# EN 1998-1-1 and 1-2:2022 DESIGN OF STRUCTURE FOR EARTHQUAKE RESISTANCE

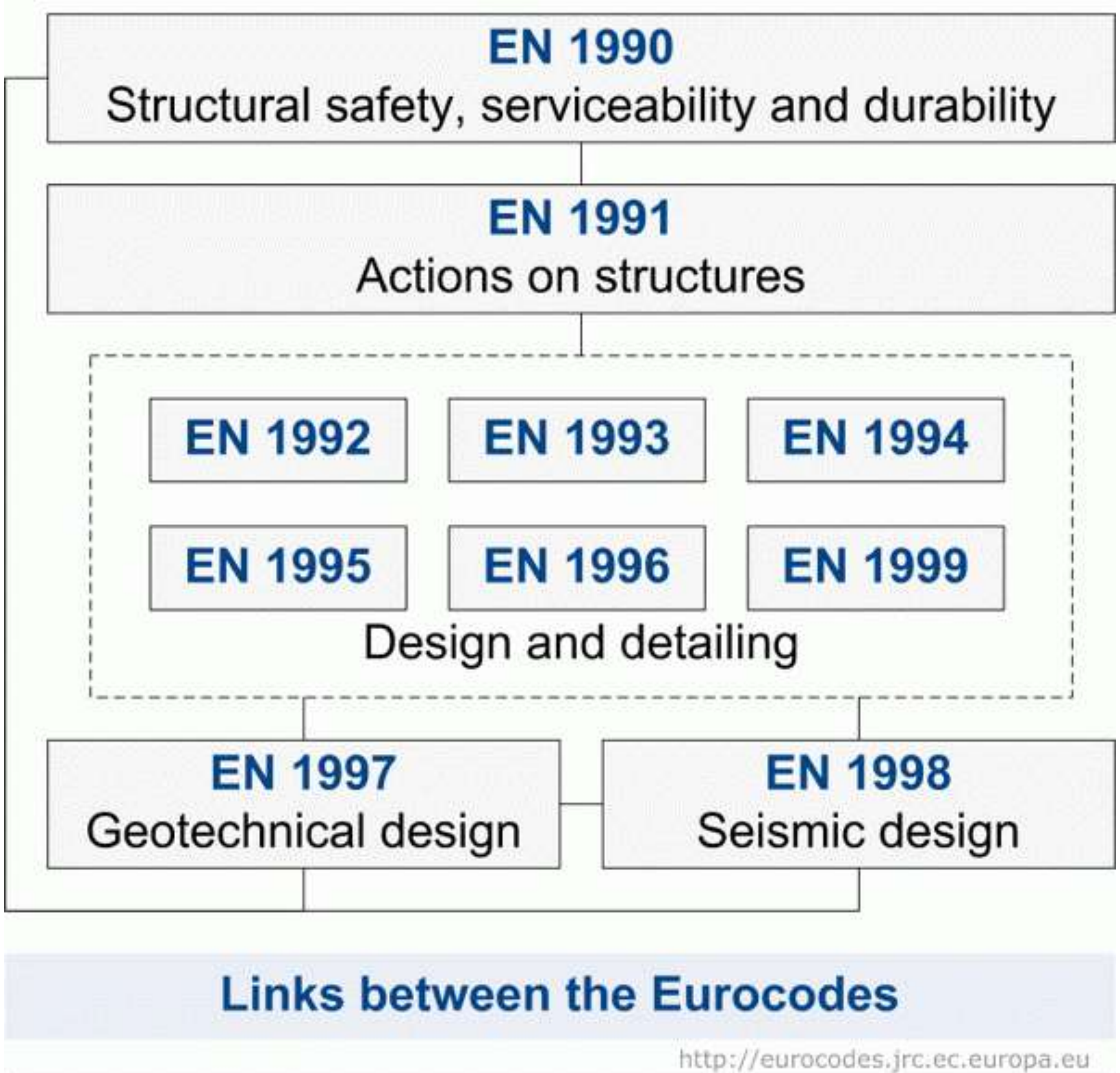
LAMBERTO BRISEGHELLA

# TERREMOTO LISBONA 1755  60.000 MORTI

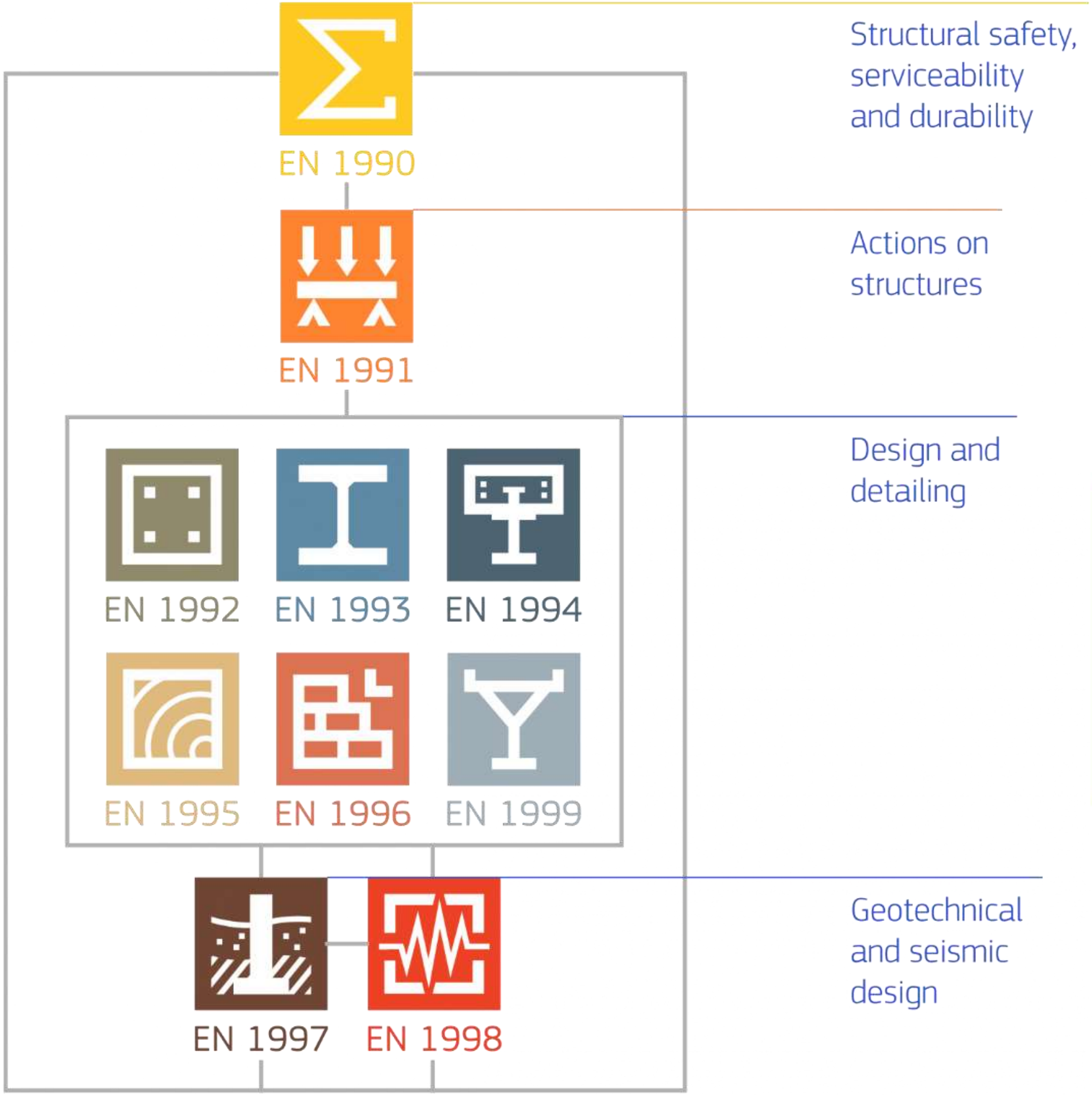
# TERREMOTO S. FRANCISCO 1906  3000 MORTI

# TERREMOTO MESSINA 28 DICEMBRE 1908  200.000 MORTI

# TERREMOTO PORT-AU-PRINCE  HAITI 2010  200.000 MORTI


EN 1990
Structural safety, serviceability and durability
EN 1991
Actions on structures
EN 1992
EN 1993
EN 1994
EN 1995
EN 1996
EN 1999
Design and detailing
EN 1997
Geotechnical design
EN 1998
Seismic design
Links between the Eurocodes
http://eurocodes.jrc.ec.europa.eu

jrc.ec


EN 1990
Structural safety, serviceability and durability
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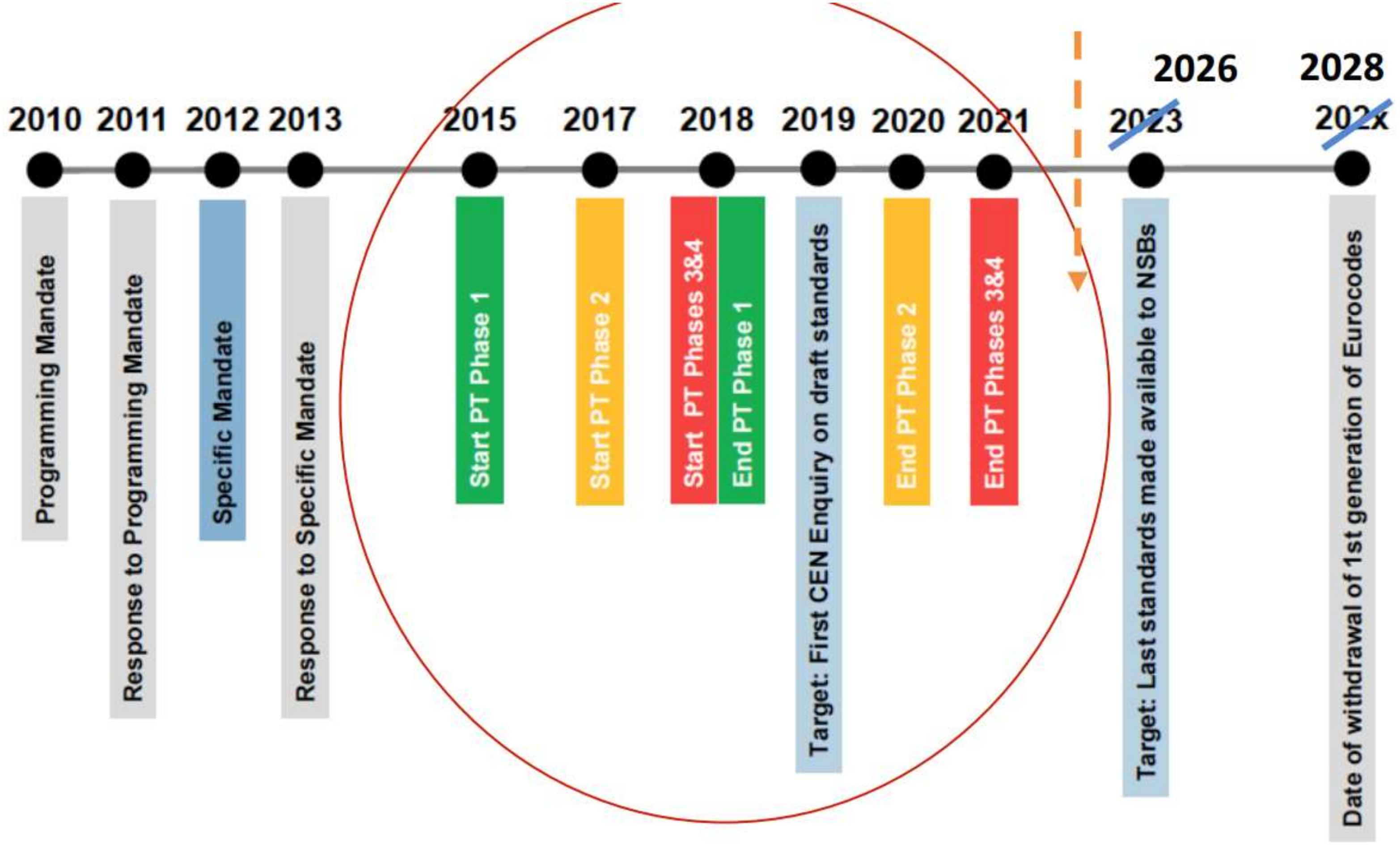
EN 1995
EN 1996
EN 1999
Design and detailing
EN 1997
EN 1998
Geotechnical and seismic design

EUROCODES

| | |
|---|---|
| EN 1990 | Eurocode: Basis of structural design |
| EN 1991 | Eurocode 1: Actions on structures |
| EN 1992 | Eurocode 2: Design of concrete structures |
| EN 1993 | Eurocode 3: Design of steel structures |
| EN 1994 | Eurocode 4: Design of composite steel and concrete structures |
| EN 1995 | Eurocode 5: Design of timber structures |
| EN 1996 | Eurocode 6: Design of masonry structures |
| EN 1997 | Eurocode 7: Geotechnical design |
| EN 1998 | Eurocode 8: Design of structures for earthquake resistance |
| EN 1999 | Eurocode 9: Design of aluminium structures |
| EN XXXX | Eurocode XX: Structural glass |

OGNI EC E' DIVISO IN PARTI, IN CAPITOLI, CLAUSES , IN ANNEXES

# Drafting Programme



# VERB FORMS IN REQUIREMENTS

- "shall" means a requirement strictly to be followed in order to conform to the Eurocodes and from which no deviation is permitted
- "should" gives a strong recommendation. Subject to national regulation and any relevant contractual provisions, alternative approaches could be appropriate where technically justified
- "may" indicates a course of action permissible within the limits of the Eurocodes

# Introduction to Eurocode 8

- **By nature, perfect protection (a null seismic risk) against earthquakes is practically not feasible, in particular because the knowledge of the hazard itself is characterised by a significant uncertainty. Therefore, in Eurocode 8, the seismic action is represented in a conventional form, proportional in amplitude to earthquakes likely to occur at a given location and representative of their frequency content. This representation is not the prediction of a particular seismic movement, and such a movement could give rise to more severe effects than those of the seismic action considered, inflicting damage greater than the one described by the Limit States contemplated in this Standard.**
- **Not only the seismic action cannot be predicted, but in addition, it should be recognised that engineering methods are not perfectly predictive when considering the effects of this specific action, under which structures are assumed to respond in the non-linear regime. Such uncertainties are taken into account according to the general EN 1990 frame with a residual risk of underestimation of the effects.**

**EUROCODE 8 is a purely technical text, SAFETY is in the hands of the Members**

prEN 1998-1-2:2022

NUOVO

EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

EN 1998-1

VECCHIO

December 2004

ICS 91.120.25

Supersedes ENV 1998-1-1:1994, ENV 1998-1-2:1994, ENV 1998-1-3:1995

Incorporating corrigendum July 2009

English version

Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings

Eurocode 8: Calcul des structures pour leur résistance aux séismes - Partie 1: Règles générales, actions sismiques et règles pour les bâtiments

Eurocode 8: Auslegung von Bauwerken gegen Erdbeben - Teil 1: Grundlagen, Erdbebeneinwirkungen und Regeln für Hochbauten

This European Standard was approved by CEN on 23 April 2004.

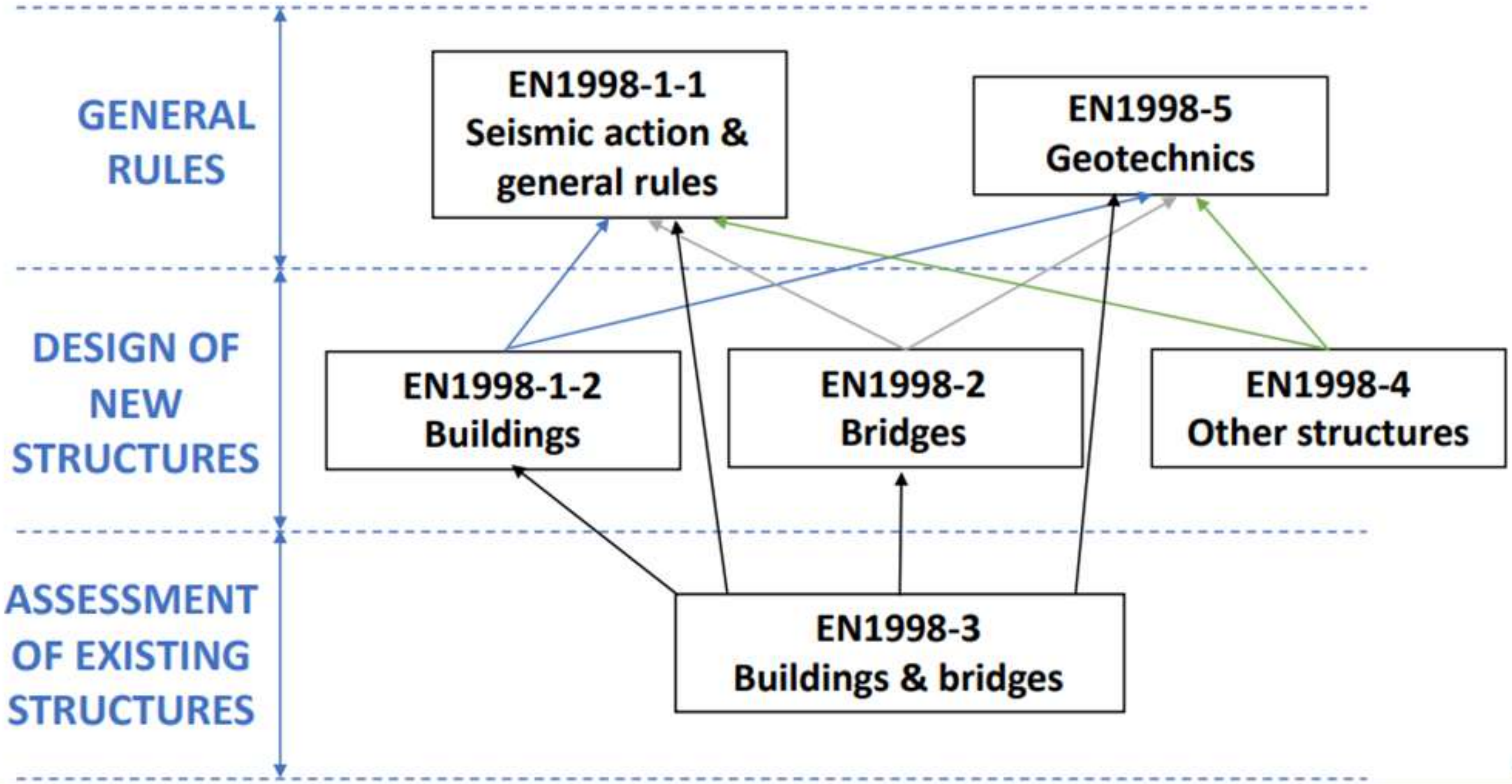
CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CEN member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the Central Secretariat has the same status as the official versions.

CEN members are the national standards bodies of Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

# Example: Restructuration of EN 1998 in three levels

→ *Identification of a general part common to all other parts to avoid repetitions*



# EC8:2022 DIVISIONE IN PARTI

– Part 1–1: General rules and seismic action,
– Part 1–2: Buildings,
– Part 2: Bridges,
– Part 3: Assessment and retrofitting of buildings and bridges,
– Part 4: Silos, tanks and pipelines, towers, masts and chimneys, and
– Part 5: Geotechnical aspects, foundations, retaining and underground structures.

