16TH EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING THESSALONIKI 18 - 21 JUNE 2018

University of Ljubljana
Faculty of Civil and Geodetic Engineering

Analysis in seismic provisions for buildings – past, present and future

The fifth Prof. Nicholas Ambraseys lecture

Peter Fajfar

Seismic response of structures

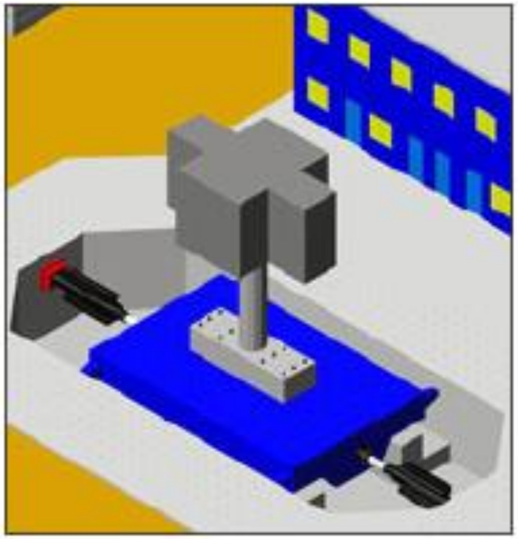
- Dynamic
- Nonlinear
- Random


Three pillars
• Dynamics
• Nonlinearity
• Probabilistics
Delphi

Blind prediction contest

RC bridge column

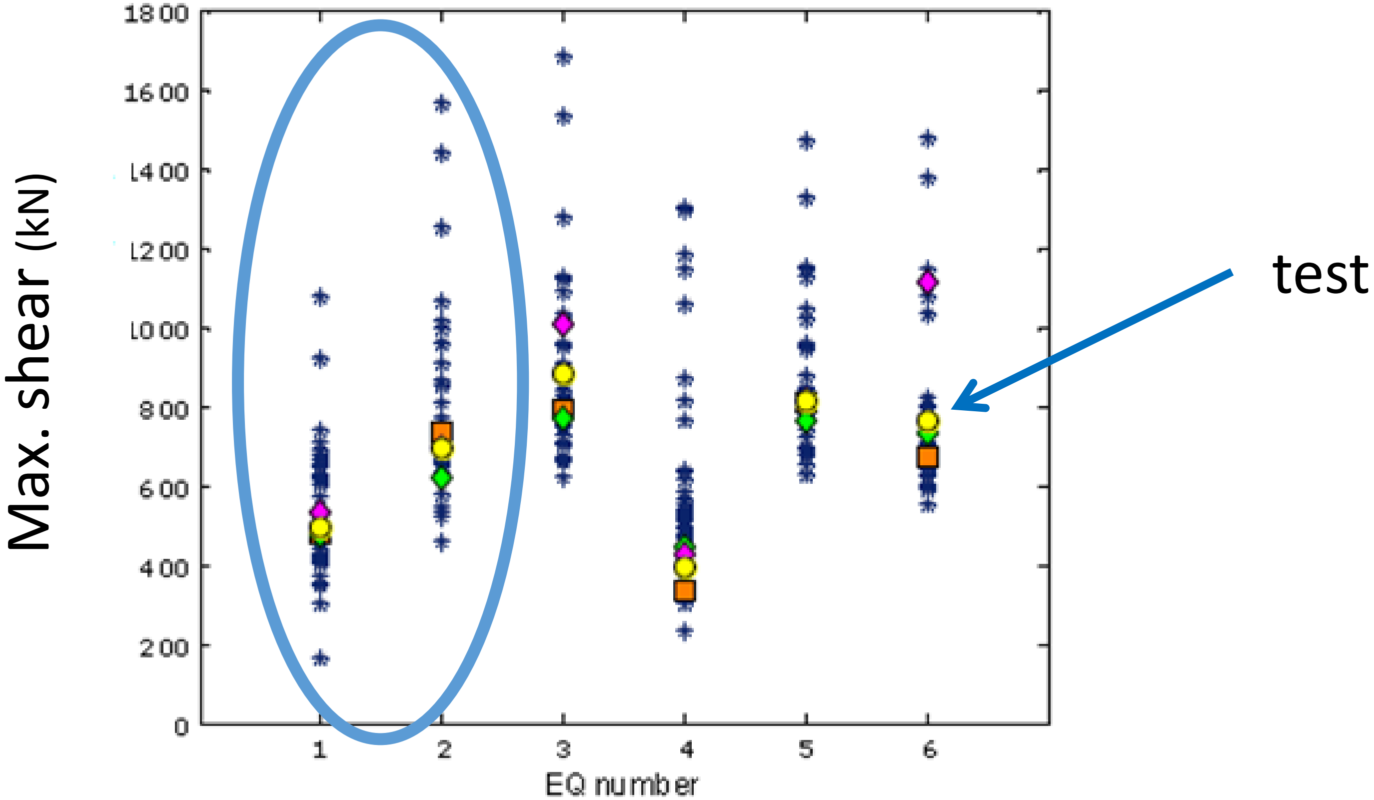
PEER UCSD outdoor shaking table 2010

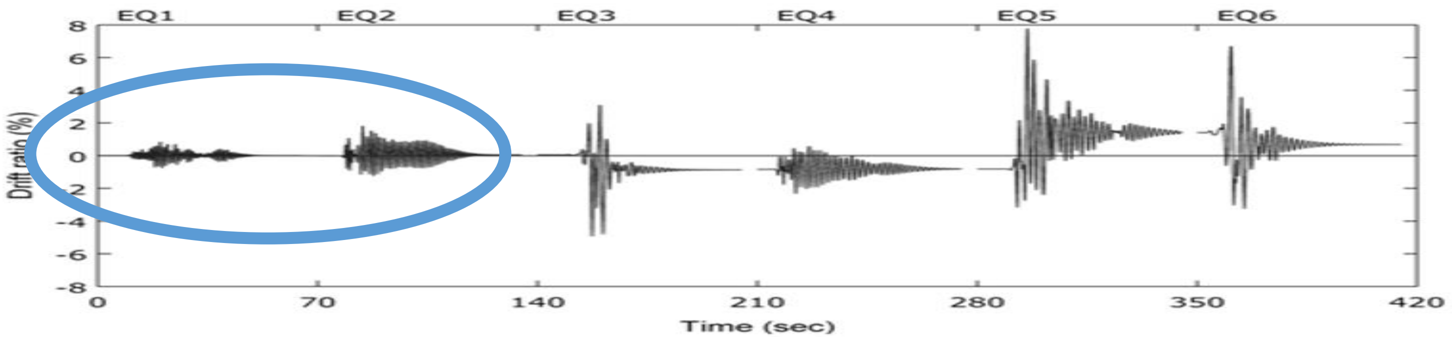


42 teams from 14 countries

Terzic et al, 2015

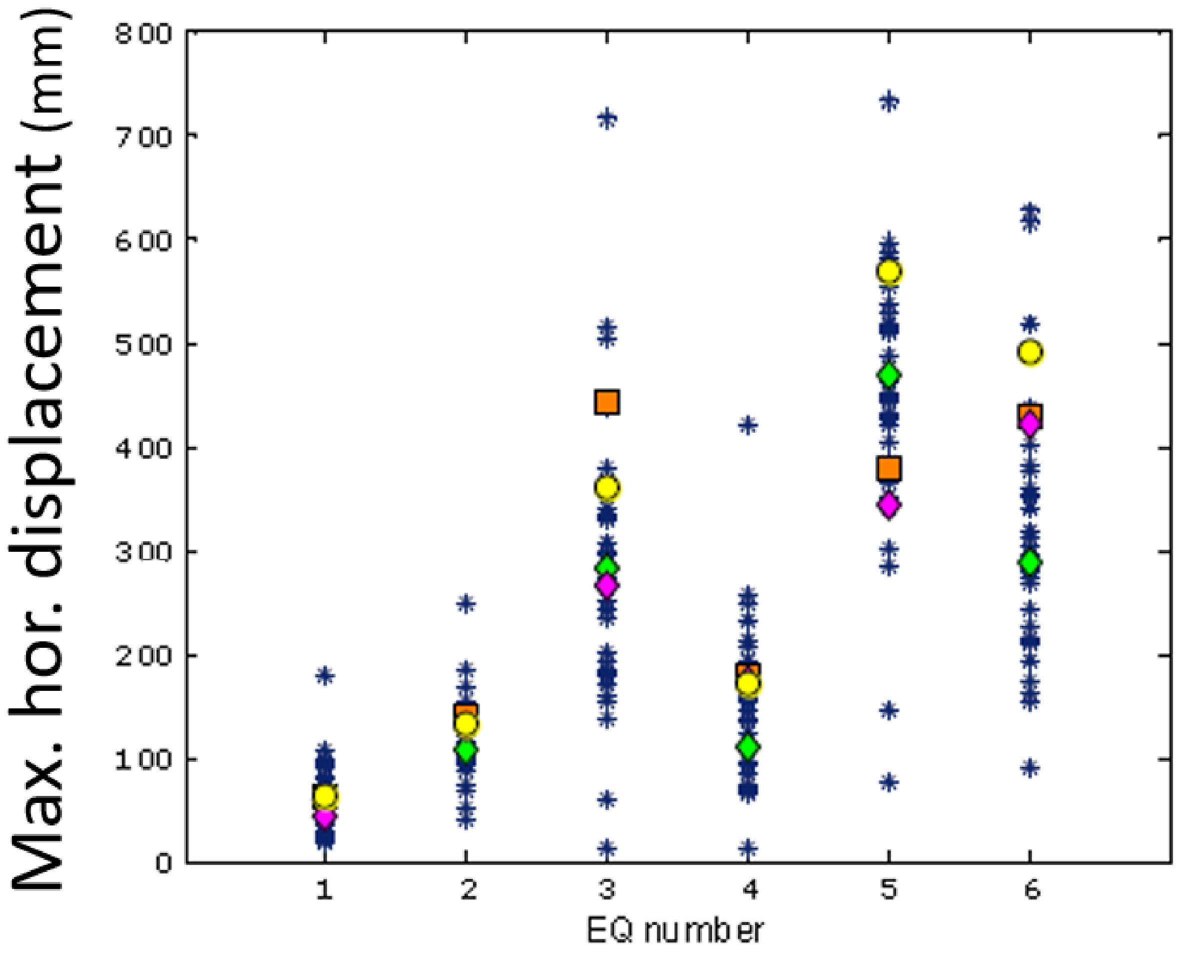
Shear force



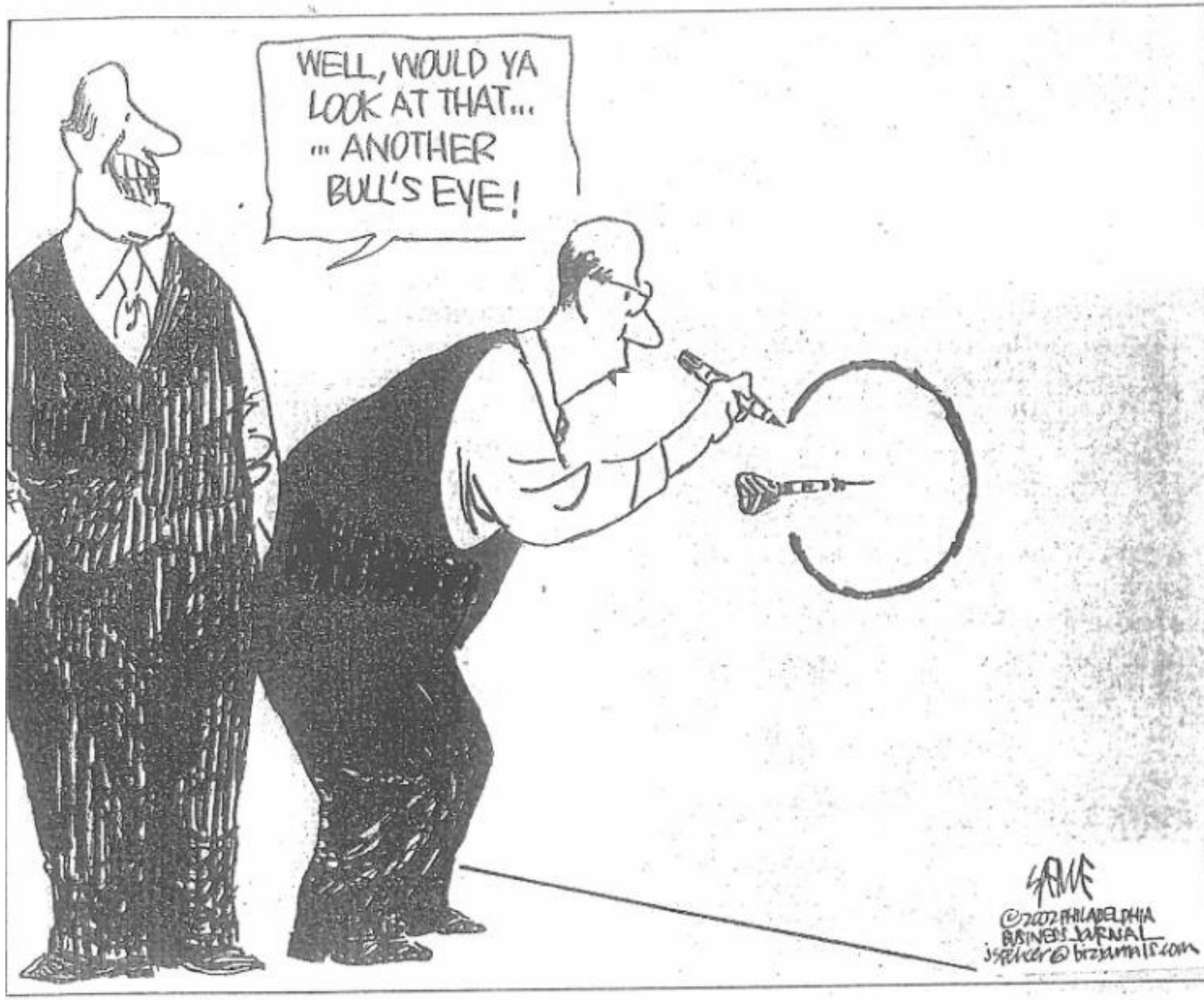


Terzic et al, 2015

Displacement



Terzic et al, 2015


WELL, WOULD YA LOOK AT THAT... ...ANOTHER BULL'S EYE!
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Lesson learned

Ability of the profession (on average) to adequately predict the seismic structural response is limited

Known:

- Ground motion
- Material characteristics

Lesson confirmed

Today, ready access to versatile and powerful software enables the engineer to do more and think less.


