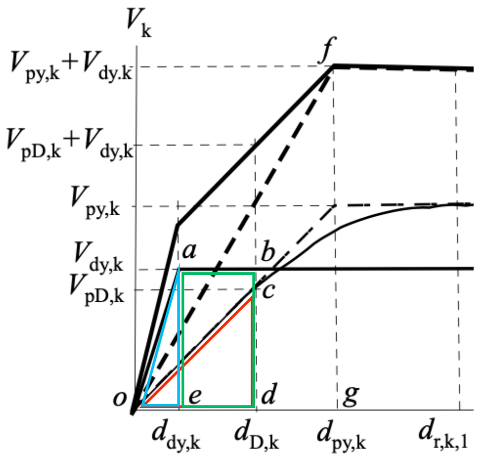
ENERGY-BALANCE BASED ANALYSIS for buildings with **DISPLACEMENT-DEPENDENT EDDs**

ADDITIONAL VERIFICATION on the Main Structural System and Energy Dissipation System

The amount of energy that the overall structure can absorb while the primary seismic members of the main structural system remain elastic	≥	The energy input be a low intensity earthquake, estimated as ¼ of the energy input by the reference seismic action (design earthquake)

Direct verification:

$$\sum_{k=1}^{N}\left(\frac{V_{pD,k}\,d_{d,k}}{2}+\frac{V_{dy,k}\,d_{dy,k}}{2}+4V_{dy,k}\left(d_{D,k}-d_{dy,k}\right)\right)\geq\underbrace{\frac{1}{4}\underbrace{\frac{1}{2}m\left[\frac{T_1}{2\pi}S_e(T_{1,e},5\%)\eta(T_1,\xi_1)\right]^2}_{\text{energy input by reference seismic action}}}_{\text{energy input by low intensity earthquake}}$$



ENERGY-BALANCE BASED ANALYSIS for buildings with DISPLACEMENT-DEPENDENT EDDs

ADDITIONAL VERIFICATIONS on the Main Structural System and Auxiliary elements of Energy Dissipation System ($E_d \leq R_d$)

The seismic action effects are calculated in the stage of maximum displacement:

$$E_{Emax,disp} = \begin{matrix}SRSS\\CQC\end{matrix}\{E_{Emax,disp,m}\}$$

$$F_{i1} = (V_{pD,1} + V_{dy,1})\left\{\left[\bar{m}_k + \frac{2T_1}{1+3T_1}\left(\sqrt{\bar{m}_k} - \bar{m}_k^2\right)\right] - \left[\bar{m}_{k+1} + \frac{2T_1}{1+3T_1}\left(\sqrt{\bar{m}_{k+1}} - \bar{m}_{k+1}^2\right)\right]\right\}$$

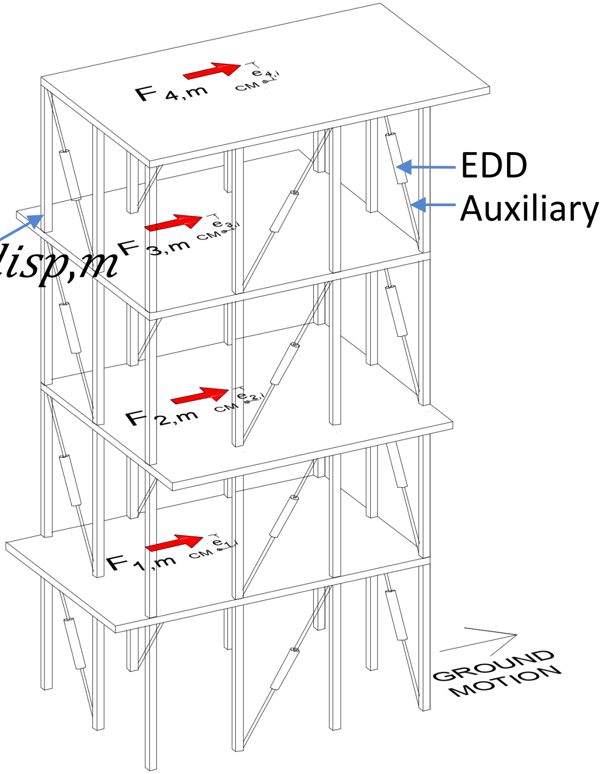
$$F_{i,m} = m_i \phi_{im} \Gamma_m S_e(T_m) \eta(T_m, \xi_m)$$

$$E_{Emax,disp,m}$$

For calculating seismic actions in auxiliary elements of the Energy Dissipation System, $F_{i,1}$ is multiplied by:

$$\{q_R q_S[1+(V_{dy,1}/V_{py,1})]/[1+q_R q_S(V_{dy,1}/V_{py,1})]\}$$

Seismic actions in auxiliary elements of the energy dissipation system should by amplified by γ_x



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Thank you for your attention

30th March 2022