# EC8-1-1:2022 MAIN CHANGES INTRODUCED BY CEN-TEC-250-SC8

- Introducing the concept of seismic action class in place of seismicity level.
- Anchoring the standard spectrum by its plateau value, $S_\alpha$, and its value at 1 s spectral period, $S_\beta$, instead of the PGA.
- Introducing, in an informative annex, two European hazard maps, one for $S_\alpha$, and one for $S_\beta$, both defined for 475 years return period, based on the ESHM20 hazard model.
- Revising the site categorization by introducing the bed rock depth in addition to the shear wave velocity.
- Introducing new site amplification factors based on this site categorisation and dependent on input motion level.
- Introducing a new spatial model of input motion for bridges and pipelines.
- Providing miscellaneous specifications on conventional values of magnitude and strong motion duration, dependence of spectra to damping, …

## EC8-1-1:2022

1. INTRODUCTION
    - 1.1 OUTLINES OF EC8 DEVELOPMENT PROCESS
    - 1.2 EC8 TEXT VERSUS NATIONAL CHOICES
    - 1.3 GENERIC EC8 CONCEPT THAT INTERACT WITH SEISMIC ACTION
    - 1.4 EC PHILOSOPHY OF THE SEISMIC ACTION
    - 1.5 A MAJOR EVOLUTION IN STANDARD RESPONSE SPECTRA ANCHORING
2. SAFETY RELATED FACETS OF THE SEISMIC ACTION
    - 2.1 SEISMIC ACTION CLASSES
    - 2.2 RETURN PERIODS AND PERFORMANCE FACTORS
3. SITE CATEGORIZATION
    - 3.1 SITE STABILITY  AND SITE SPECIFIC HAZARD ANALYSIS
    - 3.2 DEFINITION OF SITE CATEGORIES
    - 3.3 ALTERNATIVE IDENTIFICATION OF SITE CATEGORY
4. SEISMIC HAZARD MAPS
    - 4.1 MAPPING RULES AND SEISMICITY LEVELS
    - 4.2 INFORMATIVE EUROPEAN HAZARD MAPS
    - 4.3 SPECTRAL DESCRIPTION OF THE SEISMIC ACTION
5. SPECTRAL DESCRIPTION OF THE SEISMIC ACTION
    - 5.1  STANDARDIZATION OF SPECTRAL SHAPES
    - 5.2 SITE AMPLIFICATION FACTORS
    - 5.3 ADDITIONAL INFORMATION ON STANDARD RESPONSE SPECTRA
6. MAGNITUDE, TIME SERIES AND SPECTRAL VARIABILITY
    - 6.1 CONVENTIONAL MAGNITUDE AND STRONG MOTION DURATION
    - 6.2 INPUT MOTION IN THE FORM OF TIME SERIES
    - 6.3 SPATIAL VARIABILITY OF THE SEISMIC INPUT MOTION

For the purpose of safety, Eurocodes classify structures into Consequence Classes (CC), depending on the consequences of failure or malfunction of the structure in terms of loss of human life or personal injury, as well as in terms of economic, social or environmental consequences. For instance, when considering buildings, agricultural buildings are classified as CC1, residential and office buildings as CC2, concert halls as CC3. For the purpose of seismic protection, the consequence class CC3 is subdivided, except in Part 5, into CC3-a (schools, assembly halls, cultural institutions …) and CC3-b, which includes structures of buildings that are vital in the event of an earthquake (hospitals, fire stations, communication centres …). It is the same for bridges and for industrial installations dealt with in Part 4. Structures of the highest consequence class, CC4 (e.g. nuclear facilities, large dams), are covered by dedicated rules and regulations, not by the Eurocodes.

# Seismic situation & limit states

- Homogenisation of Limit States definition through all parts with better consistency with EN1990 (ULS and SLS)
- Verification of Operational (OP) limit state

1st GENERATION

| PARTS 1 & 2 | PART 3 |
|---|---|
| | NEAR COLLAPSE |
| NO COLLAPSE | SIGNIFICANT DAMAGE |
| DAMAGE LIMITATION | DAMAGE LIMITATION |

2nd GENERATION

| | Limit state |
|---|---|
| ULS | NEAR COLLAPSE (NC) |
| | SIGNIFICANT DAMAGE (SD) |
| SLS | DAMAGE LIMITATION (DL) |
| | OPERABILITY (OP) |

- At least one ULS verification is mandatory (safety of the structure)
- Choice of SLS to be verified is up to the NA or the contract

The Eurocodes approach for the design of structures is based on the concept of Limit States (LS). We distinguish between ultimate limit states, the non-exceedance of which controls safety of structures, and serviceability limit states. For the purpose of seismic protection, four limit states are considered. Two of them are ultimate limit states, namely Near Collapse (NC) and Significant Damage (SD), the two other ones are serviceability limit states, namely Damage Limitation (DL) and Fully Operational (OP).

# Performance requirements

## Objectives to be met with an appropriate degree of reliability:

— human lives are protected

— damage is limited

— facilities important for civil protection remain operational

## Design verification principles for new structures:

— verification of SD limit state mandatory

— ensure deformation capacity and cumulative energy dissipation capacity

— avoid brittle failure or the premature formation of unstable mechanisms

# NEW DEFINITION OF ELASTIC SPECTRUM

ATTENZIONE: ASCISSE IN SCALA LOGARITMICA

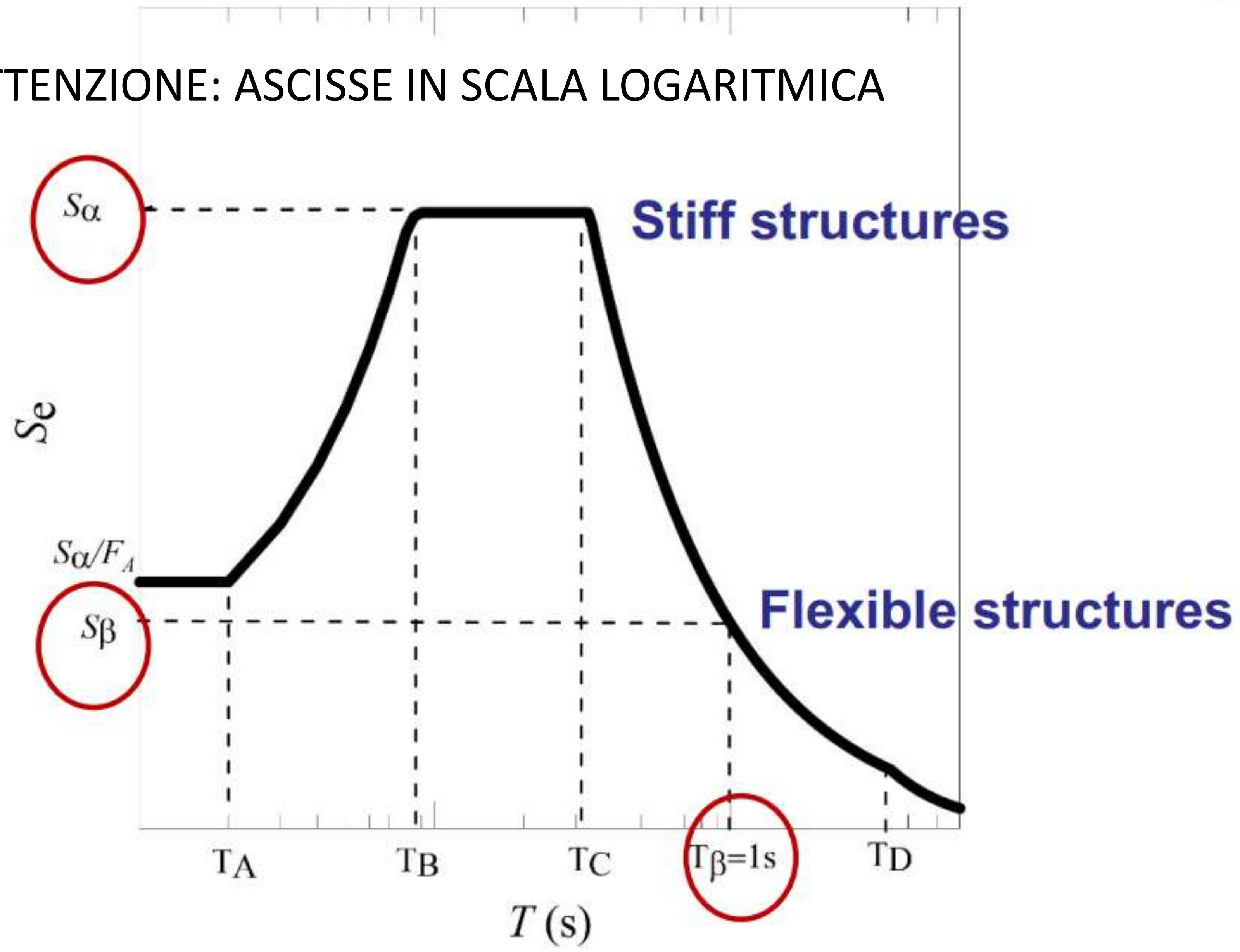


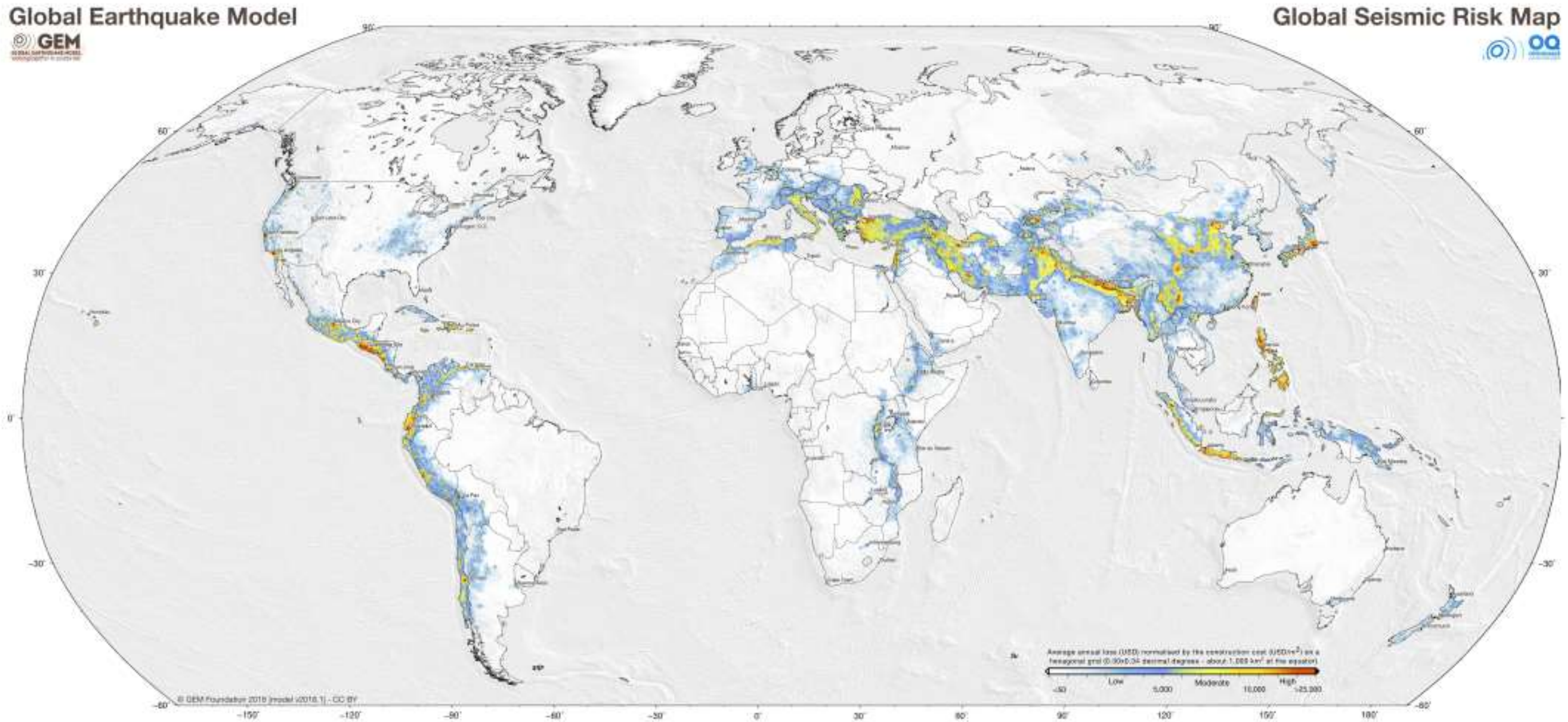
**Table 2** Standard site categorisation according to the 2021-draft, in case both $V_{s,H}$ and $H_{800}$ are available

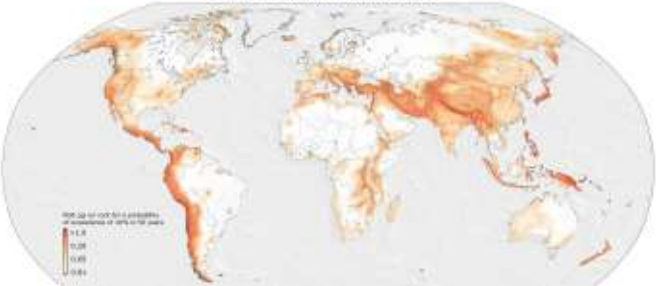
| Depth class | Ground class<br>$V_{s,H}$ range<br>$H_{800}$ *range* | Stiff<br>400 m/s $\leq V_{s,H} <$ 800 m/s | Medium stiff<br>250 m/s $\leq V_{s,H} <$ 400 m/s | Soft<br>150 m/s $\leq V_{s,H} <$ 250 m/s |
|---|---|---|---|---|
| Very shallow | $H_{800} \leq 5$ m | A | A | E |
| Shallow | 5 m $< H_{800} \leq$ 30 m | B | E | E |
| Intermediate | 30 m $< H_{800} \leq$ 100 m | B | C | D |
| Deep | $H_{800} >$ 100 m | B | F | F |

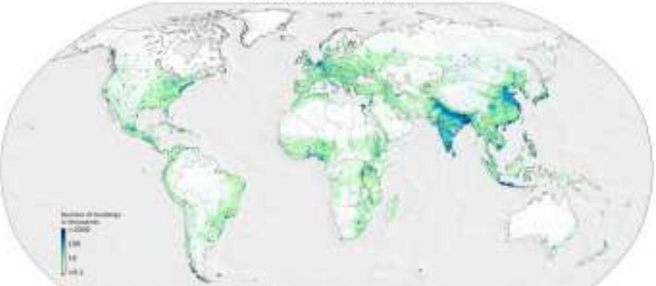
**Table 4** Site amplification factors according to the 2021-draft

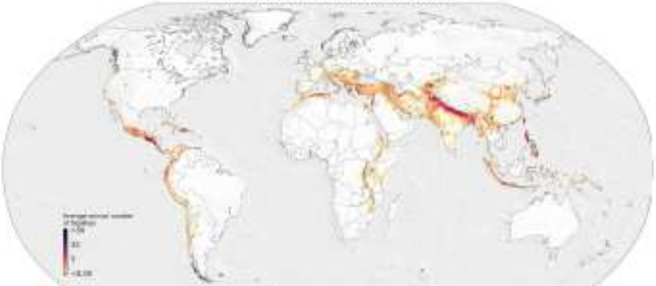
| Site category | $F_\alpha$ | | $F_\beta$ | |
|---|---|---|---|---|
| | $H_{800}$ and $V_{s,H}$ available | Default value | $H_{800}$ and $V_{s,H}$ available | Default value |
| A | 1,0 | 1,0 | 1,0 | 1,0 |
| B | $\left(\frac{V_{s,H}}{800}\right)^{-0,40r_\alpha}$ | $1,3 * (1 - 0,1 * S_{\alpha,RP}/g)$ | $\left(\frac{V_{s,H}}{800}\right)^{-0,70r_\beta}$ | $1,6 * (1 - 0,2 * S_{\beta,RP}/g)$ |
| C | | $1,6 * (1 - 0,2 * S_{\alpha,RP}/g)$ | | $2,3 * (1 - 0,3 * S_{\beta,RP}/g)$ |
| D | | $1,8 * (1 - 0,3 * S_{\alpha,RP}/g)$ | | $3,2 * (1 - S_{\beta,RP}/g)$ |
| E | $\left(\frac{V_{s,H}}{800}\right)^{-0,40r_\alpha \frac{H}{30}\left(4-\frac{H}{10}\right)}$ | $2,2 * (1 - 0,5 * S_{\alpha,RP}/g)$ | $\left(\frac{V_{s,H}}{800}\right)^{-0,70r_\beta \frac{H}{30}}$ | $3,2 * (1 - S_{\beta,RP}/g)$ |
| F | $0,90 \cdot \left(\frac{V_{s,H}}{800}\right)^{-0,40r_\alpha}$ | $1,7 * (1 - 0,3 * S_{\alpha,RP}/g)$ | $1,25 \cdot \left(\frac{V_{s,H}}{800}\right)^{-0,70r_\beta}$ | $4,0 * (1 - S_{\beta,RP}/g)$ |
| | $r_\alpha = 1 - \frac{S_{\alpha,RP}/g}{V_{s,H}/150}$; $r_\beta = 1 - \frac{S_{\beta,RP}/g}{V_{s,H}/150}$ | | | |

# WORLD SEISMIC HAZARD





Global Seismic Hazard Map


Global Exposure Map


Global Seismic Fatalities Map

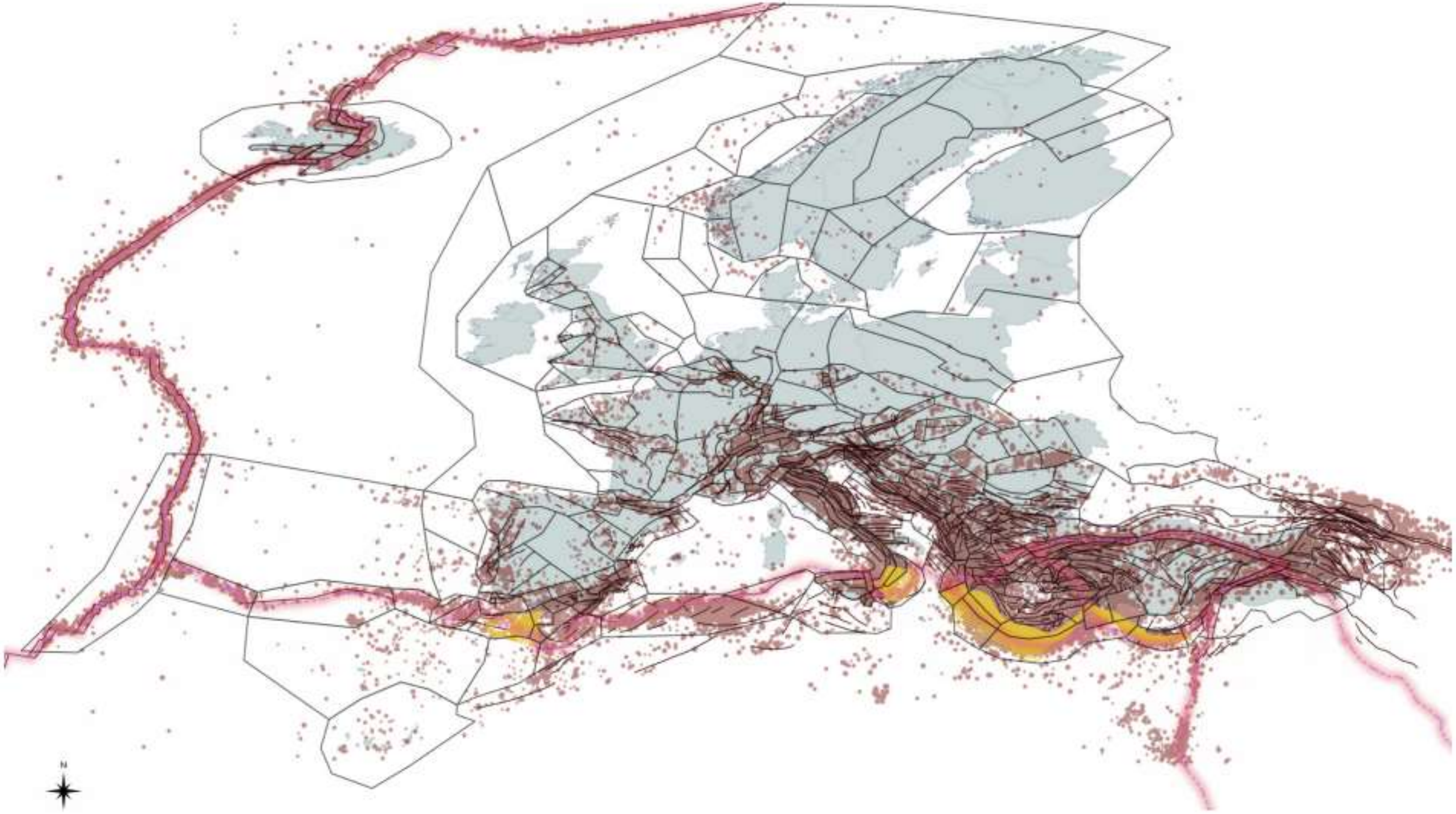
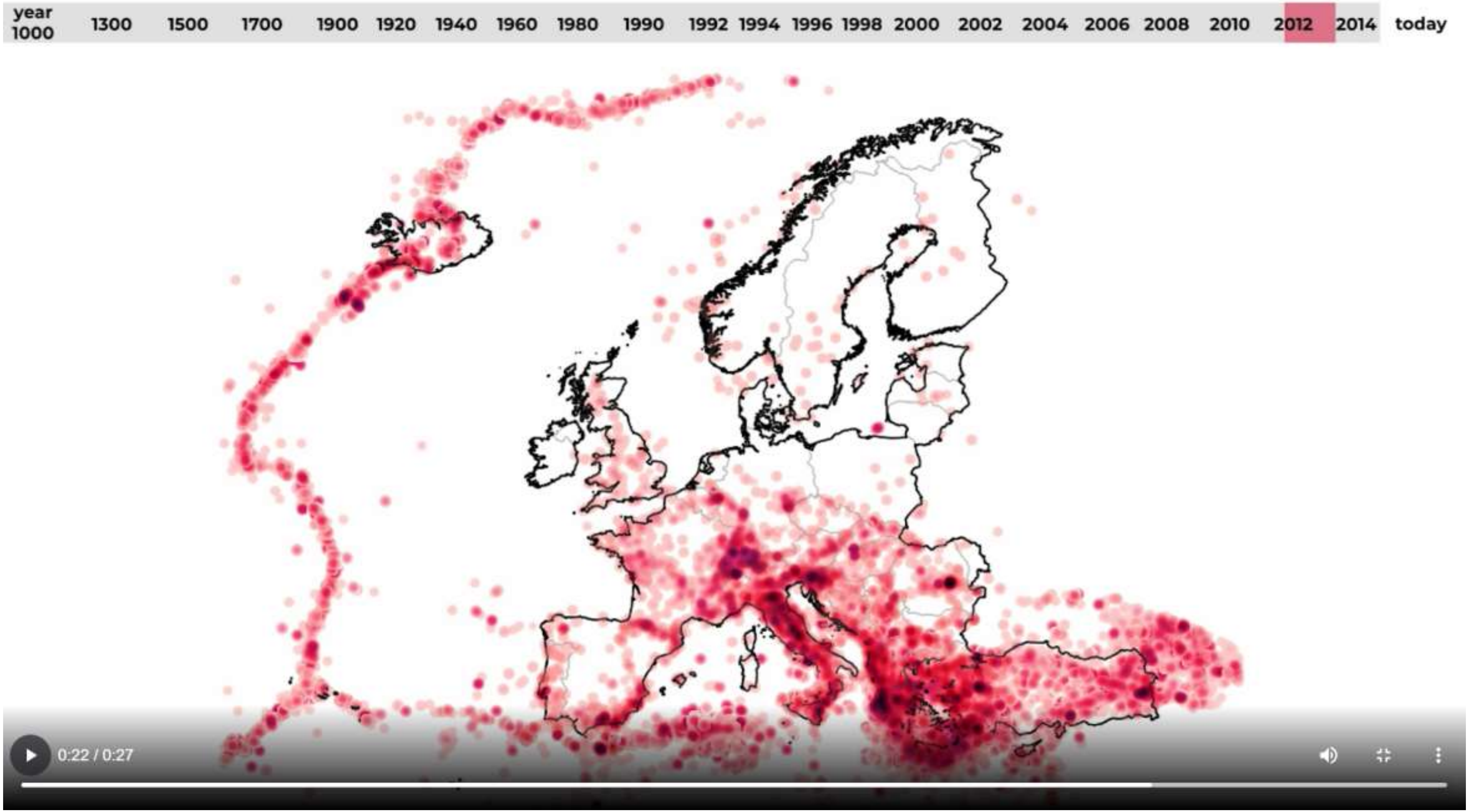