M. Sozen (A Way of Thinking, EERI Newsletter, 2002)

Scope

- Introduction
- History
- Present
- Future
- Conclusions

Earthquake engineering is a twentieth century development.

1908 Messina earthquake was responsible for the birth of practical earthquake design of structures.

G.W.Housner 1984

History (1908 - 1978)

Dominated by equivalent static analysis

Gradual implementation of dynamics

Italy 1909

- First seismic analysis in codes (after 1908 Messina Eq.)
- Equivalent static analysis
- Seismic coefficient

  C_s = Horizontal force / Weight = about 10%

Japan 1924

- First seismic code in Japan (after 1923 Great Kanto Eq.)
- Equivalent static analysis
- C_s = 10%

USA

- **1906** San Francisco earthquake
- **1927** Optional seismic provisions (UBC)
- **1933** First mandatory seismic code
- **1943** $C_s = C_s(H)$
- **1956** $C_s = C_s(T)$
- **1959** Energy dissipation (SEAOC model code)

C_s = up to 10%

Dynamic analysis

A. Danusso proposed a dynamic analysis method (Italy 1908)

Implementation of the **modal response spectrum analysis** in code (USSR 1957)

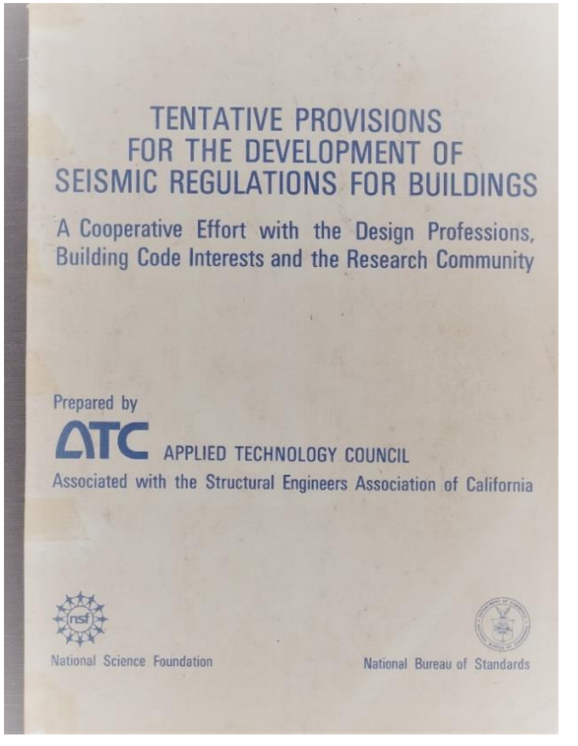
Popular in Europe

Main method in Eurocode 8

Milestone

ATC 3-06

Tentative provisions (1978)