**Fig. 3.** Schematic illustration of the ESHM20’ seismogenic source model overlaying the area source (black polygons) active faults (black lines) and subduction sources (orange polylines) with the tectonic plate boundaries (red lines) and the earthquakes (red dots) of the unified earthquake catalogue.


year 1000
1300
1500
1700
1900
1920
1940
1960
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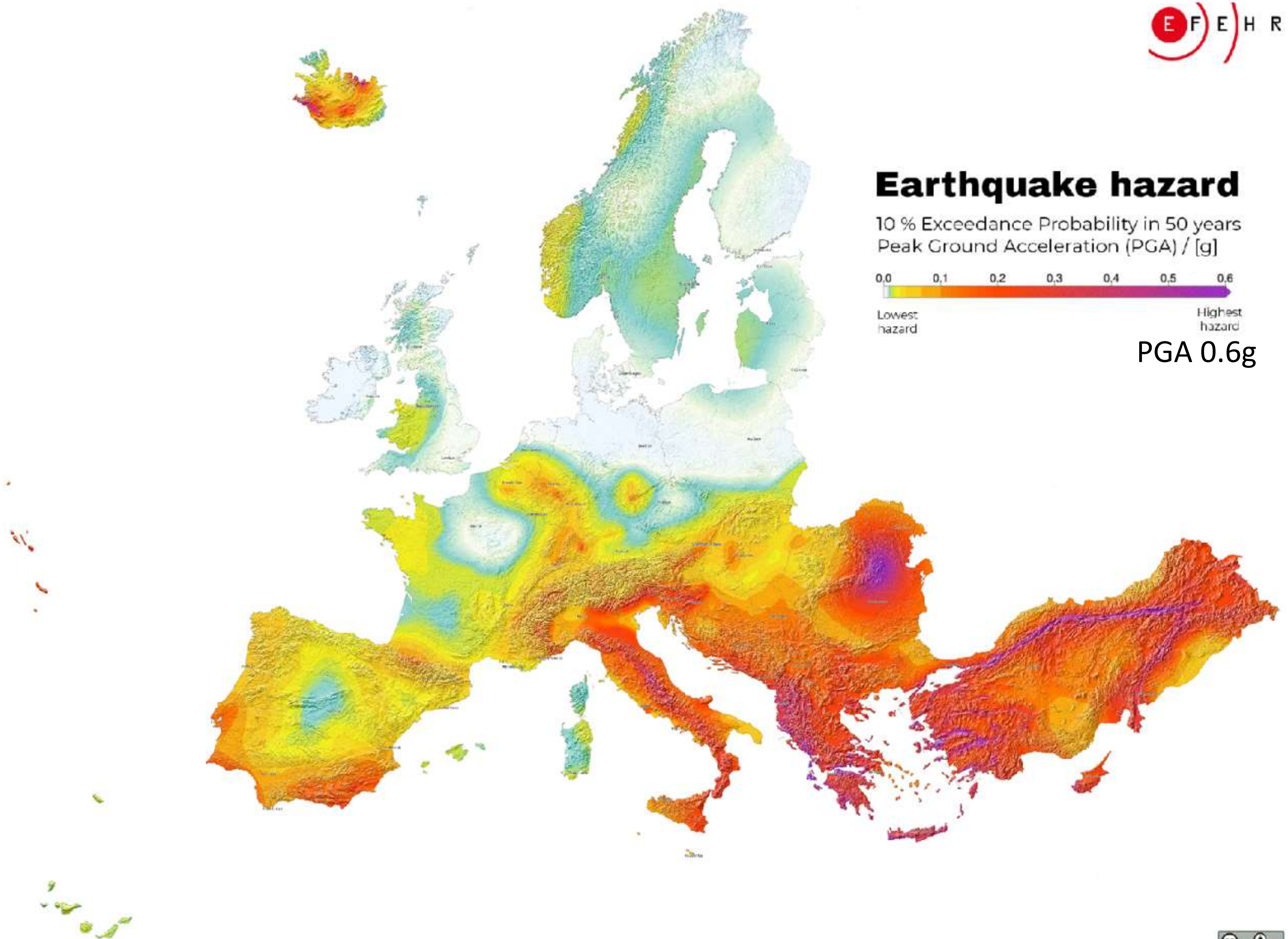
2006
2008
2010
2012
2014
today
0:22 / 0:27



# Earthquake hazard

10 % Exceedance Probability in 50 years
Peak Ground Acceleration (PGA) / [g]



PGA 0.6g

# ESHM20

EARTHQUAKE CATALOGUE

ACTIVE FAULTS DATABASE

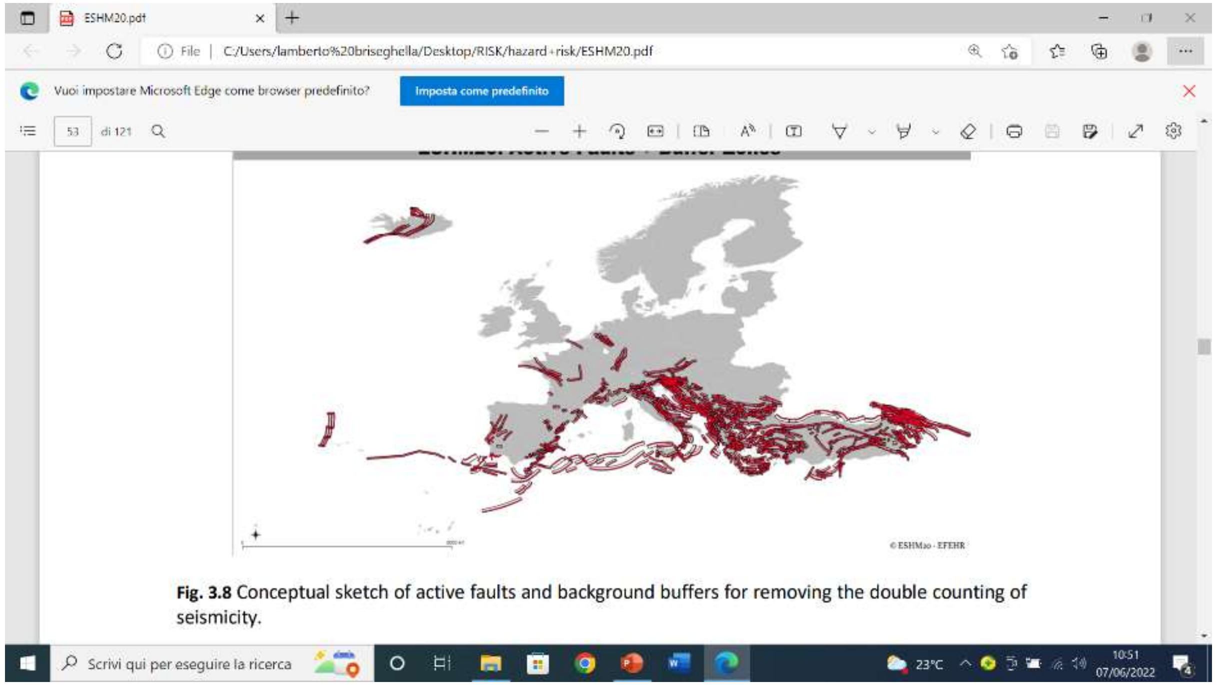
SEISMOGENIC SOURCE MODELS

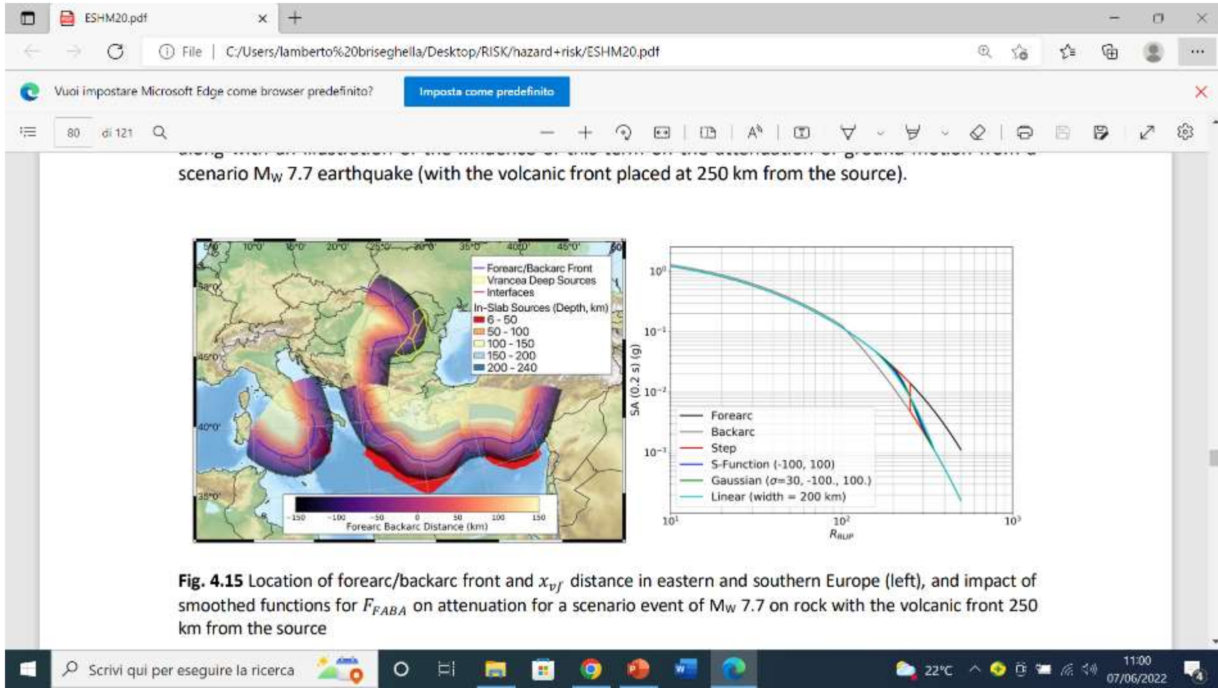
GROUND MOTION DATA AND MODEL

HAZARD COMPUTATION

RISK COMPUTATION

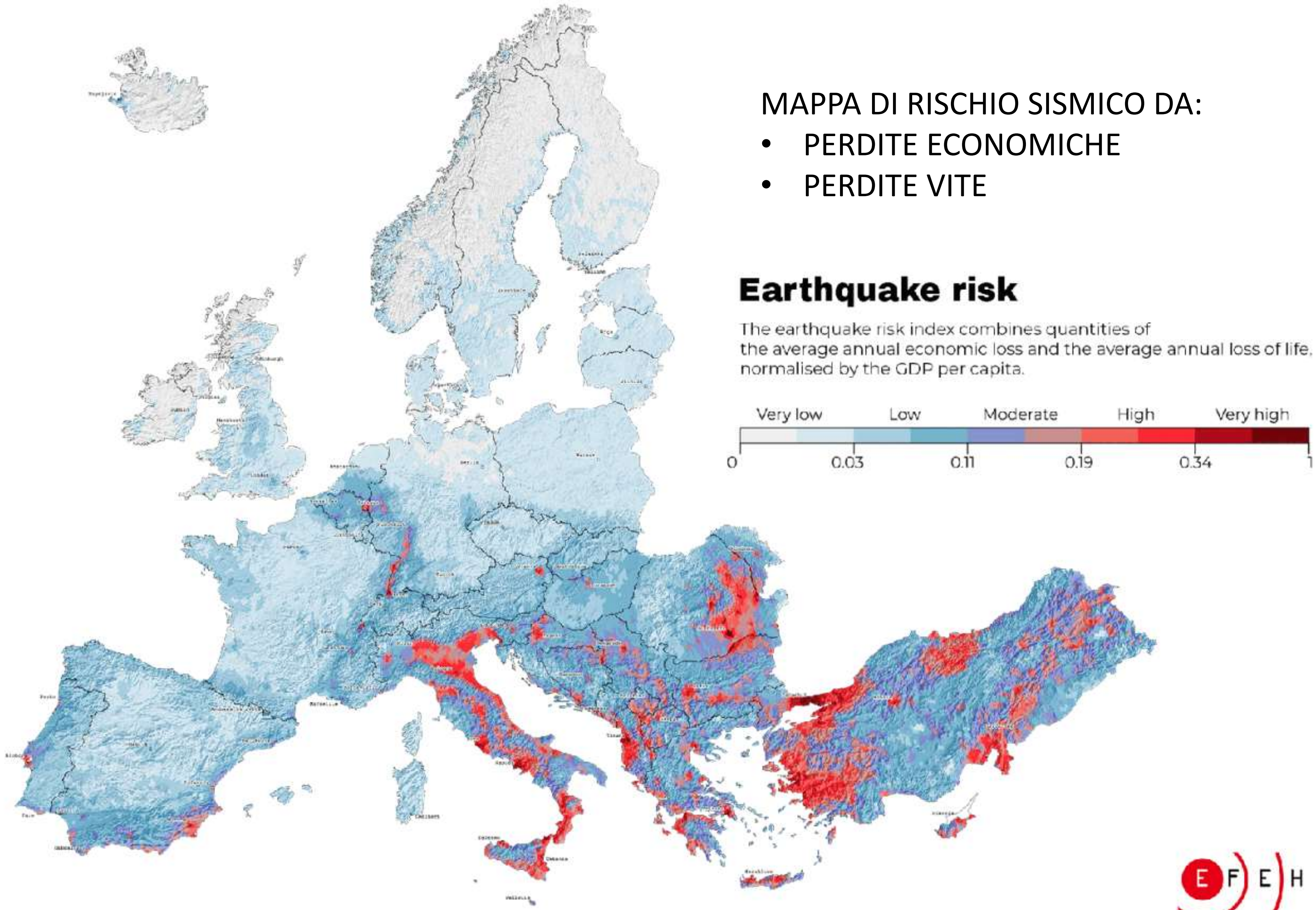
ETH, GEM, EPOS



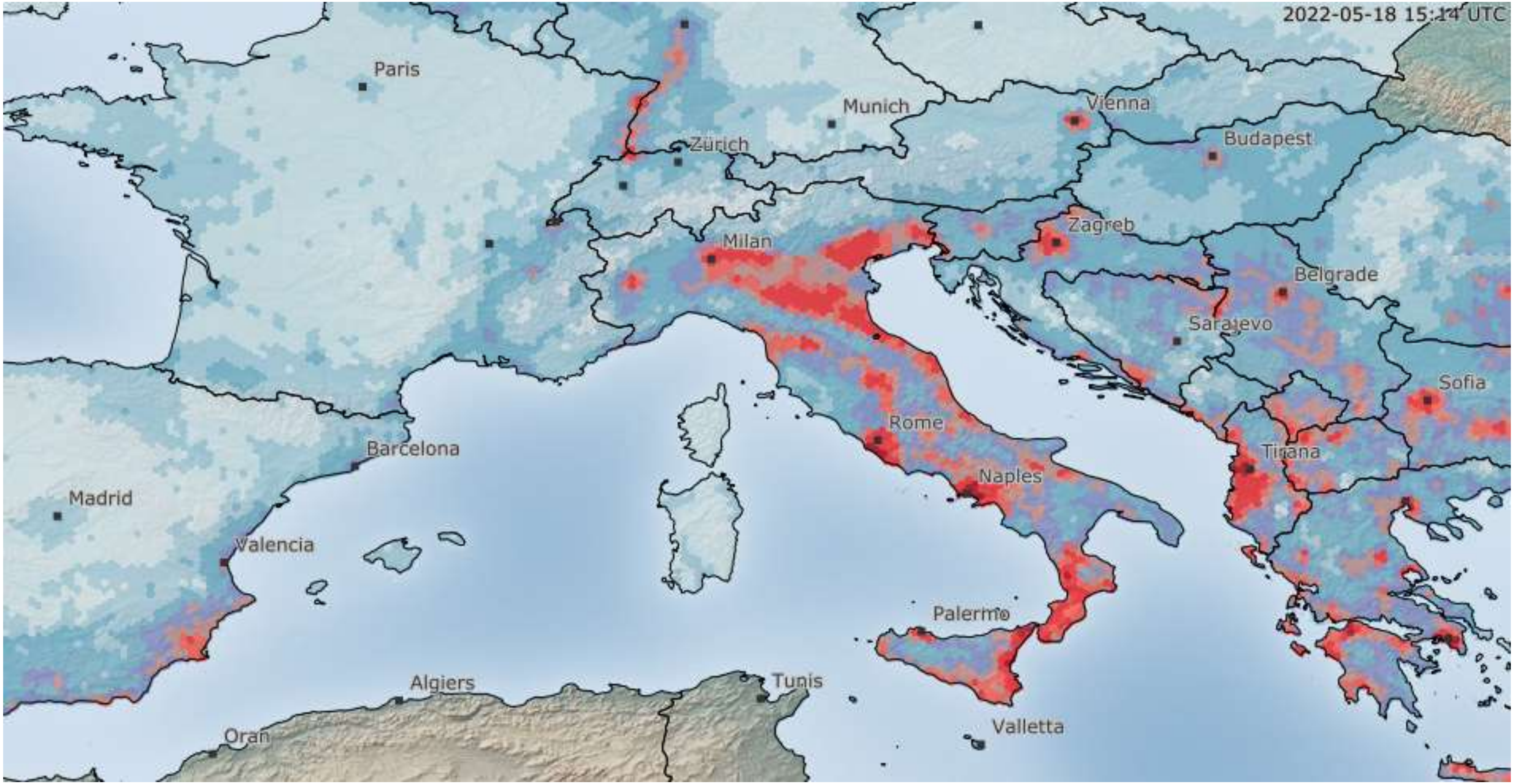



MAPPA DI RISCHIO SISMICO DA:

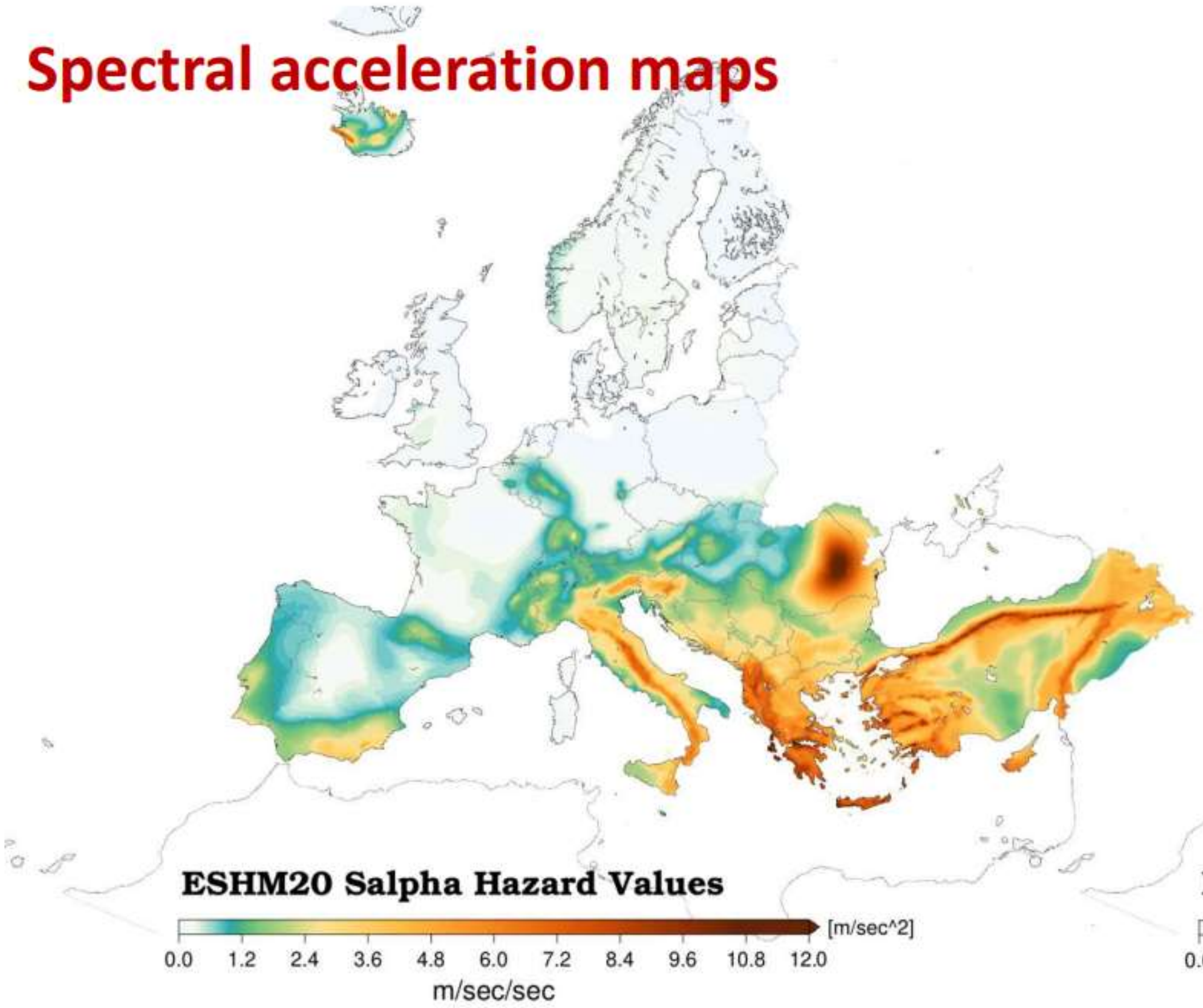
- PERDITE ECONOMICHE
- PERDITE VITE

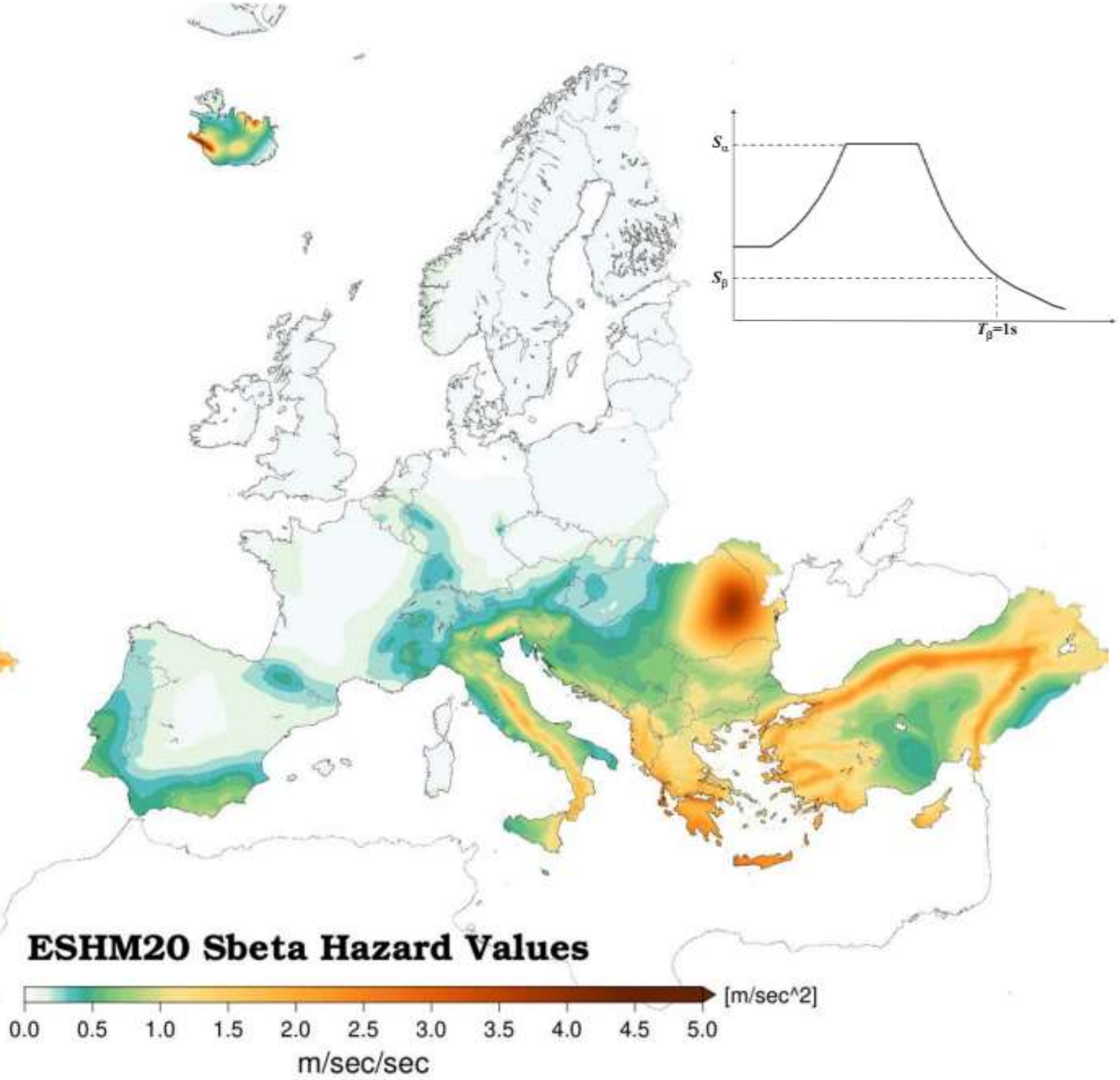


# RISCHIO DA PERDITE ECONOMICHE E VITE UMANE



# ESHM20 Salpha and Sbeta Hazard Values



# SEISMIC ACTION CLASS

$$S_\delta = \delta F_\alpha F_T S_{\alpha,475}$$

**Table 1.** Seismic action index values and associated seismic action classes.

| Range of seismic action index | Seismic action class |
|---|---|
| $S_\delta < 1{,}30\ \mathrm{m/s^2}$ | Very low |
| $1{,}30\ \mathrm{m/s^2} \leq S_\delta < 3{,}25\ \mathrm{m/s^2}$ | Low |
| $3{,}25\ \mathrm{m/s^2} \leq S_\delta < 6{,}50\ \mathrm{m/s^2}$ | Moderate |
| $S_\delta \geq 6{,}50\ \mathrm{m/s^2}$ | High |

**Table 2.** Recommended $\delta$ values in different parts of prEN1998.

| Consequence class | CC1 | CC2 | CC3-a | CC3-b |
|---|---|---|---|---|
| Part 1–2 and Part 2 | 0.6 | 1 | 1.25 | 1.6 |
| Part 4 | 0.6 | 1 | 1.4 | 1.8 |
| Part 5 | 0.6 | 1 | 1.5 | |

# RETURN PERIODS

**Table 3.** Recommended return period values (years) in different parts of prEN1998.

| Limit States | Part1-2 | | | | Part 2 | | | |
|---|---|---|---|---|---|---|---|---|
| | CC1 | CC2 | CC3-a | CC3-b | CC1 | CC2 | CC3-a | CC3-b |
| NC | 800 | 1600 | 2500 | 5000 | 800 | 1600 | 2500 | 5000 |
| SD | 250 | 475 | 800 | 1600 | 250 | 475 | 800 | 1600 |
| DL | 50 | 60 | 60 | 100 | 50 | 60 | 100 | 200 |
| | Part 4 | | | | Part 5 | | | |
| | CC1 | CC2 | CC3-a | CC3-b | CC1 | CC2 | CC3 | |
| NC | 800 | 1600 | 2500 | 5000 | 800 | 1600 | 2500 | |
| SD | 250 | 475 | 1300 | 2500 | 250 | 475 | 800 | |
| DL | 50 | 60 | 150 | 250 | 50 | 60 | 60 | |

# PERFORMANCE FACTOR

**Table 4.** Recommended performance factor values in different parts of prEN1998.

| Limit States | Part1-2 | | | | Part 2 | | | |
|---|---|---|---|---|---|---|---|---|
| | CC1 | CC2 | CC3-a | CC3-b | CC1 | CC2 | CC3-a | CC3-b |
| NC | 1.2 | 1.5 | 1.8 | 2.2 | 1.2 | 1.5 | 1.8 | 2.2 |
| SD | 0.8 | 1 | 1.2 | 1.5 | 0.8 | 1.0 | 1.25 | 1.5 |
| DL | 0.4 | 0.5 | 0.5 | 0.6 | 0.5 | 0.5 | 0.6 | 0.7 |
| | Part 4 | | | | Part 5 | | | |
| | CC1 | CC2 | CC3-a | CC3-b | CC1 | CC2 | CC3 | |
| NC | 1.2 | 1.5 | 1.8 | 2.2 | 1.2 | 1.5 | 1.8 | |
| SD | 0.8 | 1.0 | 1.4 | 1.8 | 0.8 | 1.0 | 1.2 | |
| DL | 0.4 | 0.5 | 0.7 | 0.8 | 0.4 | 0.5 | 0.5 | |

# SITE CATEGORIZATION

**Table 5.** Standard site categorisation.

| | **Ground class** | Stiff | Medium | Soft |
|---|---|---|---|---|
| **Depth class** | $v_{sH}$ in m/s | 800–400 | 400–250 | 250–150 |
| Very shallow | $H_{800} \leq 5$ m | A | A | E |
| Shallow | $5 \text{ m} < H_{800} \leq 30$ m | B | E | E |
| Intermediate | $30 < H_{800} \leq 100$ m | B | C | D |
| Deep | $H_{800} > 100$ m | B | F | F |

# ALTERNATIVE IDENTIFICATION SITE CATEGORY

**Table 6.** Site categorisation based on $v_{s,H}$ and $f_0$.

| Combination of $f_0$ (Hz) and $v_{s,H}$ (m/s) | Site category |
|---|---|
| $f_0 \geq 10$ and $v_{s,H} \geq 250$ | A |
| $f_0 < 10$ and $400 \leq v_{s,H} < 800$ | B |
| $v_{s,H}/250 \leq f_0 < v_{s,H}/120$ and $250 \leq v_{s,H} < 400$ | C |
| $v_{s,H}/250 \leq f_0 < v_{s,H}/120$ and $150 \leq v_{s,H} < 250$ | D |
| $v_{s,H}/120 \leq f_0 < 10$ and $150 \leq v_{s,H} < 400$, or $f_0 \geq 10$ and $150 \leq v_{s,H} < 250$ | E |
| $f_0 < v_{s,H}/250$ and $150 \leq v_{s,H} < 400$ | F |

**Table 7.** Seismicity levels and $f_h$ values.

| $S_{\alpha,475}$ (m/s$^2$) | Seismicity level | $f_h$ |
|---|---|---|
| $S_{\alpha,475} < 1.0$ | Very low | 0.2 |
| $1.0 \leq S_{\alpha,475} < 2.5$ | Low | 0.2 |
| $2.5 \leq S_{\alpha,475} < 5.0$ | Moderate | 0.3 |
| $5.0 \leq S_{\alpha,475}$ | High | 0.4 |

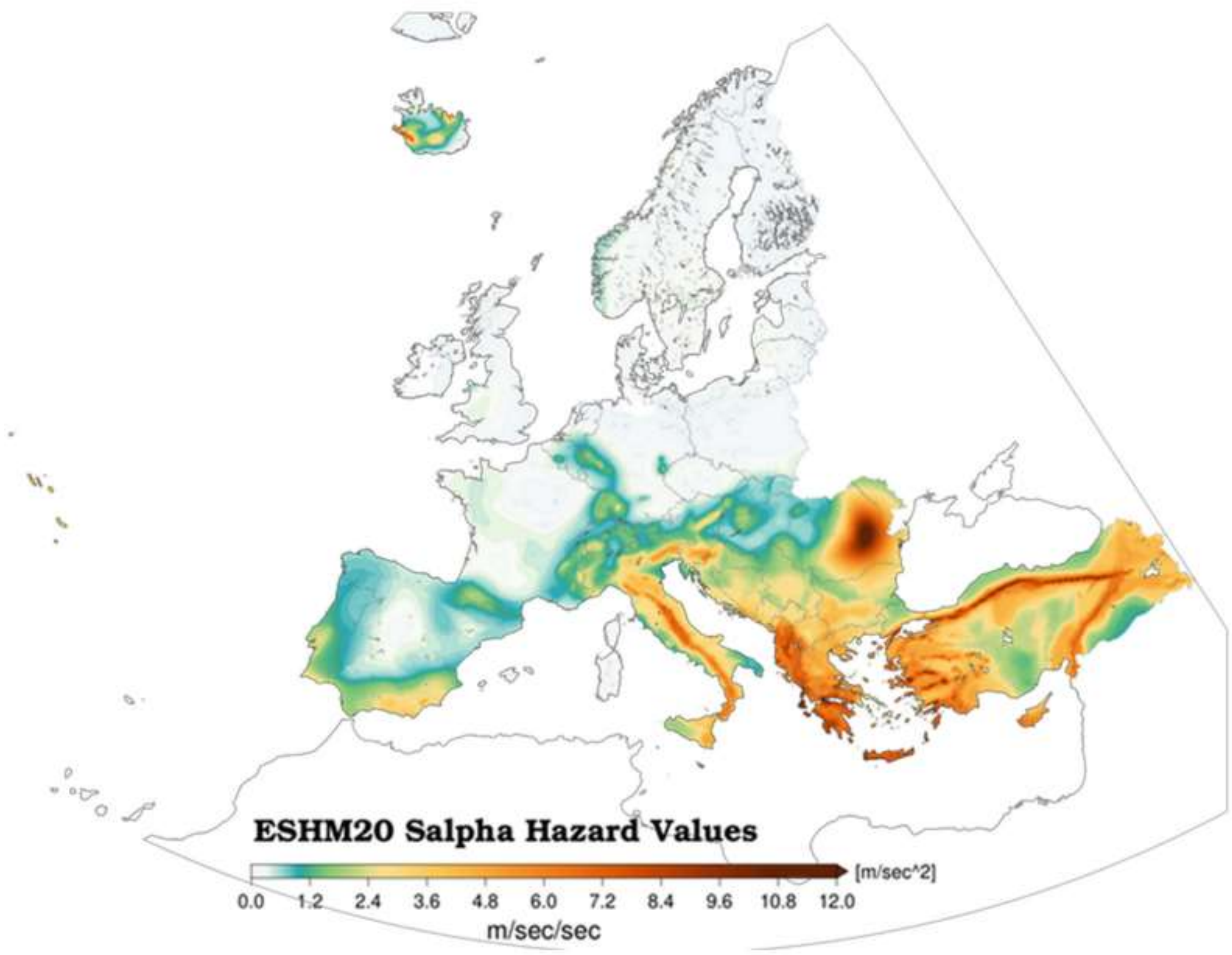



**Fig. 2.** A representation of $S_{\alpha,475}$ European map for rock sites, based on ESHM20.

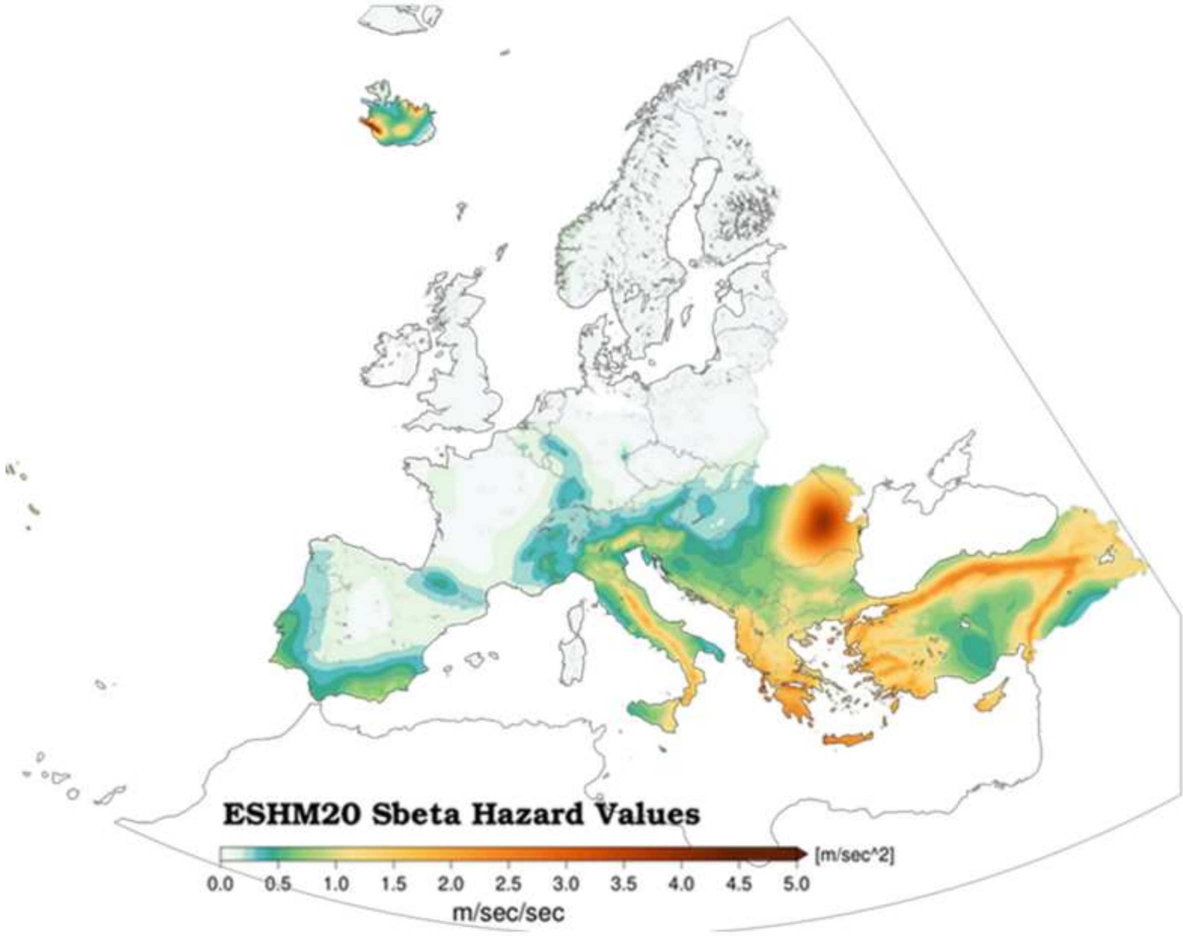



**Fig. 3.** A representation of $S_{\beta,475}$ European map for rock sites, based on ESHM20

$$S_{\alpha} = F_{\alpha} F_{\mathrm{T}} S_{\alpha,\mathrm{RP}}; S_{\beta} = F_{\beta} F_{\mathrm{T}} S_{\beta,\mathrm{RP}}$$

**Table 8.** Recommended values of $T_{\mathrm{A}}, F_{\mathrm{A}}, \chi, T_{\mathrm{D}}$

| $T_{\mathrm{A}}$ (s) | $F_{\mathrm{A}}$ | $\chi$ | $T_{\mathrm{D}}$ (s) |
|---|---|---|---|
| 0,02 | 2,5 | 4 | 2 if $S_{\beta,\mathrm{RP}} \leq 1\ \mathrm{m/s^2}$<br>$1 + S_{\beta,\mathrm{RP}}$ if $S_{\beta,\mathrm{RP}} > 1\ \mathrm{m/s^2}$ |

**Table 9a.** Short period site amplification factor $F_\alpha$.

| Site category | $H_{800}$ and $v_{s,H}$ available | Default value |
|---|---|---|
| A | 1 | 1,0 |
| B | $\left(\frac{v_{s,H}}{800}\right)^{-0,40\, r_\alpha}$ | $1{,}3\,(1-0{,}1\,S_{\alpha,RP}/g)$ |
| C | | $1{,}6\,(1-0{,}2\,S_{\alpha,RP}/g)$ |
| D | | $1{,}8\,(1-0{,}3\,S_{\alpha,RP}/g)$ |
| E | $\left(\frac{v_{s,H}}{800}\right)^{-0,40\, r_\alpha \frac{H_{800}}{30}\left(4-\frac{H_{800}}{10}\right)}$ | $2{,}2\,(1-0{,}5\,S_{\alpha,RP}/g)$ |
| F | $0{,}90\,\left(\frac{v_{s,H}}{800}\right)^{-0,40\, r_\alpha}$ | $1{,}7\,(1-0{,}3\,S_{\alpha,RP}/g)$ |

$$r_\alpha = 1 - \frac{S_{\alpha,RP}/g}{v_{s,H}/150}$$

**Table 9b.** Intermediate period site amplification factor $F_\beta$.

| Site category | $H_{800}$ and $v_{s,H}$ available | Default value |
|---|---|---|
| A | 1,0 | 1,0 |
| B | $\left(\frac{v_{s,H}}{800}\right)^{-0,70\, r_\beta}$ | $1,6\,(1-0,2\,S_{\beta,RP}/g)$ |
| C | | $2,3\,(1-0,3\,S_{\beta,RP}/g)$ |
| D | | $3,2\,(1-S_{\beta,RP}/g)$ |
| E | $\left(\frac{v_{s,H}}{800}\right)^{-0,70\, r_\beta \frac{H_{800}}{30}}$ | $3,2\,(1-S_{\beta,RP}/g)$ |
| F | $1,25\cdot\left(\frac{v_{s,H}}{800}\right)^{-0,70\, r_\beta}$ | $4,0\,(1-S_{\beta,RP}/g)$ |

$$r_\beta = 1 - \frac{S_{\beta,RP}/g}{v_{s,H}/150}$$

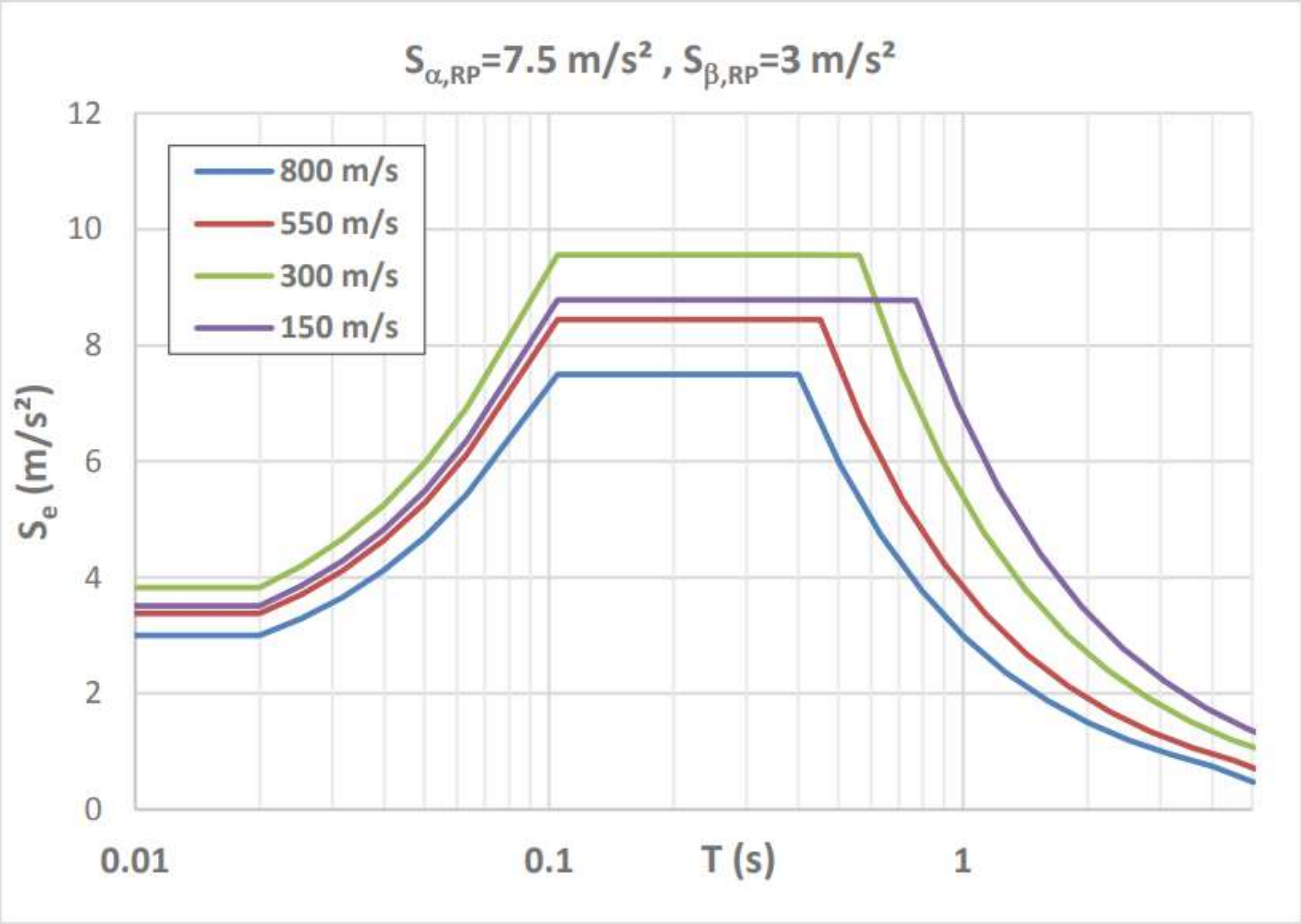



**Fig. 4.** Effects of site amplification factors on elastic response spectra in a high seismicity area for different $v_{s,H}$ values

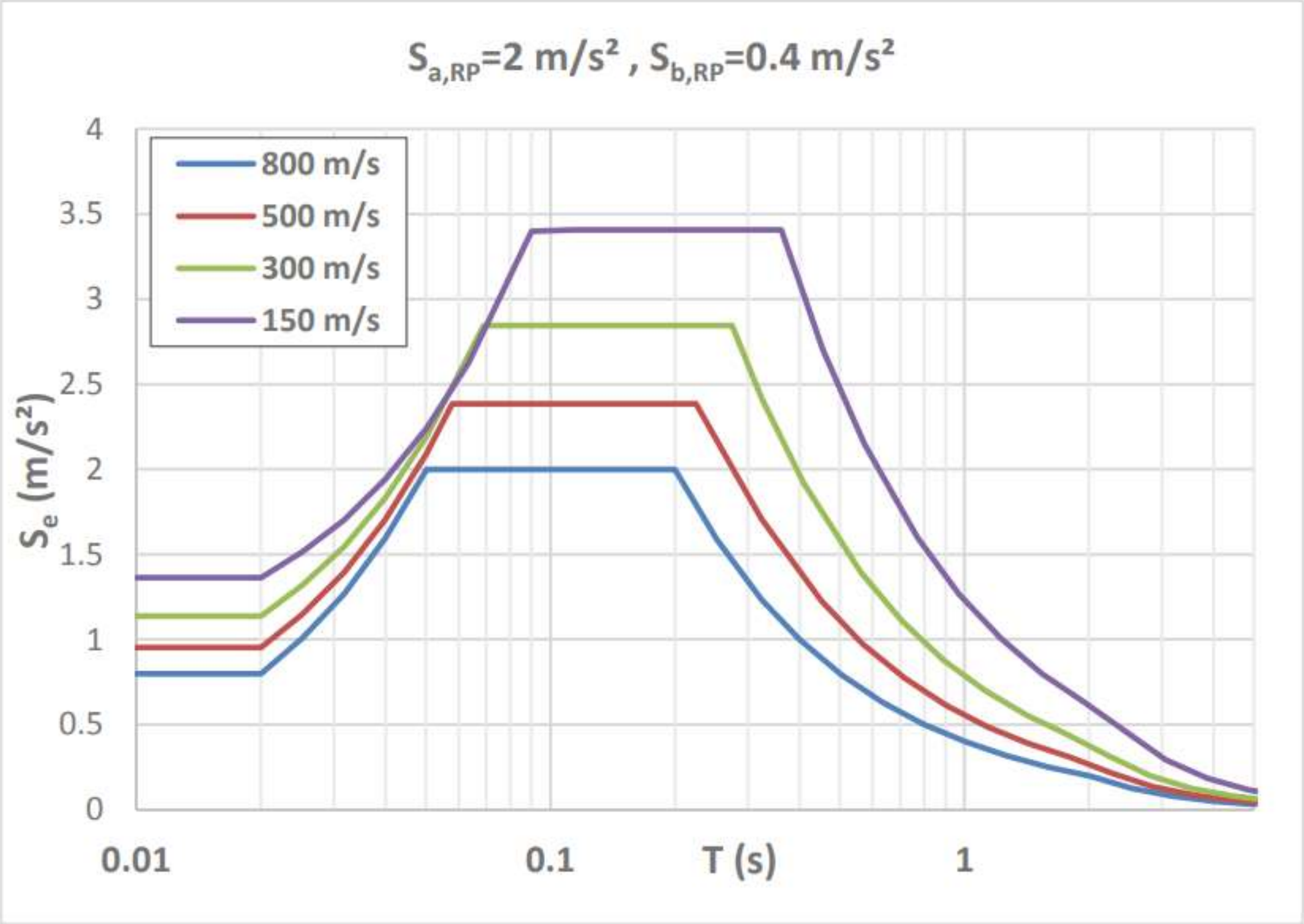



**Fig. 5.** Effects of site amplification factors on elastic response spectra in a low seismicity area for different $v_{S,H}$ values

# ELASTIC DISPLACEMENT RESPONSE SPECTRA

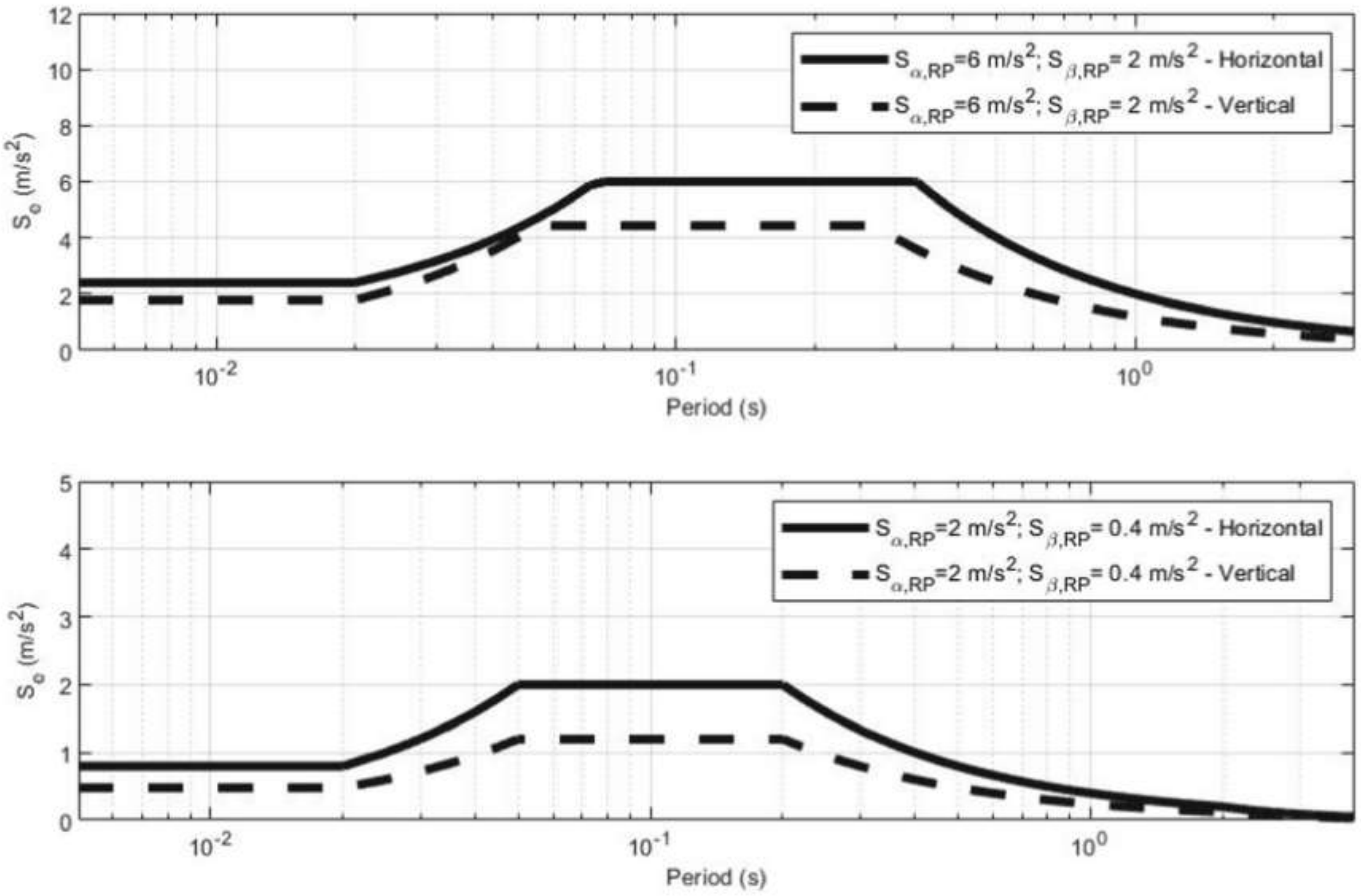



**Fig. 6.** Comparison of horizontal (continuous line) and vertical (dashed line) elastic response spectra for a high seismicity (top) and low seismicity (bottom) site category A.

# ADDITIONAL INFORMATION ON STANDARD RESPONSE SPECTRA

TOPOGRAFIC AMPLIFICATION FACTOR

DAMPING CORRECTION FACTOR

VERTICAL ELASTIC RESPONSE SPECTRUM

ELASTIC DISPLACEMENT RESPONSE SPECTRUM

GROUND MOTION PEAK VALUES

REDUCED SPECTRUM FOR FORCE BASED APPROACH

SEISMIC MOTION TRANSFERRED TO ANCILLARY ELEMENTS

# CONVENTIONAL MAGNITUDE AND STRONG MOTION DURATIONS

**Table 10.** Conventional magnitudes and strong motion durations.

| Range of $S_{\beta,RP}$ (m/s$^2$) | $M_W$ | $D_R$ | | |
|---|---|---|---|---|
| | | Site cat. A | Site cat. B & C | Other |
| $S_{\beta.RP} \leq 0.08$ | 4.5 | 0.5 | 0.6 | 0.75 |
| $0.08 < S_{\beta.RP} \leq 0.2$ | 5.0 | 1.0 | 1.2 | 1.5 |
| $0.2 < S_{\beta.RP} \leq 0.5$ | 5.5 | 2.0 | 2.4 | 3.0 |
| $0.5 < S_{\beta.RP} \leq 1.2$ | 6.0 | 4.0 | 4.8 | 6.0 |
| $1.2 < S_{\beta.RP} \leq 2.5$ | 6.5 | 8.0 | 9.6 | 12 |
| $2.5 < S_{\beta.RP} \leq 4.0$ | 7.0 | 16 | 19 | 24 |
| $S_{\beta.RP} > 4.0$ | 7.5 | 32 | 38 | 48 |

# INPUT MOTION IN THE FORM OF TIME SERIES

# SPATIAL VARIABILITY OF THE SEISMIC MOTION

$$\rho_{\mathrm{kl}} = \exp\left(-\frac{2L_{\mathrm{kl}}}{a_{\mathrm{kl}}(L_{\mathrm{g,k}} + L_{\mathrm{g,l}})}\right) \text{with } a_{\mathrm{kl}} = \exp\left(-\frac{L_{\mathrm{g,k}} - L_{\mathrm{g,l}}}{500}\right)$$

**Table 11.** Characteristic lengths.

| Site category | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| $L_g$ (m) | 400 | 300 | 250 | 200 | 300 | 200 |

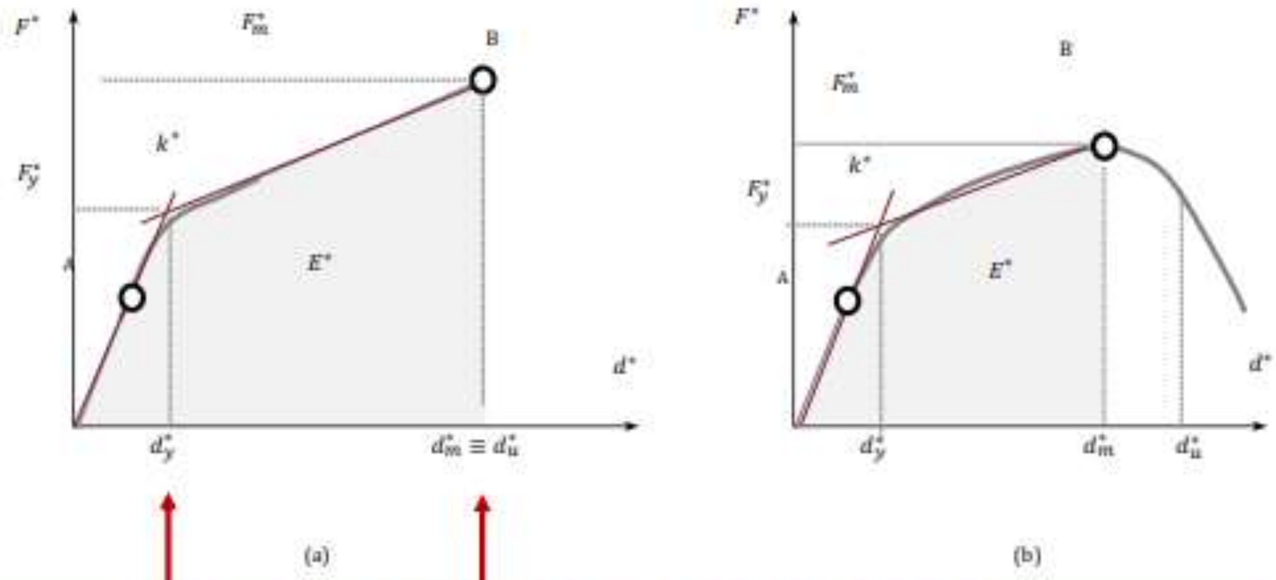
# EN1998 DESIGN OF STRUCTURE FOR EARTHQUAKE RESISTANCE

## pr EN1998-1-2:2022 vers. 15-03-2022

PARTS

| | | | |
|---|---|---|---|
| EC8-1 | 1-1 | GENERAL RULES AND SEISMIC ACTION | PIERRE LABBE’ |
| | 1-2 | NEW BUILDINGS | ANDRE PLUMIER |
| EC8-2 | | BRIDGES | FRANCHIN, KAPPOS |
| EC8-3 | | ASSESSMENT AND RETROFITTING OF BUILDINGS AND BRIDGES | ANDREAS KAPPOS |
| EC8-4 | | SILOS, TANKS, PIPELINES, TOWERS, MASTS, CHIMNEYS | BUTENWEG |
| EC8-5 | | GEOTECHNICS: GENERAL RULES AND SEISMIC ACTION | ALAIN PECKER |

# Example: bilinear model of pushover curves




**Deformation criteria developed in EN1998-1-1 for concrete and steel**

# Description of Limit States (ULS)

- LS of Near Collapse (NC) shall be defined as one in which the structure is heavily damaged, with large permanent drifts, but retains its vertical load bearing capacity; most ancillary components, where present, have collapsed.
- LS of Significant Damage (SD) shall be defined as one in which the structure is significantly damaged, possibly with moderate permanent drifts, but retains its vertical-load bearing capacity; ancillary components, where present, are damaged (e.g., partitions and infills have not yet failed out-of-plane). The structure is expected to be repairable, but, in some cases, it may be uneconomic to repair.