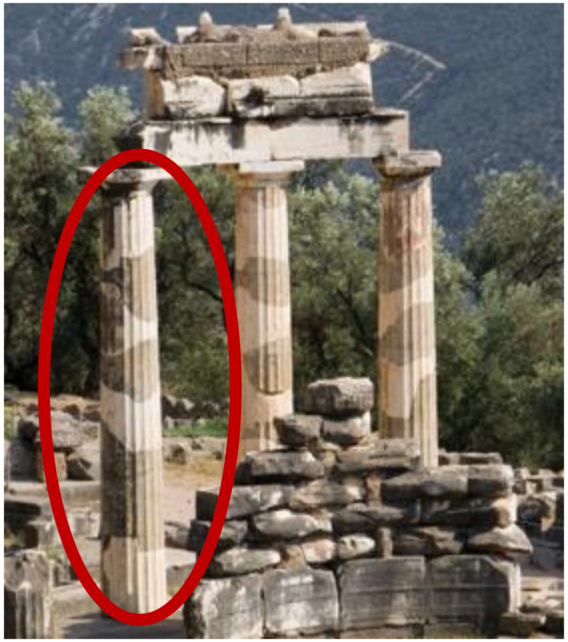


Start of modern codes

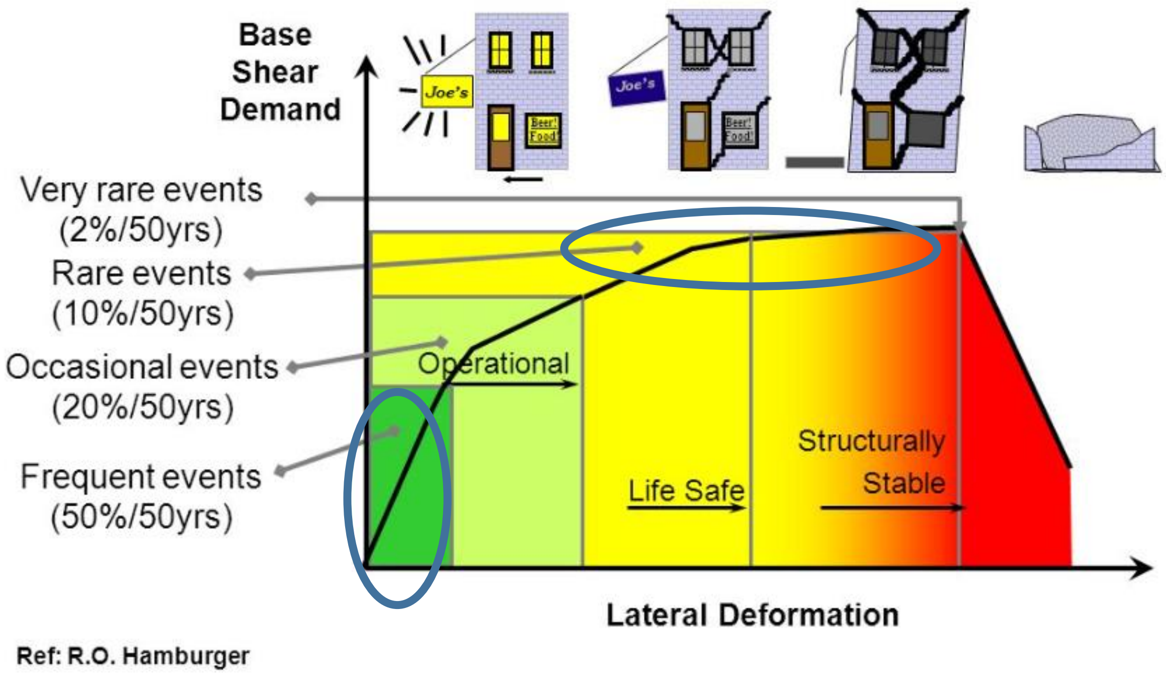
- probabilistic seismic maps
- force reduction R-factors
- modal response spectrum analysis

Present

Gradual implementation of nonlinear methods



Nonlinear analysis



Thinking in terms of displacements rather than forces is required

Nonlinear analysis

Dynamic (response-history)

Pushover - based

Nonlinear dynamic analysis

The **most advanced** available tool
Irreplaceable in research and analysis of important structures
Theoretically correct

Disadvantages for practical applications

- Computationally demanding
- Additional data needed
- Sensitivity of computed response
- Less transparent
- Significant judgement required
- Peer review needed

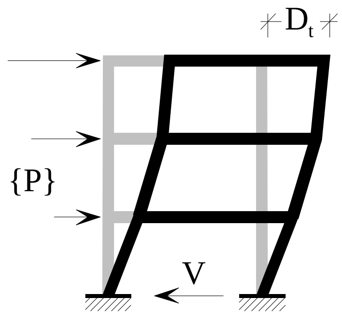
Nonlinear analysis

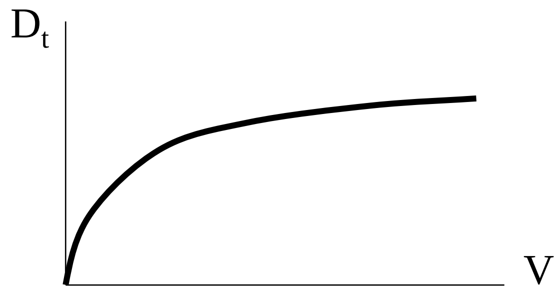
The more complex the nonlinear analysis method, the more ambiguous the decision and interpretation process is.

Helmut Krawinkler

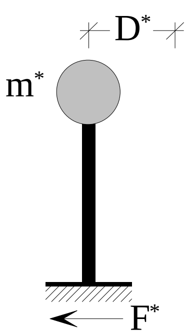
Pushover-based methods

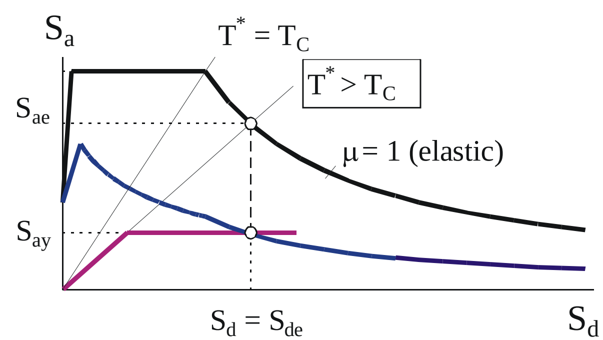
Nonlinear static (pushover) analysis of MDOF model





Response spectrum analysis of equivalent SDOF model





Limitation: structures vibrating predominatly in a single mode

Equal displacement rule

Veletsos and Newmark, 1960

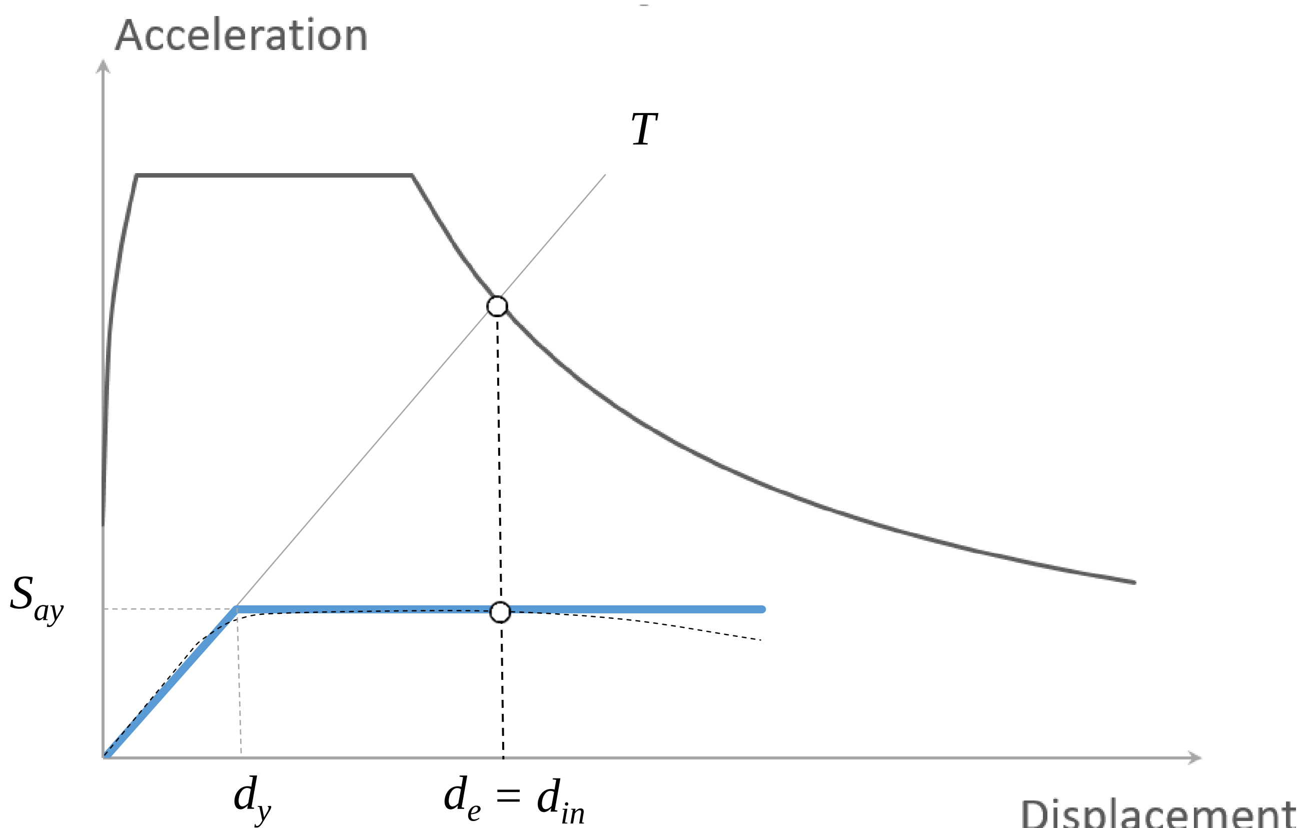
Displacement of an inelastic SDOF structure is approximately equal to the displacement of the corresponding linear elastic structure with the same stiffness and mass