+ Description of Damage Limitation (DL) and Operability (OP), both SLS

# EN1998-1-2  NEW BUILDINGS

CHAPTER
1,2,3 SCOPE, NORMATIVE REFERENCE, TERMS
4. BASIS OF DESIGN
5. MODELLING AND STRUCTURAL ANALYSIS
6. VERIFICATION OF STRUCTURAL MEMBER TO LIMIT STATES
7. ANCILLARY ELEMENTS
8. BASE ISOLATED BUILDINGS
9. BUILDINS WITH ENERGY DISSIPATION SYSTEMS
10. SPECIFIC RULES FOR CONCRETE BUILDINGS
11. SPECIFIC RULES FOR STEEL BUILDINGS
12. SPECIFIC RULES FOR COMPOSITE STEEL-CONCRETE BUILDINGS
13. SPECIFIC RULES FOR TIMBER BUILDINGS
14. SPECIFIC RULES FOR MASONRY BUILDINGS
15. SPECIFIC RULES FOR ALUMINIUM BUILDINGS

## EC8-1-2 DESIGN OF STRUCTURES FOR EARTHQUAKE RESISTANCE

ANNEXES (NORMATIVE INFORMATIVE)

A. CHARACTERISTIC OF EARTHQUAKE RESISTANT BUILDINGS AND IN PLAN REGULARITY

B. NATURAL ECCENTRICITY AND TORSIONAL RADIUS

C. FLOOR ACCELERATION FOR ANCILLARY ELEMENTS

D. BUILDINGS WITH ENERGY DISSIPATION SYSTEMS

E. SEISMIC DESIGN OF CONNECTION FOR STEEL BUILDINGS

F. STEEL LIGHT WEIGHT STRUCTURES

G.DESIGN OF COMPOSITE CONCRETE DISSIPATIVE COMPOST STEEL CONCRTE MRF

H.SEIS. DESIGN OF EXPOSED AND EMBED. STEEL AND COMP. COLUMN BASE CONNECTION

I. DESIGN OF THE SLAB OF S-C COMPOSITE BEAMS AT THE BASE COLUMN JOINTS IN MRF

J. DRIFT LIMITS FOR ECCENTRICALLY LOADED UNREINFORCED MASONRY PIERS

K. SIMPLIFIED EVALUATION OF DRIFT DEMANDS ON INFILLED FRAMES

L. LOADS DEFORMATION RELATIONSHIPS

M.MATERIALS OR PRODUCTS PROPERTIES

N. EVALUATION OF THE LATERAL DISPLACEMENTS FOR MULTISTOREY CROSS LAMINATED TIMBER (CL) SHEAR WALL

# Safety choices for buildings (NDPs)

| Return periods in years | | | | |
|---|---|---|---|---|
| Limit state (LS) | Consequence class | | | |
| | CC1 | CC2 | CC3-a | CC3-b |
| NC | 800 | 1600 | 2500 | 5000 |
| SD | 250 | 475 | 800 | 1600 |
| DL | 50 | 60 | 60 | 100 |

| Performance factors | | | | |
|---|---|---|---|---|
| Limit state (LS) | Consequence class (IC) | | | |
| | CC1 | CC2 | CC3-a | CC3-b |
| NC | 1,2 | 1,5 | 1,8 | 2,2 |
| SD | 0,8 | 1 | 1,2 | 1,5 |
| DL | 0,4 | 0,5 | 0,5 | 0,6 |

# Global safety choice: seismicity index

- **Seismicity index**

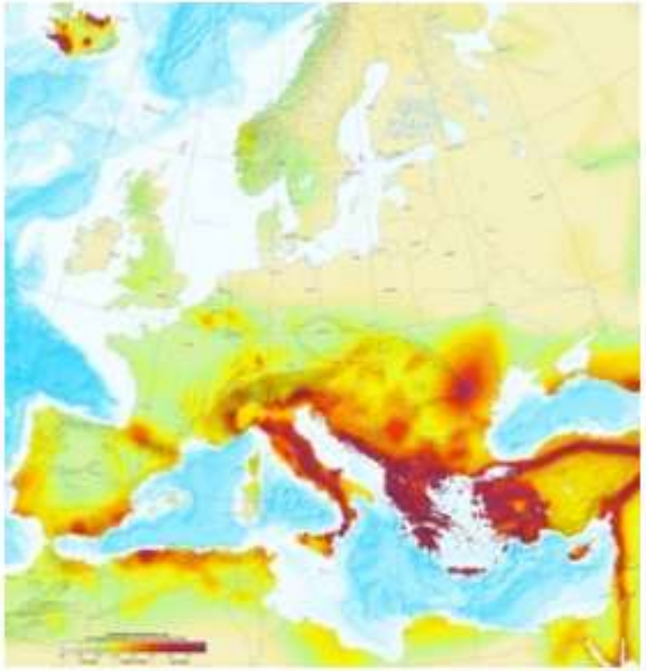
$S_d = \delta\, F_\alpha\, F_T\, S_{\alpha,475}$ → Seismic action

$\delta$ → depends on the Consequence Class of the structure (NDP)

- **Ranges of $S_\delta$ values for seismic action classes**

| **Seismic action class** | **Range of seismic action index $S_\delta$ (m/s²)** |
|---|---|
| Very low | $S_\delta < 1{,}30\ m/s^2$ |
| Low | $1{,}30\ m/s^2 \leq S_\delta < 3{,}25\ m/s^2$ |
| Moderate | $3{,}25\ m/s^2 \leq S_\delta < 6{,}50\ m/s^2$ |
| High | $S_\delta \geq 6{,}50\ m/s^2$ |

# New definition of ductility classes



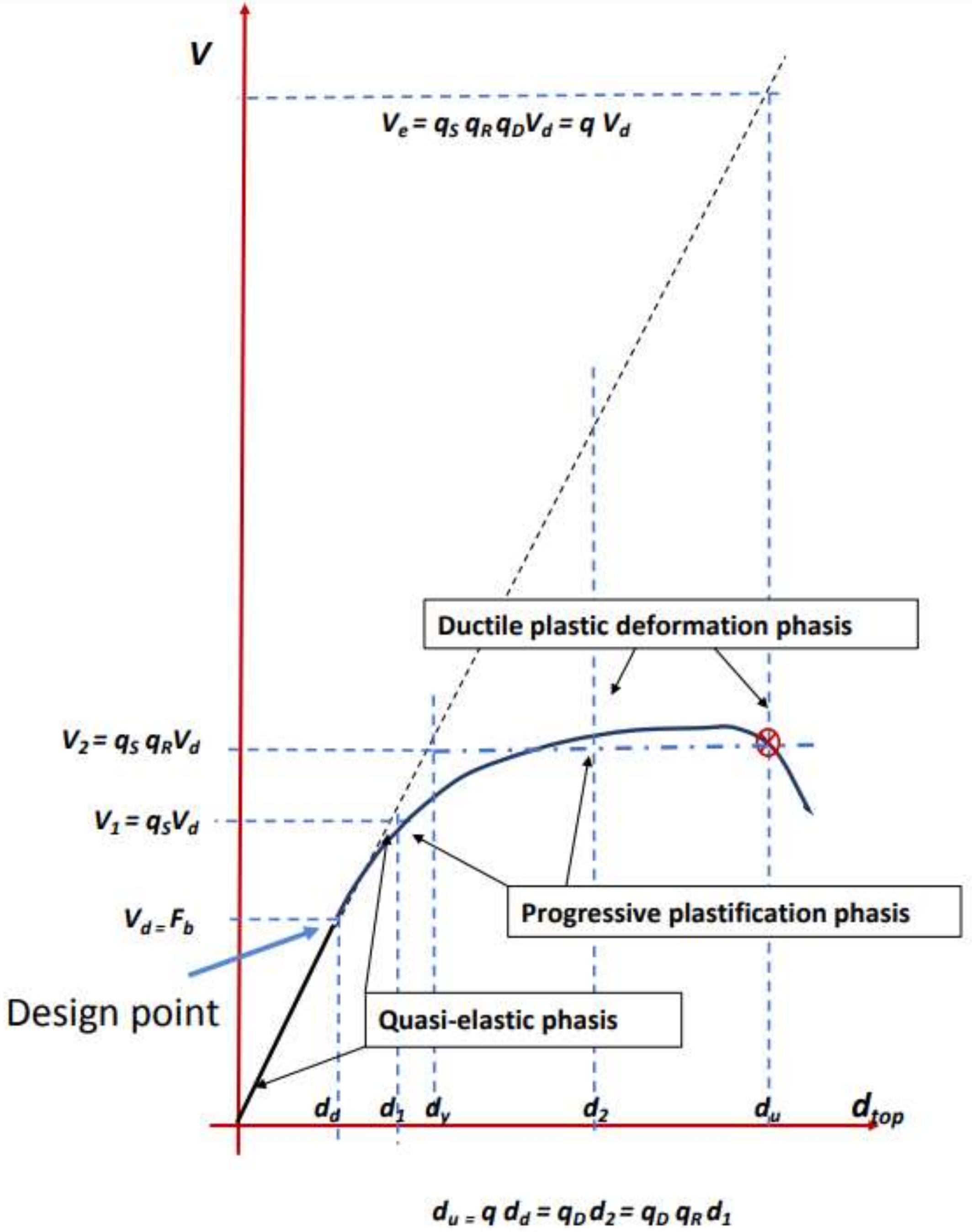
| Linear elastic design, force approach (q = 1) | |
|---|---|
| **DC1** | **Overstrength capacity (q = 1,5)** |
| **DC2** | **Overstrength capacity, local deformation capacity and local energy dissipation capacity** |
| **DC3** | **Ability of the structure to form a global plastic mechanism at SD limit state** |

# Global behaviour and *q*-factor

$q = q_R\ q_S\ q_D$

$q_S = 1{,}5$

$q_R = \alpha_u / \alpha_1$



# Values of the *q*-factor: example (RC)

<table>
<tr><th colspan="2" rowspan="2">Structural type</th><th rowspan="2">$q_R$</th><th colspan="2">$q_D$</th><th colspan="2">$q = q_R\,q_S\,q_D$</th></tr>
<tr><th>DC2</th><th>DC3</th><th>DC2</th><th>DC3</th></tr>
<tr><td rowspan="3">Moment resisting frame or moment resisting frame-equivalent dual structures</td><td>multi-storey, multi-bay moment resisting frames or moment resisting frame-equivalent dual structures</td><td>1,3</td><td rowspan="3">1,3</td><td rowspan="3">2,0</td><td>2,5</td><td>3,9</td></tr>
<tr><td>multi-storey, one-bay moment resisting frames</td><td>1,2</td><td>2,3</td><td>3,6</td></tr>
<tr><td>one-storey moment resisting frames</td><td>1,1</td><td>2,1</td><td>3,3</td></tr>
<tr><td>Moment resisting frame or moment resisting frame-equivalent dual structures with interacting masonry infills</td><td></td><td>1,1</td><td>1,2</td><td>1,7</td><td>2,0</td><td>3,0</td></tr>
<tr><td rowspan="4">Wall- or wall-equivalent dual structures</td><td>wall-equivalent dual structures</td><td>1,2</td><td>1,3</td><td rowspan="3">2,0</td><td>2,3</td><td>3,6</td></tr>
<tr><td>coupled walls structures</td><td>1,2</td><td>1,4</td><td>2,5</td><td>3,6</td></tr>
<tr><td>uncoupled walls structures</td><td>1,0</td><td>1,3</td><td>2,0</td><td>3,0</td></tr>
<tr><td>large walls structures</td><td>--</td><td colspan="2">--</td><td colspan="2">3,0 $k_w$</td></tr>
<tr><td colspan="2">Flat slab structures</td><td>1,1</td><td>1,2</td><td>--</td><td>2,0</td><td>--</td></tr>
</table>

# Domain of application of ductility classes: example (Steel)

| Structural type | Limits of seismic action index $S_{\delta}$ $(m/s^2)$ | | |
|---|---|---|---|
| | DC1 | DC2 | DC3 |
| Moment frames | 5,0 | 6,5 | no limit |
| Frames with concentric or eccentric bracings | 5,0 | 6,5 | no limit |
| Buckling-restrained braced frames | - | - | no limit |
| Dual frames (moment frames with bracings) | 5,0 | 7,5 | no limit |
| Steel structure with concrete cores/walls | 5,0 | 7,5 | no limit |
| Lightweight steel frame wall systems | 5,0 | 7,5 | no limit |
| Inverted pendulum | 2,5 | 5,0 | no limit |
| Moment resisting frames with unconnected interacting concrete or masonry infills | 2,5 | 5,0 | no limit |
| Moment resisting frames with non-interacting infills | 5,0 | 6,5 | no limit |

# Verifications to SD LS

- Equilibrium condition
- Control of second order effects
- Limitation of interstorey drift
- Verifications of members stability
- Capacity design in DC2 & DC3
- Verifications of resistance according to material Eurocodes (force based approach)
- (materials)

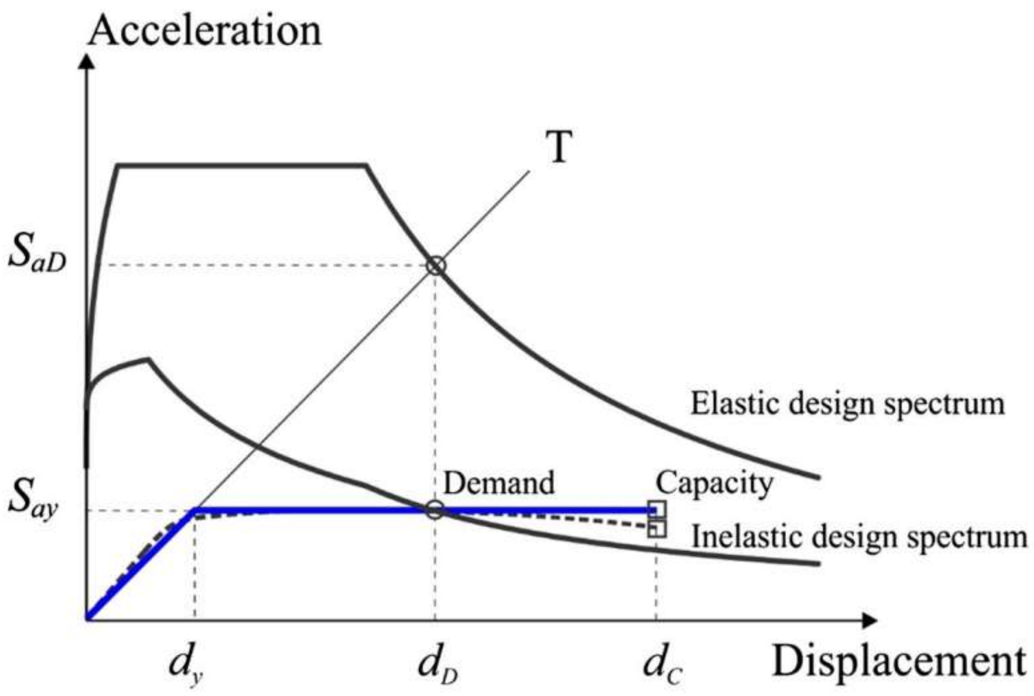
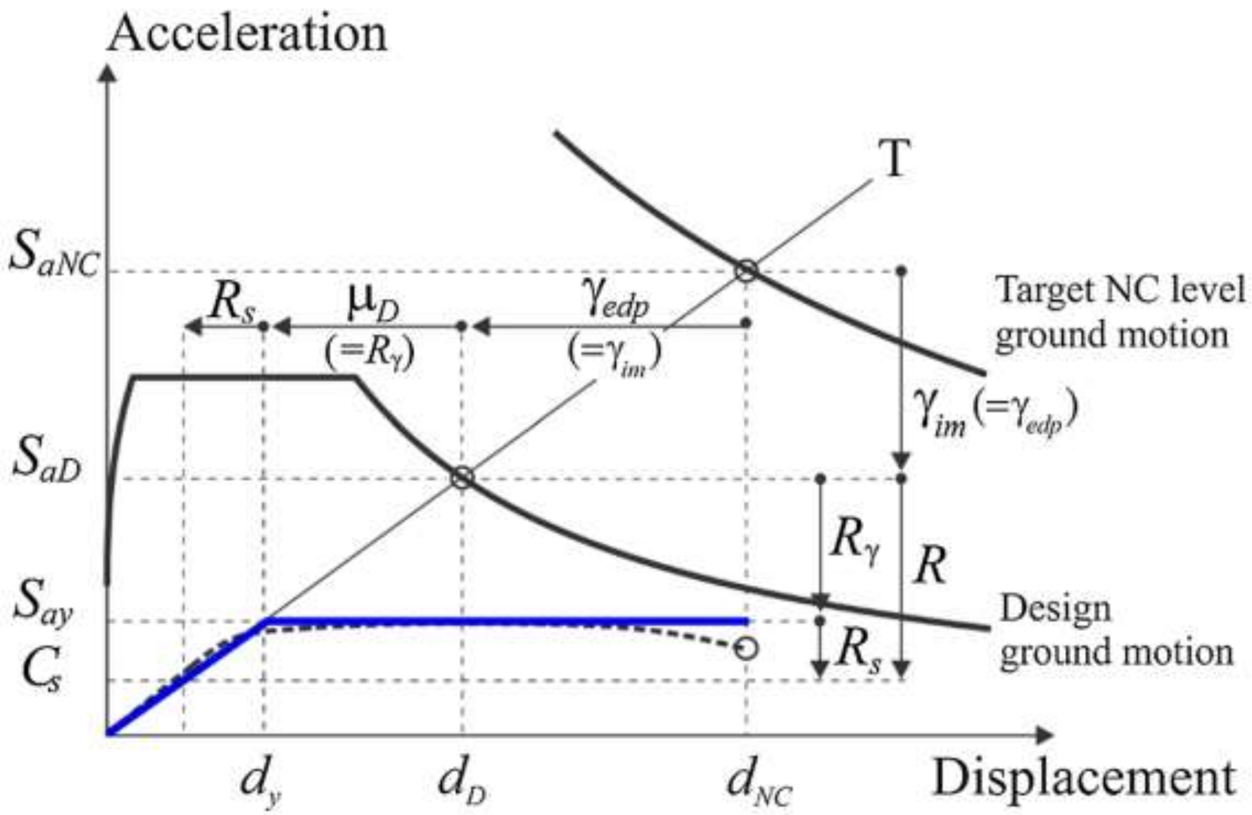



**Fig. 3** Comparison of demand and capacity in the acceleration–displacement (AD) format




$$R = \frac{S_{aD}}{C_s} = \frac{S_{aD}}{S_{ay}}\frac{S_{ay}}{C_s} = R_\mu R_s = \frac{R_{\mu NC} R_s}{\gamma_{im}}, \qquad S_{aD} = \frac{S_{aNC}}{\gamma_{im}}, \qquad d_D = \frac{d_{NC}}{\gamma_{edp}}$$

**Fig. 6** Illustration of parameters relevant for the determination of the capacities and force reduction factors. In the plot the validity of the equal displacement rule was assumed. The presented parameters apply to a general case, with the exception of the equalities in brackets which apply only in the case if the equal displacement rule is valid

Table 1. Qualification of Consequences Classes

| Consequence Class | Description of consequences | Examples for buildings | Examples for Geotechnical structures |
|---|---|---|---|
| CC3–b | Highest | Buildings of installations of vital importance for civil protection, e.g. hospitals, fire stations, etc. and their equipment | |
| CC3–a | Higher | Buildings whose seismic resistance is of importance in view of the consequences associated with a collapse, e.g. schools, assembly halls, cultural institutions | Large earth dams, deep excavations, tunnels for major infrastructures |
| CC2 | Normal | Residential and office buildings small buildings | Natural slopes, small earth dams, tunnels, retaining structures |
| CC1 | Lower | Agricultural buildings Storage buildings | Embankments and retaining walls, with height less than 3m |

**Table 4.2 (NDP) — $\delta$ values for buildings**

| | Consequence class (CC) | | | |
|---|---|---|---|---|
| | CC1 | CC2 | CC3-a | CC3-b |
| δ | 0,60 | 1,0 | 1,25 | 1,60 |

# RETURN PERIODS OF SEISMIC ACTION $T_{CC,LS}$

| Limit state | Consequence class (CC) | | | |
|---|---|---|---|---|
| | CC1 | CC2 | CC3-a | CC3-b |
| NC | 800 | 1600 | 2500 | 5000 |
| SD | 250 | 475 | 800 | 1600 |
| DL | 50 | 60 | 60 | 100 |

PERFORMANCE FACTORS OF SEISMIC ACTION GCC,LS

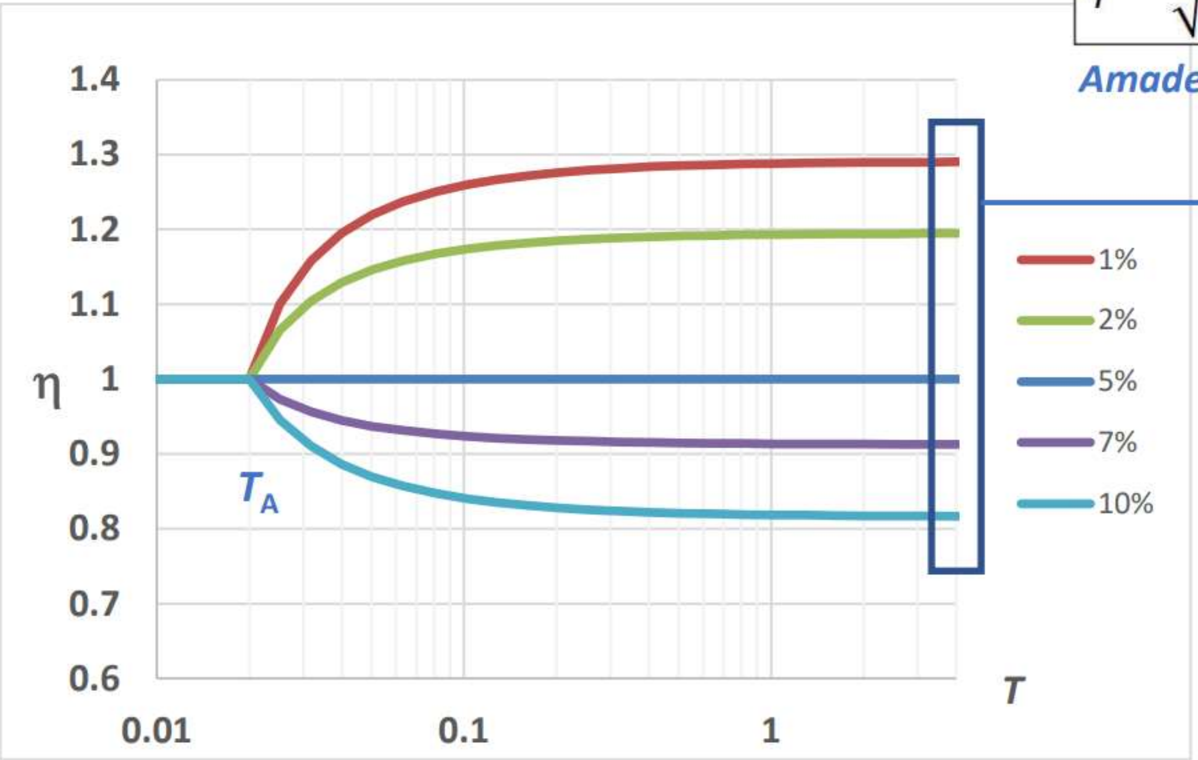
| | CC1 | CC2 | CC3-a | CC3-b |
|---|---|---|---|---|
| NC | 1,2 | 1,5 | 1,8 | 2,2 |
| SD | 0,8 | 1 | 1,2 | 1,5 |
| DL | 0,4 | 0,5 | 0,5 | 0,6 |

# Seismic action, § 5.2 / Standard response spectrum, § 5.2.2.2

## Damping correction factor

$$\eta = \sqrt{\left(10 + \frac{T_C(\xi - 5)}{T_C + 30\,(T - T_A)}\right) / (5 + \xi)} \quad T \leq 4\text{s}$$

*Amadeo Benavent-Climent*




Current EC8 values

# Seismic action, § 5.2 / Site amplification factors, § 5.2.2.2

$S_\alpha = F_T F_\alpha S_{\alpha,RP}$

$S_\beta = F_T F_\beta S_{\beta,RP}$

RP is the return period associated to the CC and LS under consideration. For instance the RP default value for a CC3-a bridge verified at the NC limit state is 2500 y.