Empirical observation, repeatedly confirmed as a good approximation for a large number of structures

A computational tool for determining the displacement of an inelastic structure

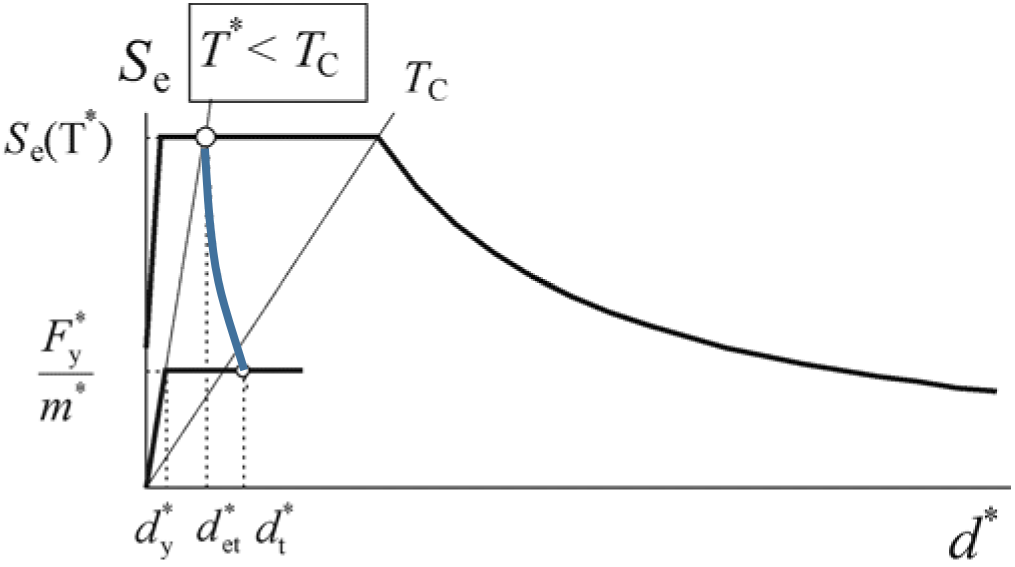
Equal displacement rule

Allows development of simplified rules in nonlinear analysis
Allows clear graphic presentations
Facilitates undestanding
Limitations apply!



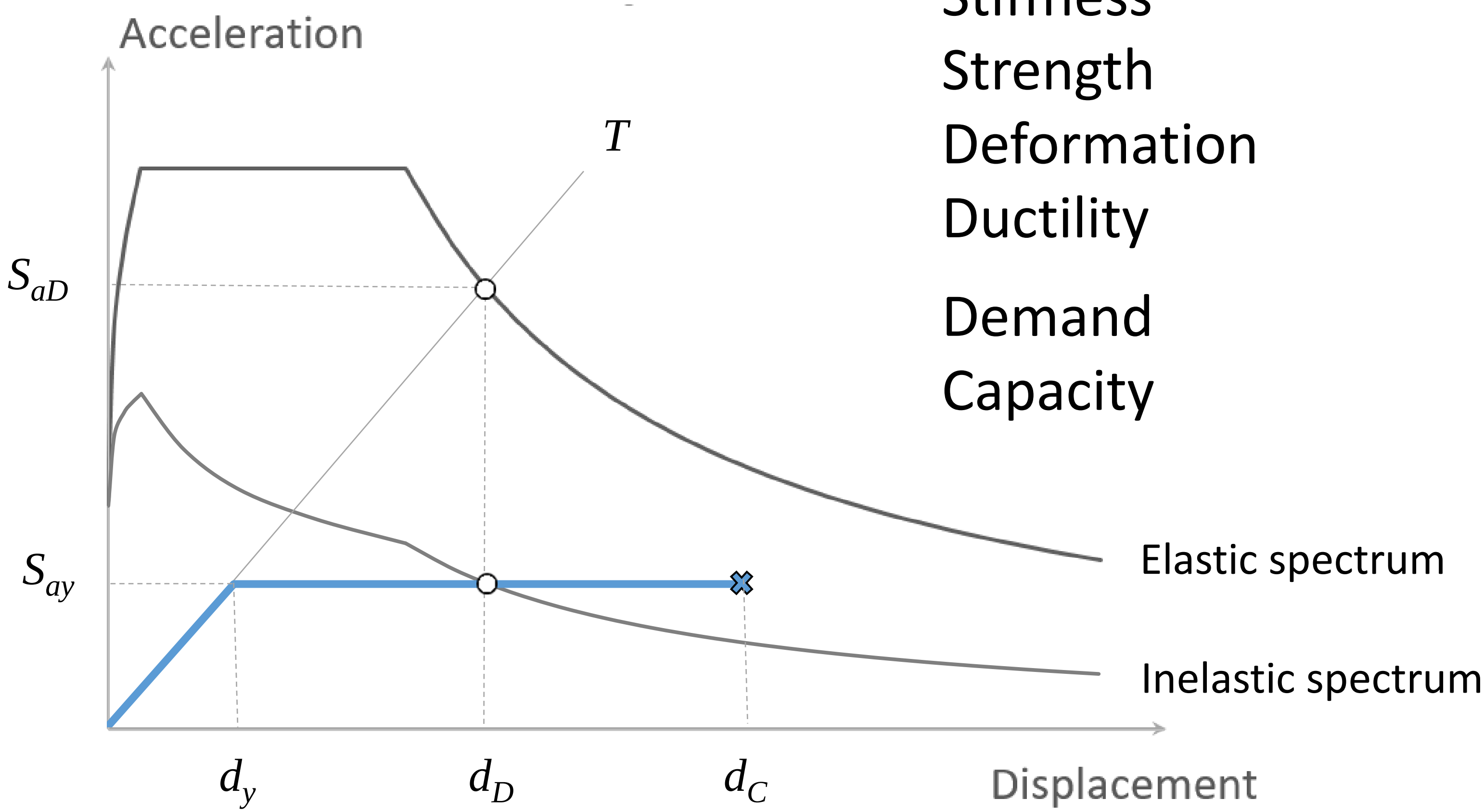
Inelastic displacement

Short period structures in EC8



Graphical representation

ADRS (AD) format: Mahaney, Paret, Kehoe, Freeman (1993)



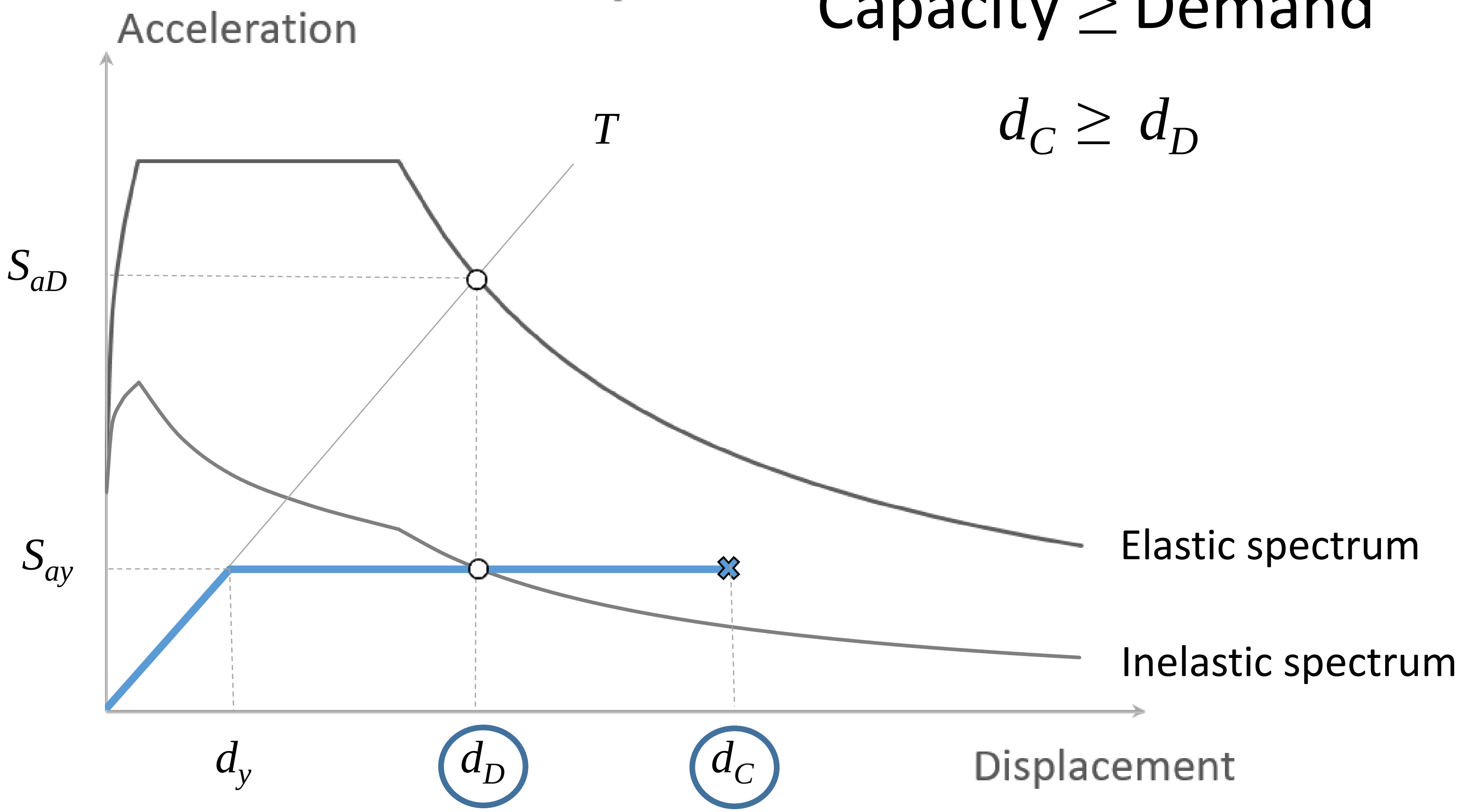
Stiffness
Strength
Deformation
Ductility