- $S_{\alpha,RP}$ and $S_{\beta,RP}$ can be obtained from hazard maps at the considered return period RP,
- or by applying:

  $S_{\alpha,RP} = \gamma_{SD,CC} S_{\alpha,Ref}$

  $S_{\beta,RP} = \gamma_{SD,CC} S_{\beta,Ref}$

  ($\gamma_{SD,CC}$ =1,8 for the above bridge case)

e.g. Part 2 table of return periods

| | CC1 | CC2 | CC3-a | CC3-b |
|---|---|---|---|---|
| NC | 800 | 1600 | 2500 | 5000 |
| SD | 250 | 475 | 800 | 1600 |
| DL | 50 | 60 | 100 | 200 |

e.g. Part 2 table of $\gamma_{SD,CC}$

| | | | | |
|---|---|---|---|---|
| NC | 1,2 | 1,5 | 1,8 | 2,2 |
| SD | 0,8 | 1,0 | 1,25 | 1,5 |
| DL | 0,5 | 0,5 | 0,6 | 0,7 |

$S_{\alpha,Ref} = S_{\alpha,475}$ in the vast majority of countries.

# Seismic action, § 5.2 / Site amplification factors, § 5.2.2.2

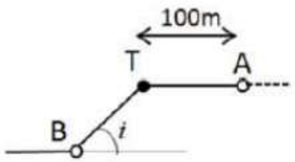
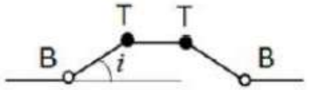
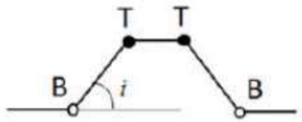
$F_T$ is the topography amplification factor;

$F_\alpha$ is the short period site amplification factor;
$F_\beta$ is the intermediate period ($T = T_\beta$) site amplification factor;

## Scientific background documentation for $F_\alpha$ and $F_\beta$ :

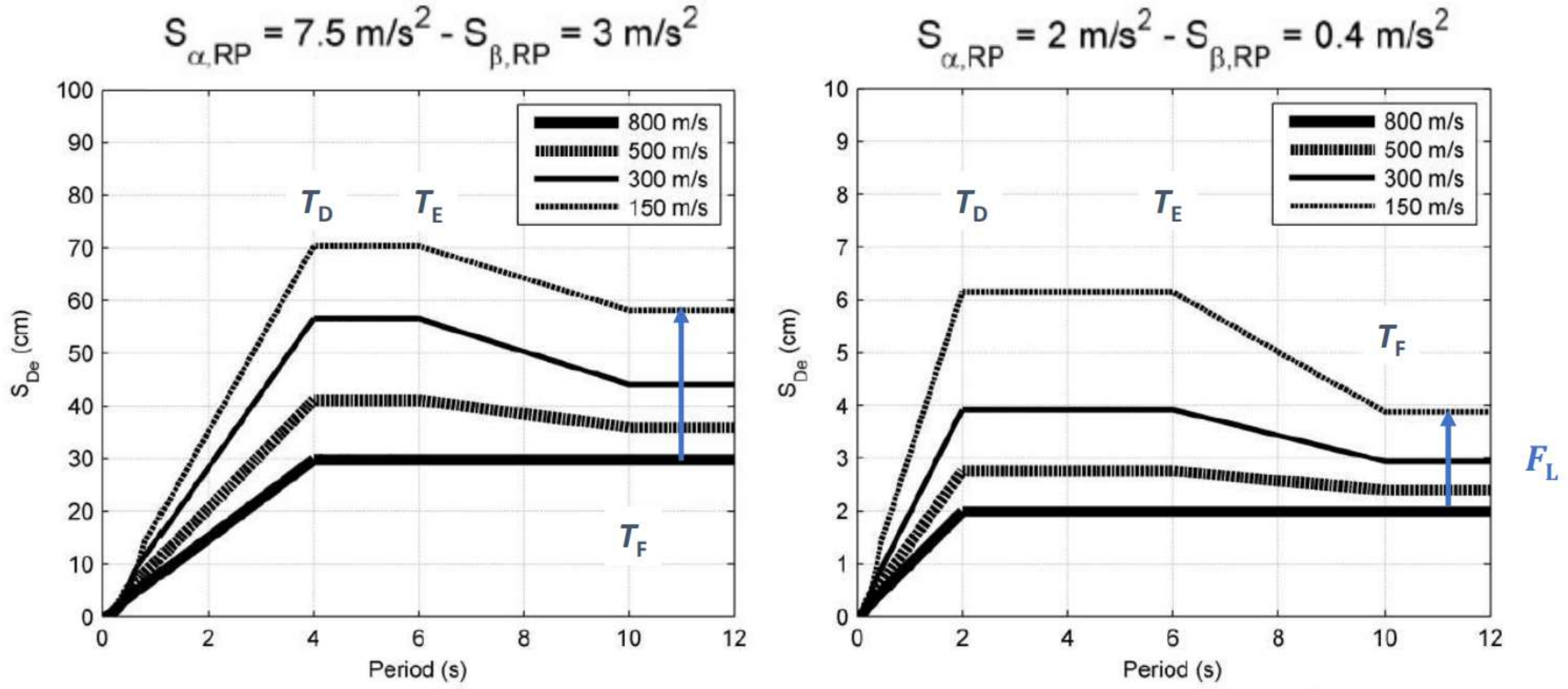
See background document as well as
Paolucci, R., Aimar, M., Ciancimino, A. *et al.* Checking the site categorization criteria and amplification factors of the 2021 draft of Eurocode 8 Part 1–1. *Bull Earthquake Eng* 19, 4199–4234 (2021).

Pitilakis K, Riga E, Anastasiadis A (2013) New code site classification, amplification factors and normalized response spectra based on a worldwide ground-motion database. Bull Earthq Eng 11(4):925–966

| $F_T$ | Simplified sketch* |
|---|---|
| 1,0 | |
| 1,2 |  |
| 1,2 |  |
| 1,4 |  |

*According to current Part 5*

# Seismic action, § 5.2 / Elastic displacement response spectrum, § 5.2.2.2



# Seismic action, § 5.2 / Design peak values, § 5.2.2.4

- **Displacement**

$$PGD_{\mathrm{e}} = S_{\mathrm{De}}(T_{\mathrm{F}}) = 0,025\, T_{\beta} T_{\mathrm{D}} F_{\mathrm{L}}\, F_{\mathrm{T}}\, S_{\beta,\mathrm{RP}}$$

*Considerations on displacement and velocity are not anymore disseminated in other Parts.*

$F_{\mathrm{L}}$ is the long period site amplification factor $F_{\mathrm{L}} = \left(\frac{v_{\mathrm{s,H}}}{800}\right)^{-0,4}$

**Replaces the current formula, built on a non-observed correlation between PGA and PGD:**

$$d_g = 0,025 \cdot a_g \cdot S \cdot T_C \cdot T_D$$

Paolucci R., C. Smerzini (2018). Empirical evaluation of peak ground velocity and displacement as a function of elastic spectral ordinates for design. Earthquake Engineering and Structural Dynamics, 47: 245-255.

# Seismic action, § 5.2 / Alternative representations § 5.2.3

## Spatial model of the seismic action §5.2.3.2

**For the purpose of Part 2, it is necessary that the correlation coefficient between input motion at two distant supports be introduced.**

$$\rho_{kl} = \exp\left(-\frac{2\,L_{kl}}{a_{kl}\left(L_{g,k}+L_{g,l}\right)}\right) \qquad a_{kl} = exp\left(-\frac{L_{g,k}-L_{g,l}}{500}\right)$$

$L_{kl}$ is the distance between supports *k* and *l*;

$L_{g,k}$ and $L_{g,l}$ are characteristic lengths given in Table 5.7 as functions of the site category of the considered supports *k* and *l*, respectively;

| Site category | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| $L_g$ (m) | 400 | 300 | 250 | 200 | 300 | 200 |

**In case of time-history analysis, the normalized cross-correlation between input motions at two different supports should not exceed the largest of $\rho_{kl}$ and 0,2.**

# Seismic action, § 5.2 / Alternative representations § 5.2.3

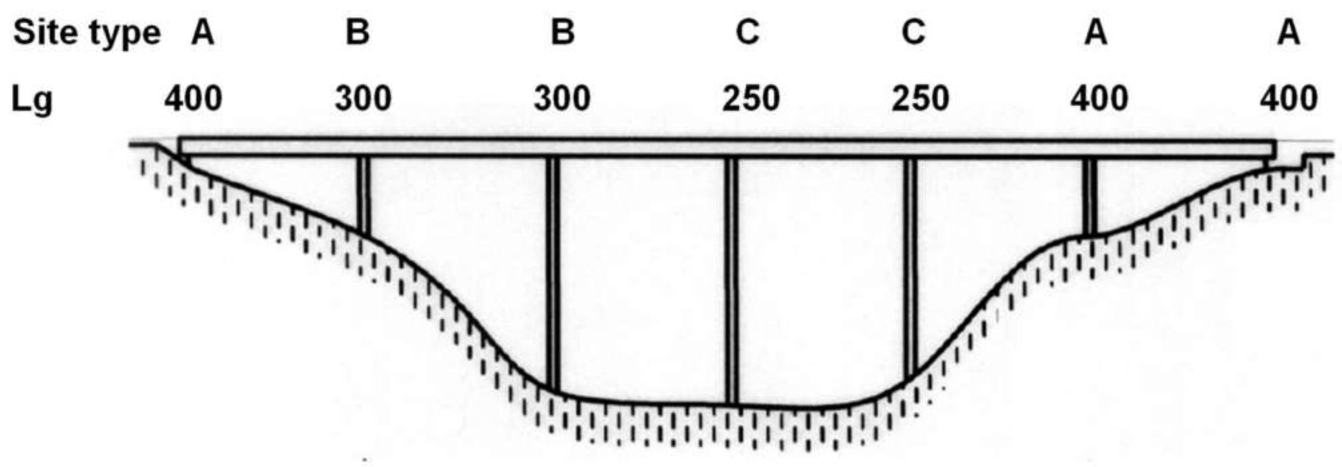
## Spatial model of the seismic action §5.2.3.2

**The between support correlation effect was addressed in a common PT6-PT4 meeting. Two causes of variability were identified:**

a) **Distance between supports and travelling wave effect.**
b) **Filtering effect through soil profiles.**

**It was recognized that b) prevails. Taking it into account is very easy through soil profiles features and CQC formula. However it might result in high correlation coefficient for distant supports.**

**Therefore distance dependance was introduced as expressed in formulas (5-29) and (5-30).**




***Contribution Anastasios Sextos***

# EC8-1-2-5 MODELLING, ANALISYS

## Section 6: Modelling, analysis and verification

- **6.1 General**
- **6.2 Modelling**
- 6.3 Seismic action for analysis
- **6.4** Linear elastic analysis for **force-based approach**
- **6.5 Non-linear static analysis** for displacement-based approach
- 6.6 Response history analysis
- **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 $q_{disp}$

- **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-$\mu$-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

## 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

# EC8-1-2-6:2022 VERIFICATION OF STRUCTURAL MEMBERS TO LS

6.1 GENERAL

6.2 VERIFICATION OF SIGNIFICANT DAMAGE (SD) LIMIT STATES

6.3 VERIFICATION TO OTHER LIMIT STATES

## 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

## 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: $q=q_R q_S q_D$
    - 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:

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

    - $\beta$=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:

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

    - $q_V=q_S=1.5$. 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

# 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)

- Assumptions:
  - the shape of displacement vector $\mathbf{U}$ 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)

- Summary:

**MDOF (non-linear, dynamic)**

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

**Capacity**

**Demand**

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

**MDOF (non-linear, static)**

$$\mathbf{F} = \mathbf{K}\mathbf{U}$$

**SDOF (non-linear, dynamic)**

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

**Lateral loads**
**Pushover analysis, Capacity diagram**

**Equivalent SDOF model**
**Target displacement**

# 6.5 Nonlinear-static analysis: General

- **EC8: Section 6.5**
  - General
  - Lateral loads
  - Capacity diagram
  - Equivalent SDOF model
  - Target displacement
  - Annex E

- **Use of the non-linear static analysis method**
  - 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.

# 6.5 Nonlinear-static analysis: General



- **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



(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 $d_u$, 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: Target displacement (Annex E)

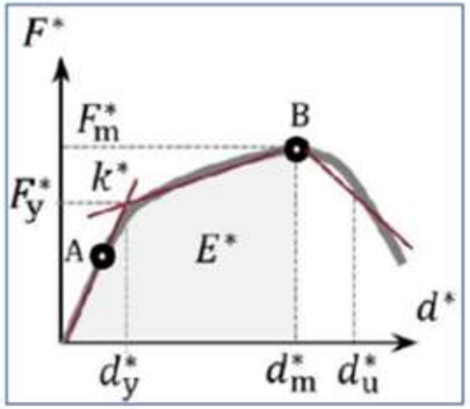


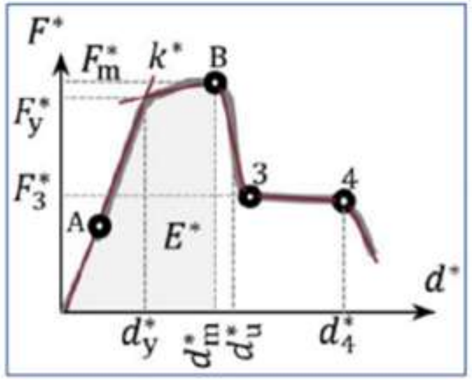
**SDOF (non-linear, dynamic)**

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

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)



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

- **EC8: Section 6.5**
  - General
  - Lateral loads
  - Capacity diagram
  - Equivalent SDOF model
  - Target displacement
  - Annex E

(1) 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

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

(3) The total shear force is $F_{\mathrm{b}} = \sum F_{\mathrm{i}} = \alpha \sum \bar{F}_{\mathrm{i}}$

(4) The control displacement $d_{\mathrm{n}}$

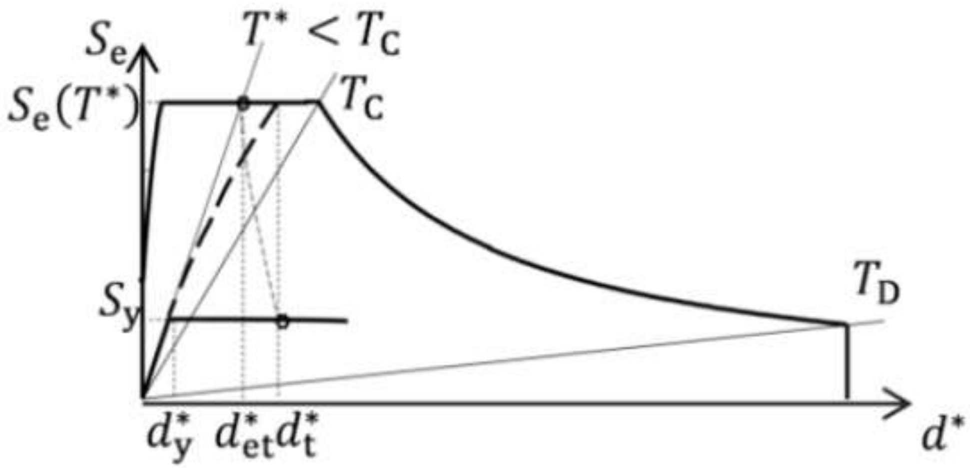
# 6.5 Nonlinear-static analysis: Target displacement

- **EC8: Section 6.5**
  - General
  - Lateral loads
  - Capacity diagram
  - Equivalent SDOF model
  - Target displacement
  - Annex E

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

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

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



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



**SDOF (non-linear, dynamic)**

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

- 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

## 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

## 6.5 Nonlinear-static analysis: Equivalent SDOF model

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

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

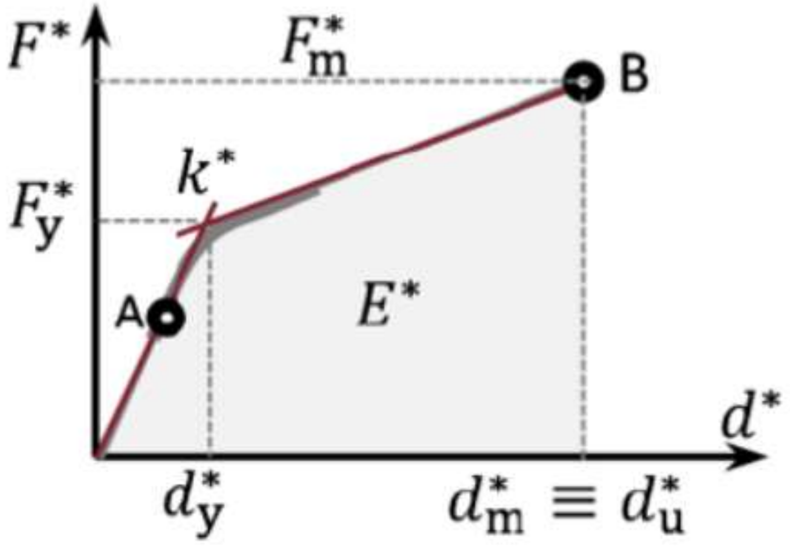
- Equivalent mass

$$m^* = \sum m_i \phi_i$$

- Force-displacement relationship

$$F^* = \frac{F_b}{\Gamma} \qquad d^* = \frac{d_n}{\Gamma \phi_n} \qquad \Gamma = \frac{m^*}{\sum m_i \phi_i^{\,2}}$$

- Bilinear (also elasto-plastic) idealisation



# 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

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

# 6.5 Nonlinear-static analysis: $S_{e,LS}$ (Annex E for Annex F)

- **EC8: Section 6.5**
  - General
  - Lateral loads
  - Capacity diagram
  - Equivalent SDOF model
  - Target displacement
  - Annex E

**SDOF (non-linear, dynamic)**

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

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 $S_{e,LS}$ can be increased due to inconsistency between target spectrum for selection of accelerograms and conditional spectrum

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

## 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

$$E_d \leq R_d$$

**Design value of action effect** | **Design value of resistance**

generalised forces and/or generalised displacements

Depends on force-based or displacement-based approach

  - 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**$_d$* based on model of ultimate deformations (Section 7 of EC8), verification of mechanisms based on forces

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

  - ***R**$_d$* based on displacement of the equivalent SDOF model

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

  - 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

$$P_{\mathrm{LS}} \leq P_{\mathrm{t,LS,CC}}$$

**Annual probability of exceedance of LS** | **Target annual probability of exceedance of LS for CC**

$$P_{\mathrm{LS}} = \int_0^{\infty} P(LS|S_{\mathrm{e}}) \left|\frac{\mathrm{d}H(S_{\mathrm{e}})}{\mathrm{d}S_{\mathrm{e}}}\right| \mathrm{d}S_{\mathrm{e}}$$

$$P_{\mathrm{LS}} = H(S_{\mathrm{e,LS}}) exp\left(0{,}5k^2\beta^2_{S_{\mathrm{e,LS}}}\right)$$

For CC2, $P_{\mathrm{t,NC,CC2}} = 2\times10^{-4}$ 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)

# EC8-1-2-7 ANCILLARY ELEMENTS

CLADDINGS RIVESTIMENTO
PARAPETS
GABLES TIMPANI
ANTENNAS
MECHANICAL APPENDAGES AND EQUIPMENTS APPENDICI MECCANICHE E ATTREZZATURE
CURTAIN WALLS
PARTITIONS DIVISORI
RAILINGS RINGHIERE
CEILINGS CONTROSOFFITTI

7.1 VERIFICATIONS

7.2 SD SEISMIC ACTION $F_{ap} = \gamma_{ap} M_{ap} S_{ap} / q'_{ap}$

$S_{ap}$ FLOOR ACCELERATION SPECTRUM
$\gamma_{ap}$ PERFORMANCE FACTORS
$q'_{ap}$ BEHAVIOUR FACTOR

7.3 NC

7.4 MASONRY INFILLED FRAMES

7.5 STRUCTURES WITH CLADDINGS

7.6 PARTITIONS

# EC8-1-2-8:2022 BASE ISOLATED BUILDINGS.

8.1 FIELD OF APPLICATION

8.2 BASIS OF DESIGN

8.3 STRUCTURAL ANALYSIS

8.4 VERIFICATION OF SD LS

# EC8-1-2-9  BUILDING WITH ENERGY DISSIPATION SYSTEMS

9.1 GENERAL

9.2 BASIS OF DESIGN

9.3 STRUCTURAL ANALYSIS

9.4 VERIFICATION TO LS

## 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 $F=Cv^{\alpha}ve$ , 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 $\gamma_X$).
- 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.

STRUCTURES WITH **FULL** ISOLATION

STRUCTURES WITH **PARTIAL** ISOLATION

STRUCTURES WITH ENERGY DISSIPATION SYSTEMS

## ANALYSIS METHODS

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

STRUCTURES WITH FULL ISOLATION

## Fundamental-mode equivalent linear response-spectrum analysis*

- 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 $\xi_{eff}$ depend on design displacement $d_{bd}$ (iterations required).

*≈ simplified linear analysis in current EN1998-1

## 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, $\alpha_{ve}$ , $\eta_{loss}$ 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**

## 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 $\xi_{eff}$ 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 $\xi$ of a non-isolated structure.
- The response in each mode through response spectrum analysis.

*≈ full modal analysis in current EN1998-1

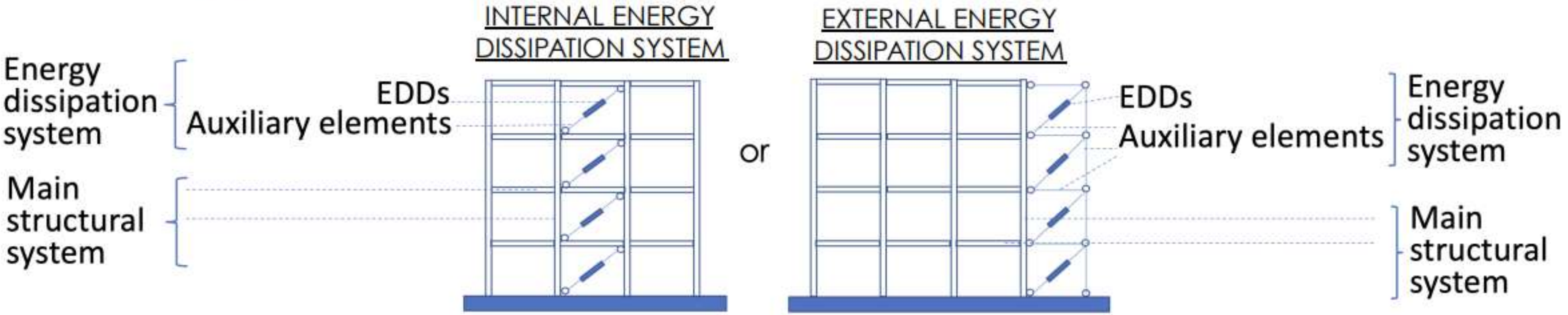
## COMMON ASPECTS OF BOTH ANALYSIS METHODS:

- 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.

## 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 |

STRUCTURES WITH FULL OR PARTIAL ISOLATION

STRUCTURES WITH ENERGY DISSIPATION SYSTEMS

## Response-history analysis

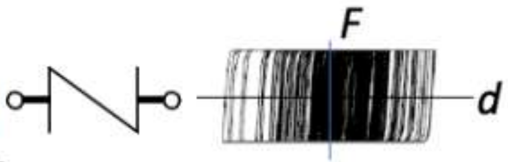
- Constitutive relationships of anti-seismic devices must adequately reproduce their behaviour in the range of deformations and velocities of the design seismic situation
- In structures on near-fault sites, each pair of horizontal input motion component should be rotated to the fault-normal and fault-parallel 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 ENERGY DISSIPATION SYSTEMS - Chapter 9 of EN1998-1-2

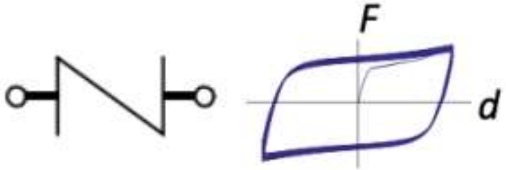
Two types of energy dissipation devices are considered:

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

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



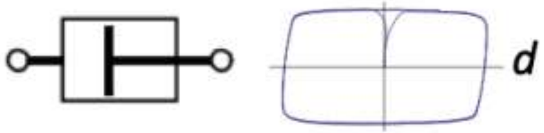

  (b) multilinear hysteresis (e.g. metallic dampers)




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

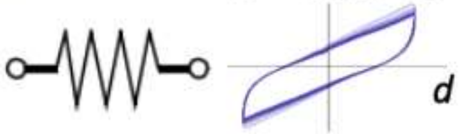
  (a) viscous (fluid) devices

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

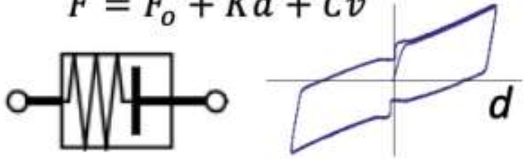



  (b) viscoelastic (solid or fluid) devices

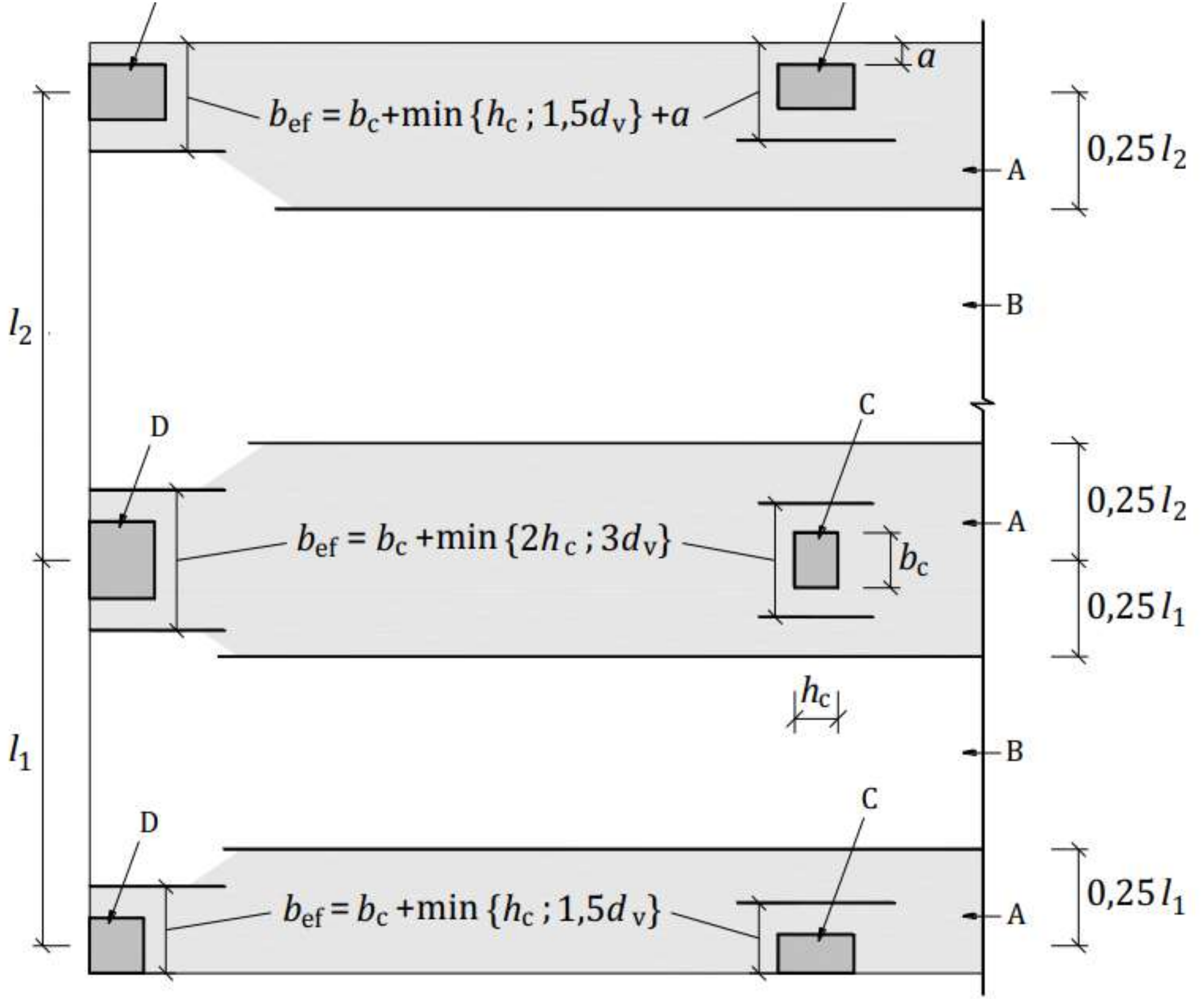
$F = Kd + Cv$



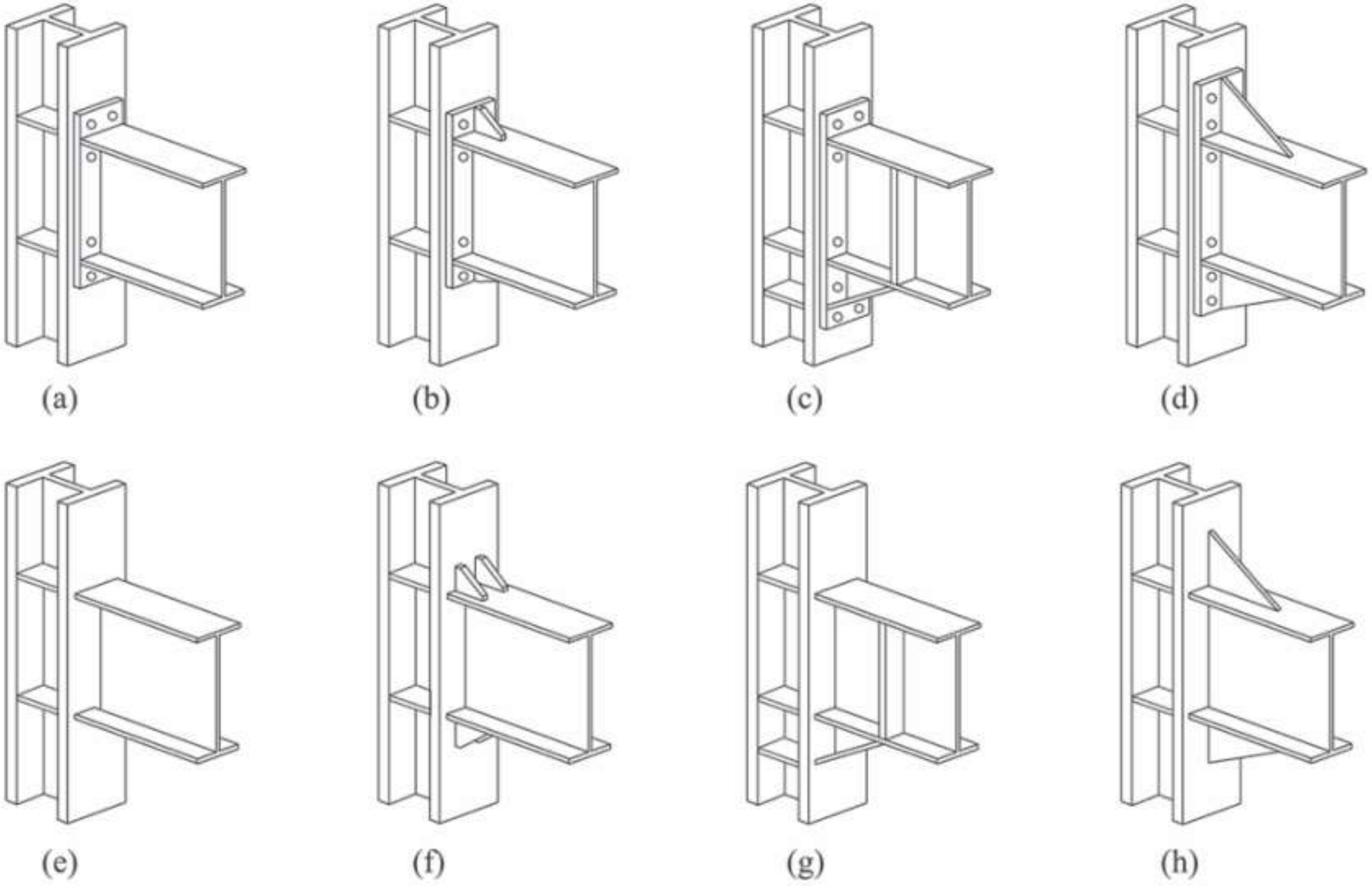

$F = F_o + Kd + Cv$



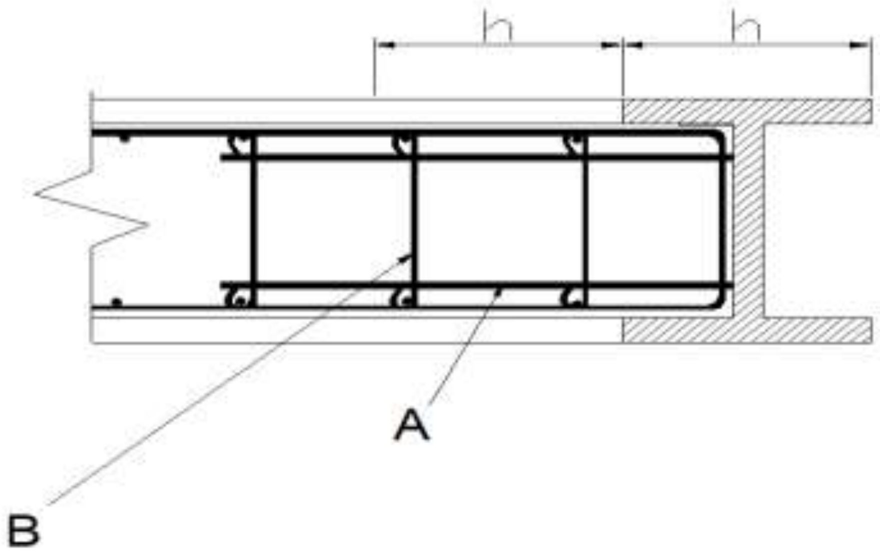
# EC8-1-2-10 SPECIFIC RULES FOR CONCRETE BUILDINGS



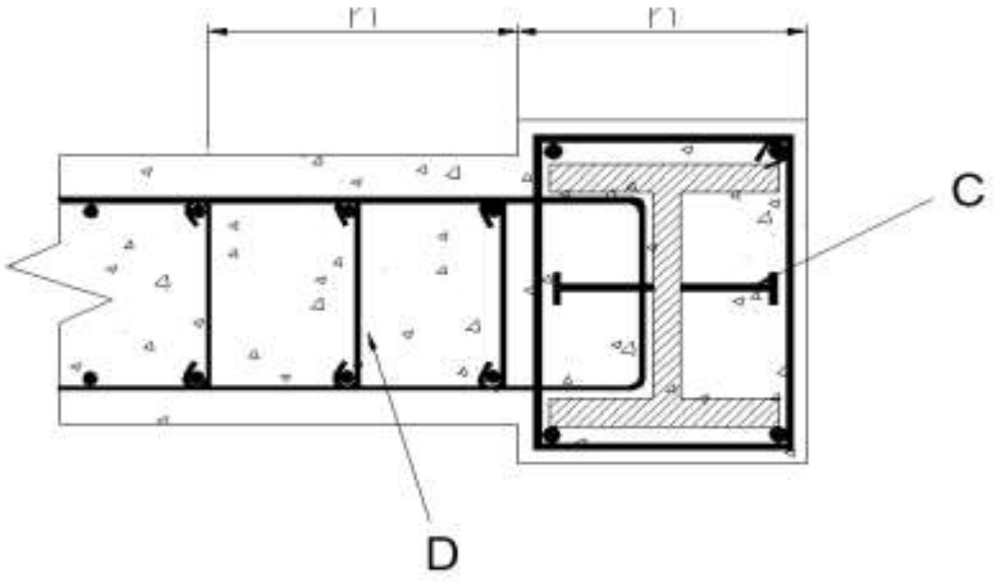
# EC8-1-2-11 SPECIFIC RULES FOR STEEL BUILDINGS



# EC8-1-2-12 SPECIFIC RULES FOR COMPOSITE STEEL-RC BUILDINGS

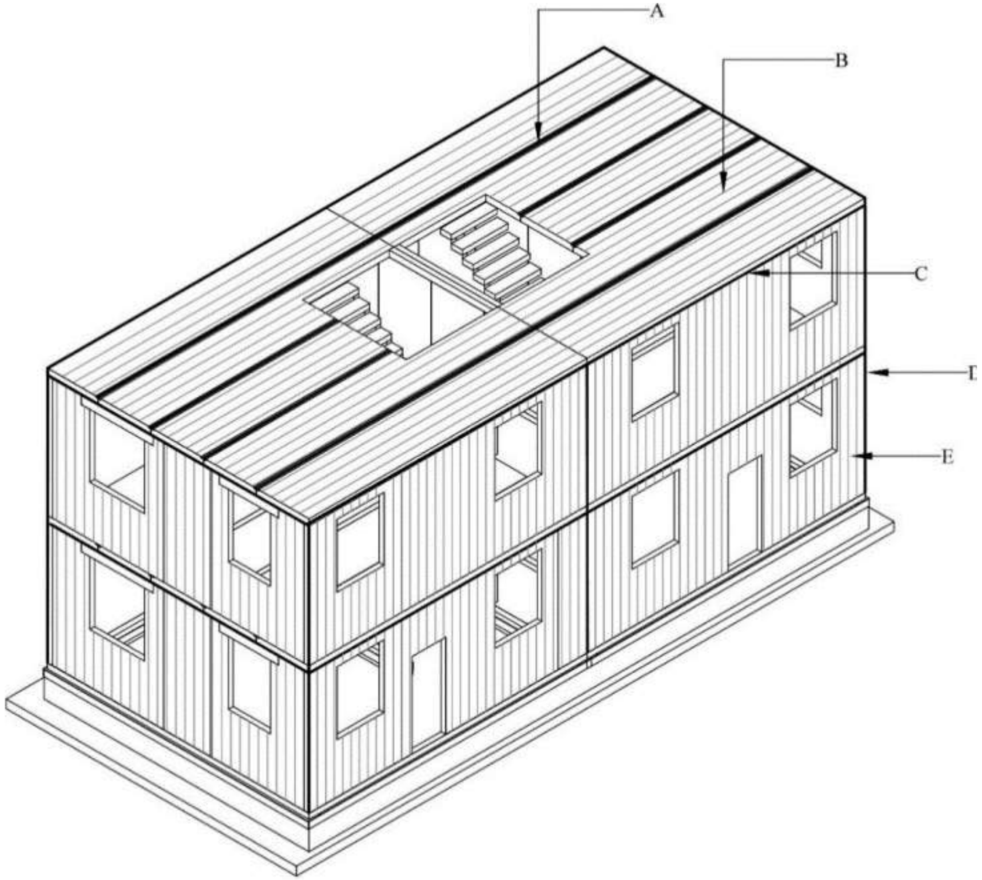



(a) Partially encased composite




(b) Fully encased composite

# EC8-1-2-13 SPECIFIC RULES FOR TIMBER STRUCTURES




# EC8-1-2-14 SPECIFIC RULES FOR MASONRY BUILDINGS

# EC8-1-2-15 SPECIFIC RULES FOR ALUMINIUM BUILDINGS

END (390 PAGES)