Demand
Capacity

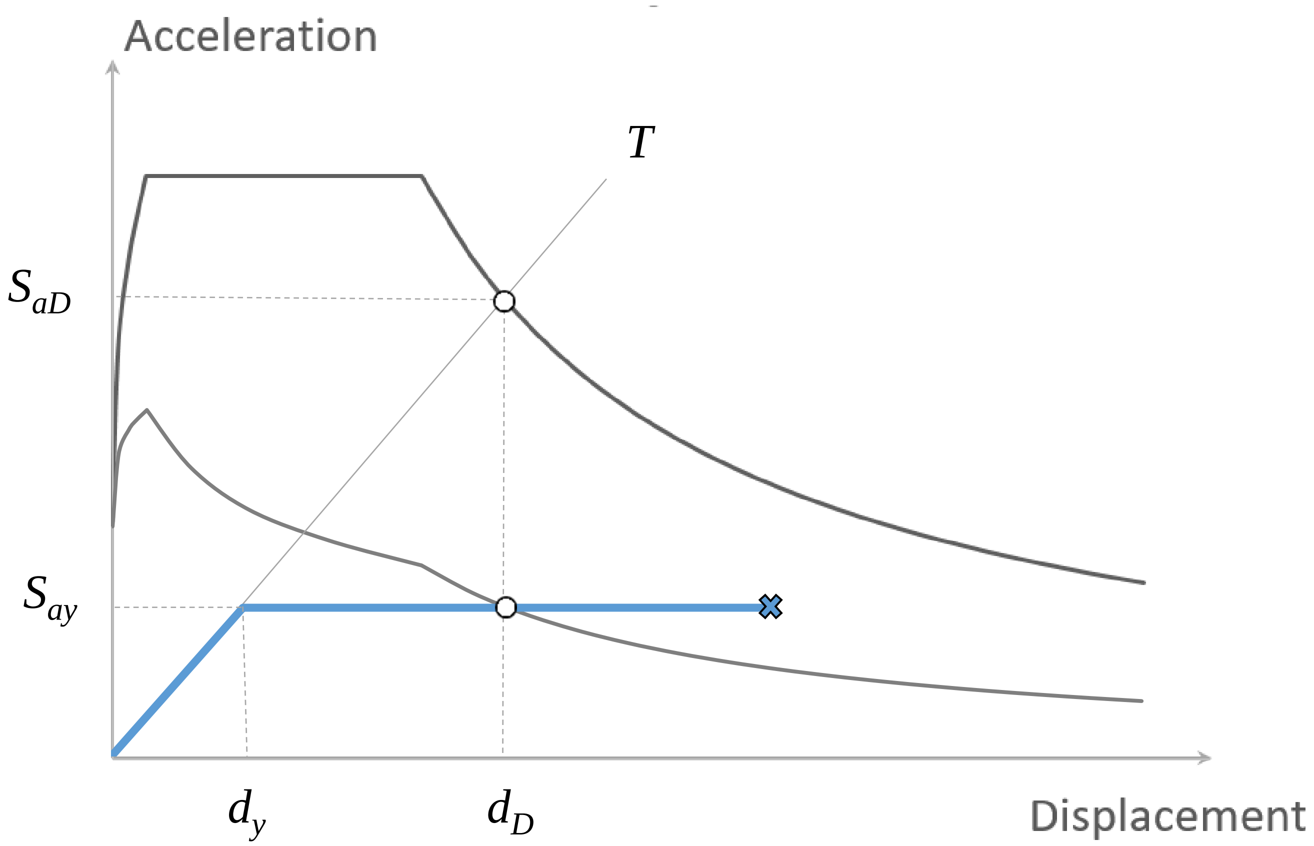
Assessment

Capacity $\geq$ Demand

$$d_C \geq d_D$$



Direct displacement based design



Extensions of pushover-based methods

Pushover analyses were introduced as simple methods …

Refining them to a degree that may not be justified by their underlying assumptions and making them more complicated than the nonlinear response-history analysis …

defeats the purpose of using such procedures.

Baros and Anagnostopoulos, 2008

Torsion and higher modes in elevation

Extended N2 method

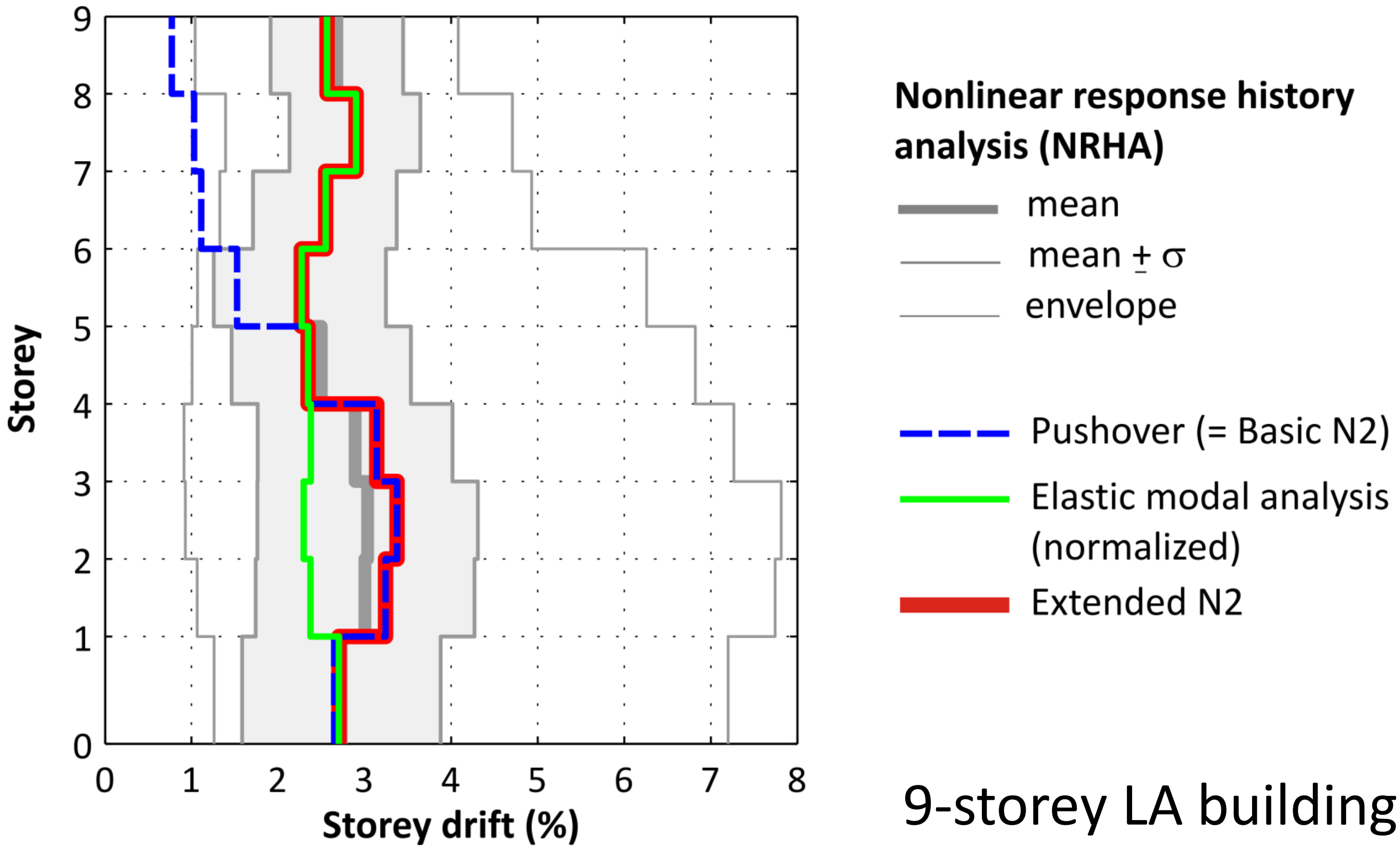
Combination (envelope) of

- Basic pushover analysis
- Elastic modal response spectrum analysis (normalized)

Implemented in the 2nd generation EC8-1 (final draft)

Similar idea in ASCE 41 and recent NZ guidelines
(for higher modes in elevation)

Higher modes in elevation

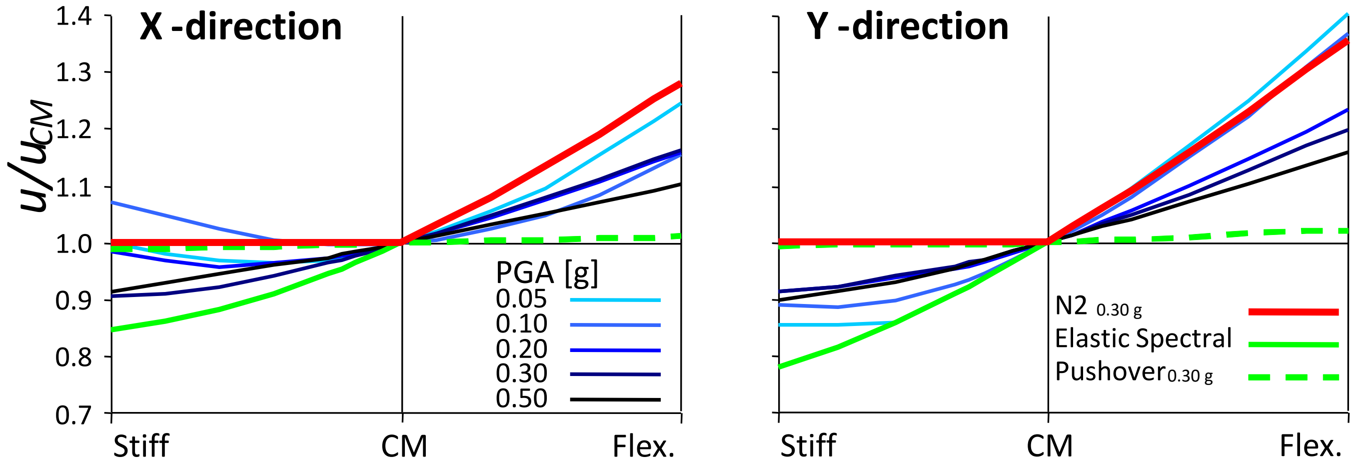


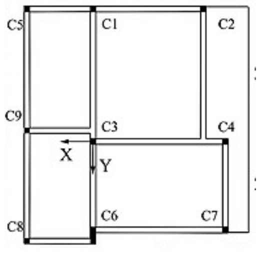
9-storey LA building (SAC)

Kreslin and Fajfar, EESD, 2011

SPEAR building

Torsion





SPEAR building

Comments on pushover-based analysis

Provides important information not available in the case of **linear elastic analysis**.

In principle, less accurate than **nonlinear dynamic analysis**. Limitations apply.

However

- is much simpler
- permits visualization of structural response and of interaction between important parameters
- **contributes to a better understanding of the structural behaviour during strong earthquakes**

Future

Risk assessment

Is it a feasible option for codes?

Probabilistic methods

- Engineers not familiar and hesitant
- Research community skeptical
- Rigorous explicit approaches too complex

Not used in engineering practice
(average uncertainty included in safety factors)

Highly simplified methods are needed

Probabilistic analysis in current codes

Maps

- Seismic hazard maps
- Risk-targeted ground motion maps (US)

Explicit probabilistic approach is permitted by US (ASCE) code

Probabilistic analysis in future codes ?

2^{nd} generation EC8-1 (final draft):

Informative Annex F
“Simplified reliability-based verification format”

Initially drafted by Dolšek et al.

Basic ideas and formulas for a simplified approach

Pushover-based Risk Assessment (PRA) method

Practice-oriented explicit probabilistic method

Combination of

- Cornell’s closed form formula for the probability of exceedance of LS (SAC-FEMA probabilistic approach, “risk equation”)
- Pushover-based N2 method

PRA method

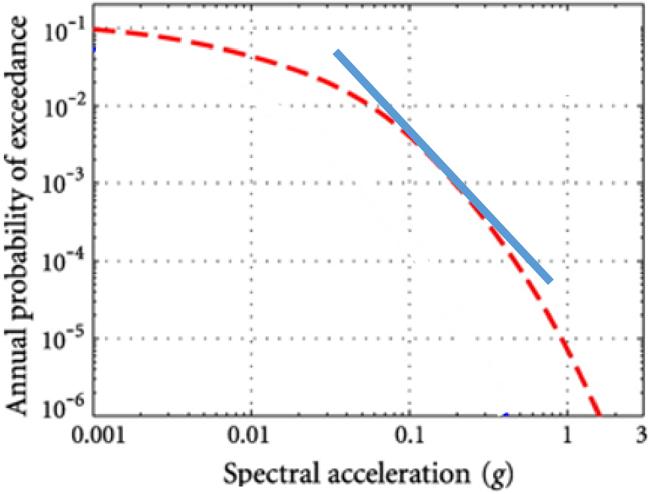
P_{NC} annual probability of "failure"

NC limit state = economic failure

$$P_{NC} = e^{0.5\,k^2 \beta_{NC}^2} H(S_{aNC})$$

$$H(S_a) = k_o S_a^{-k}$$

$$S_a = S_a(T_1) \text{ or } PGA$$

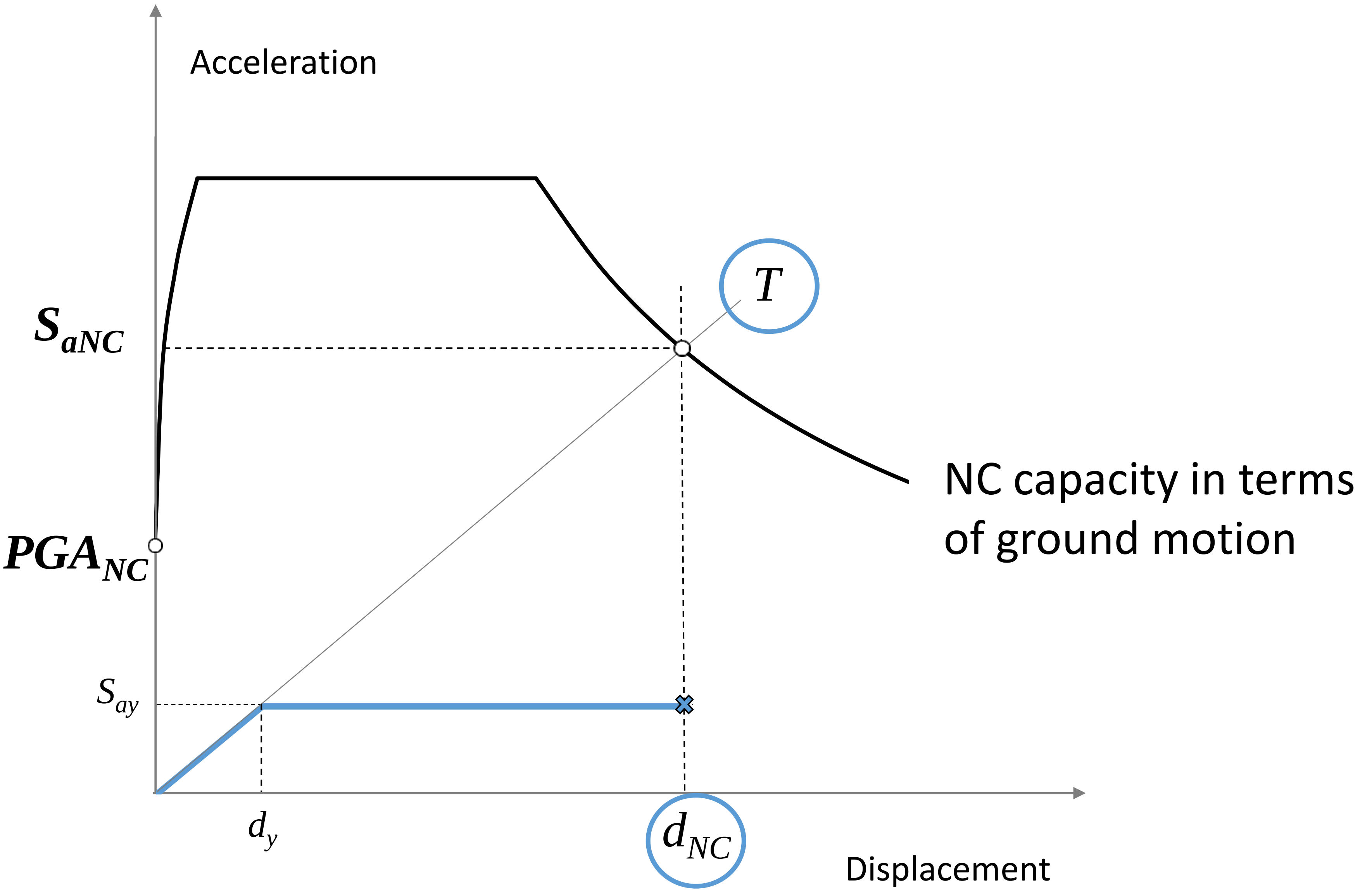


k, k_o parameters of the hazard curve

β_{NC} dispersion measure (predetermined value)

S_{aNC} NC (failure) capacity in terms of S_a (N2 method)

Determination of S_{aNC}



Probability of failure P_{NC} versus probability of ground motion $H(S_{aNC})$

$$P_{NC} = e^{0.5\,k^2 \beta_{NC}^{\;2}} H(S_{aNC})$$

$k = 3,\ \beta_{NC} = 0.5$	3.08
$\beta_{NC} = 0$	1.0

Calculated versus tolerable probability

$$P_{NC} \leq P_t$$

Calculated probabilities of failure $\boldsymbol{P_{NC}}$ in 50 years (NC LS)

Code designed buildings: **0.25**% - **1**%
Buildings not designed for seismic resistance: up to **40**%

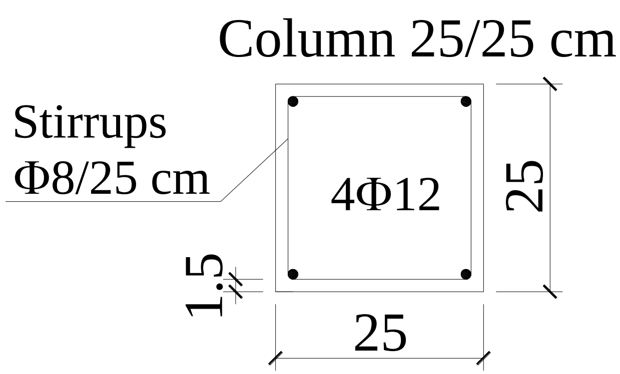
Tolerable (acceptable, target) probabilities of failure $\boldsymbol{P_t}$ in 50 years (common buildings)

US and EC8 (2nd generation): **1**%
Survey (Slovenia): **0.1**%

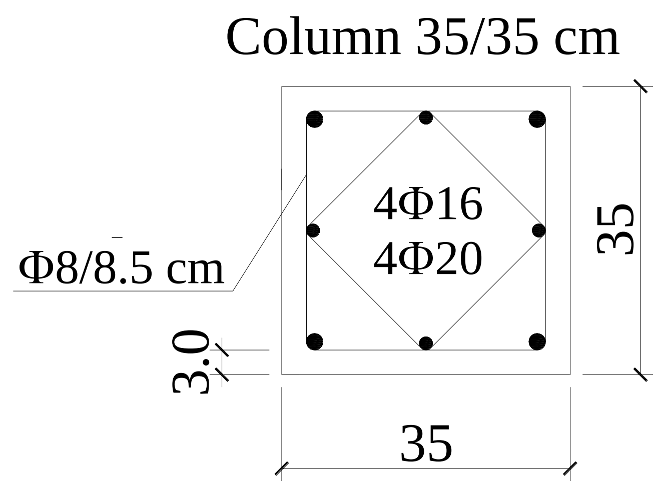
SPEAR building

Typical cross-sections of columns

Test building

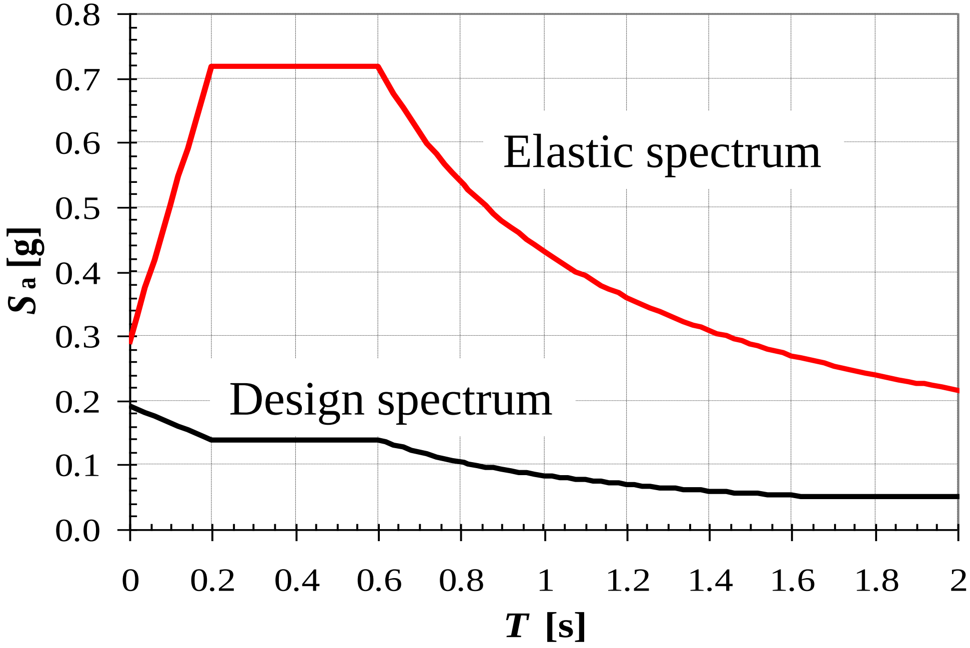


EC8 H



Seismic loading

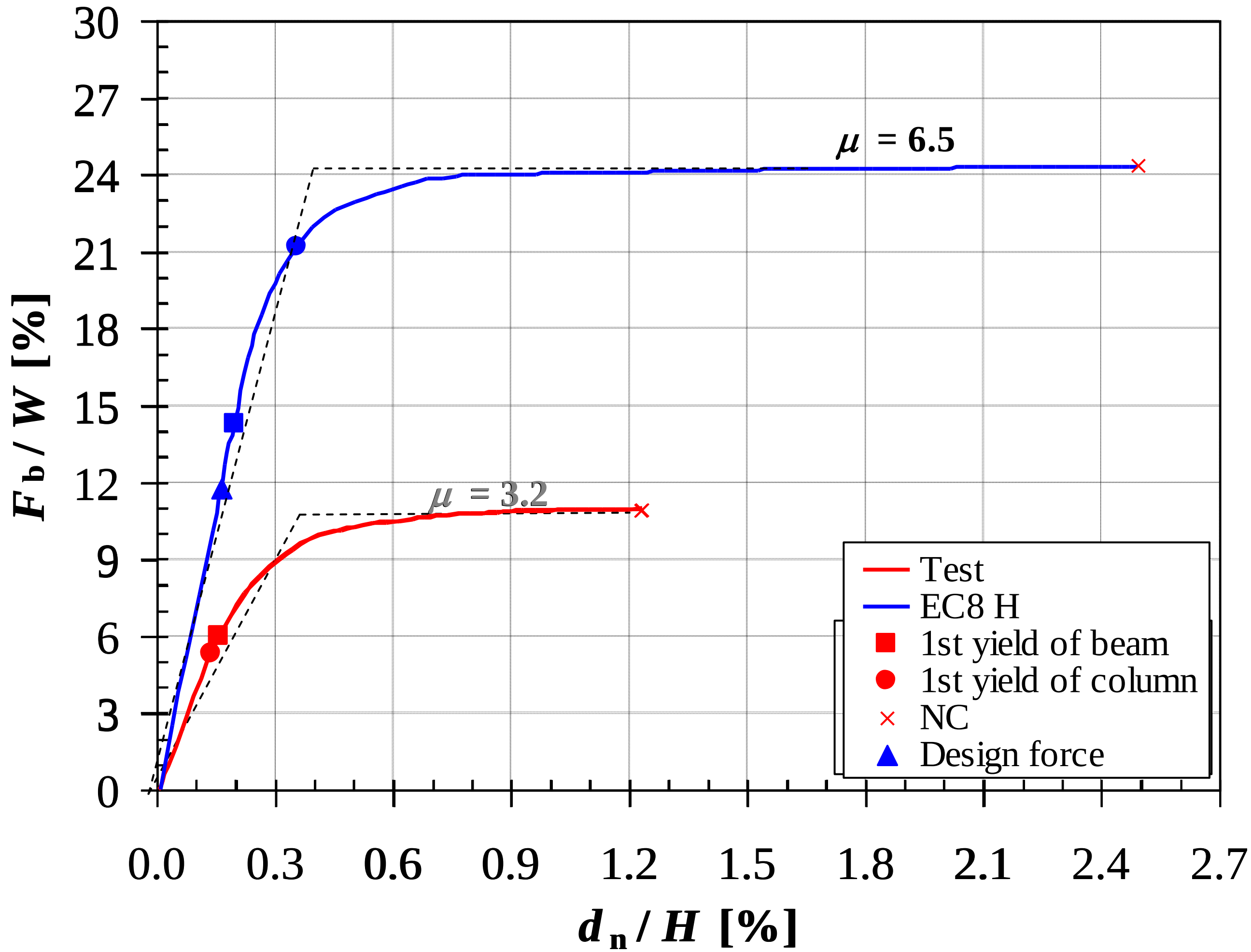
EC8, Soil type C



Pushover curves

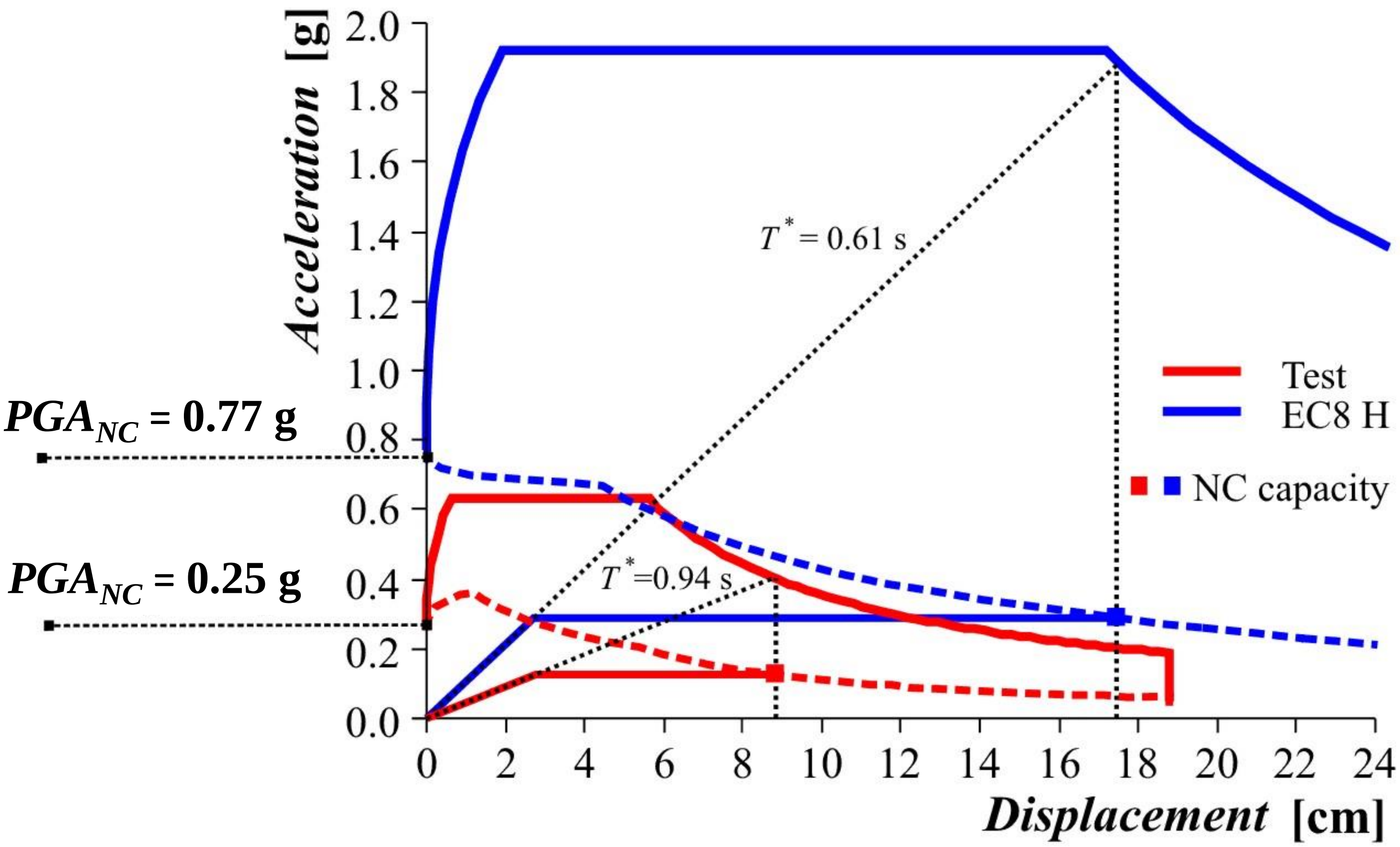
X direction

- Test
- EC8 H



Seismic capacity (NC)

- Test
- EC8 H



Probability of failure

Test building

PGA_{NC} = 0.25 g

$\boldsymbol{P_{NC}} \cong$ **30% in 50 years**

EC8 H building

PGA_{NC} = 0.77 g

$\boldsymbol{P_{NC}} \cong$ **1% in 50 years**

Risk-targeted approach

Based on work (idea, formulation and development of formulas) of **M.Dolšek** and his former PhD students

- Žižmond and Dolšek, 2014 (unpublished manuscript)
- Žižmond and Dolšek, 2017 (16WCEE)
- Dolšek et al., 2017 (EESD)

Used for assessment or design

Takes into account the target probability of failure

Risk-targeted safety factor γ

$$P_{NC} = e^{0.5\,k^2 \beta_{NC}{}^2}\; H(S_{aNC})$$

$$\frac{S_{aNC}}{S_{aD}} = e^{0.5\,k\,\beta_{NC}^2} \left(\frac{T_{NC}}{T_D}\right)^{\frac{1}{k}} = \gamma$$

$T_{NC} = T_t$ target return period of failure ($T_t = 1/P_t$)

T_D return period of design ground motion

Quantification of γ

$$\gamma = e^{0.5\,k\,\beta_{NC}^2}\left(\frac{T_{NC}}{T_D}\right)^{\frac{1}{k}}$$

3.20   1.46   2.19

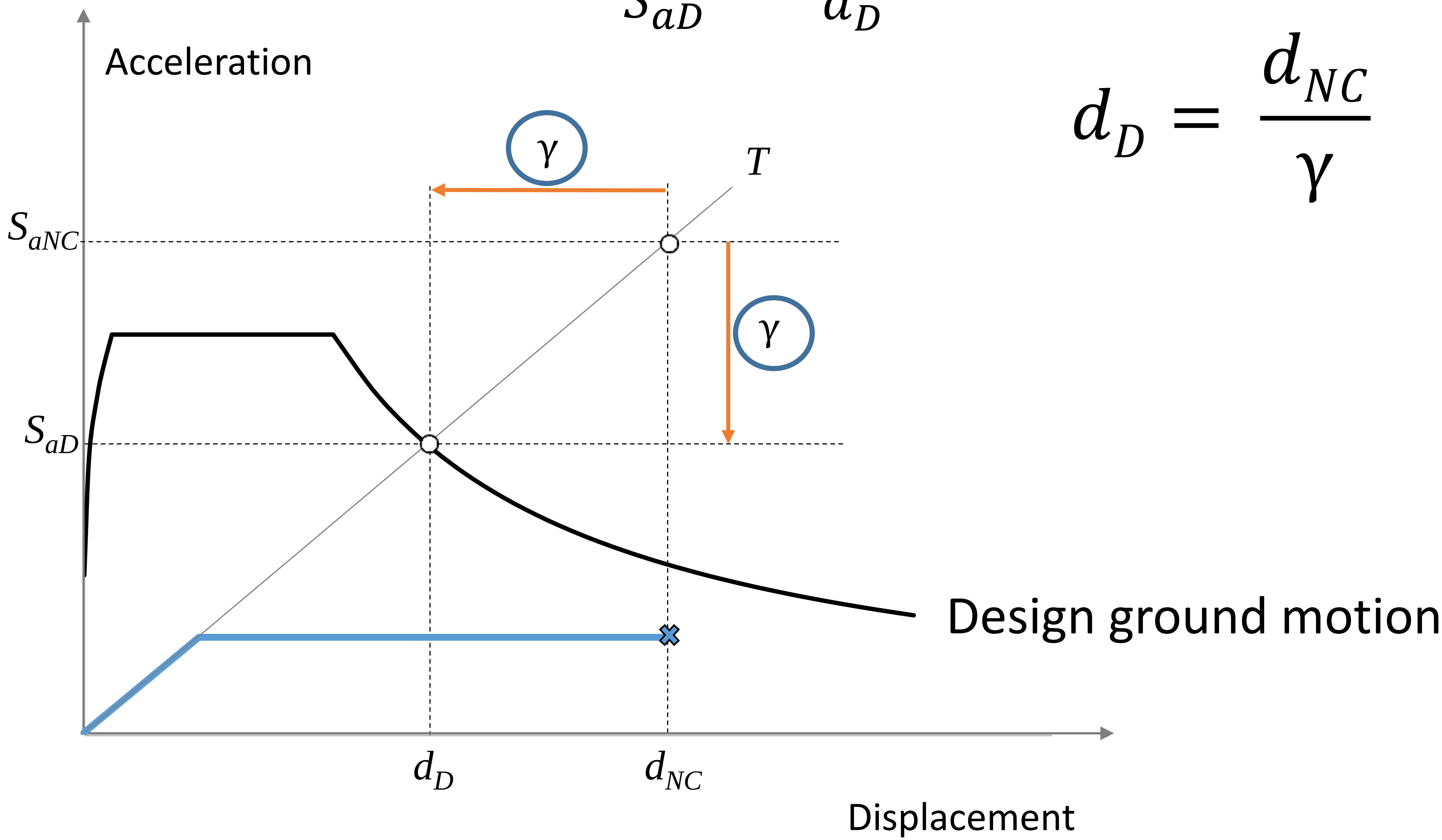
1.0 if $\beta_{NC} = 0$ 1.0 if $T_D = T_{NC}$

$k = 3$ T_{NC} = 5000 years (P_t = 1% in 50 years)

$\beta_{NC} = 0.5$ T_D = 475 years (P_D = 10% in 50 years)

Graphical representation of γ

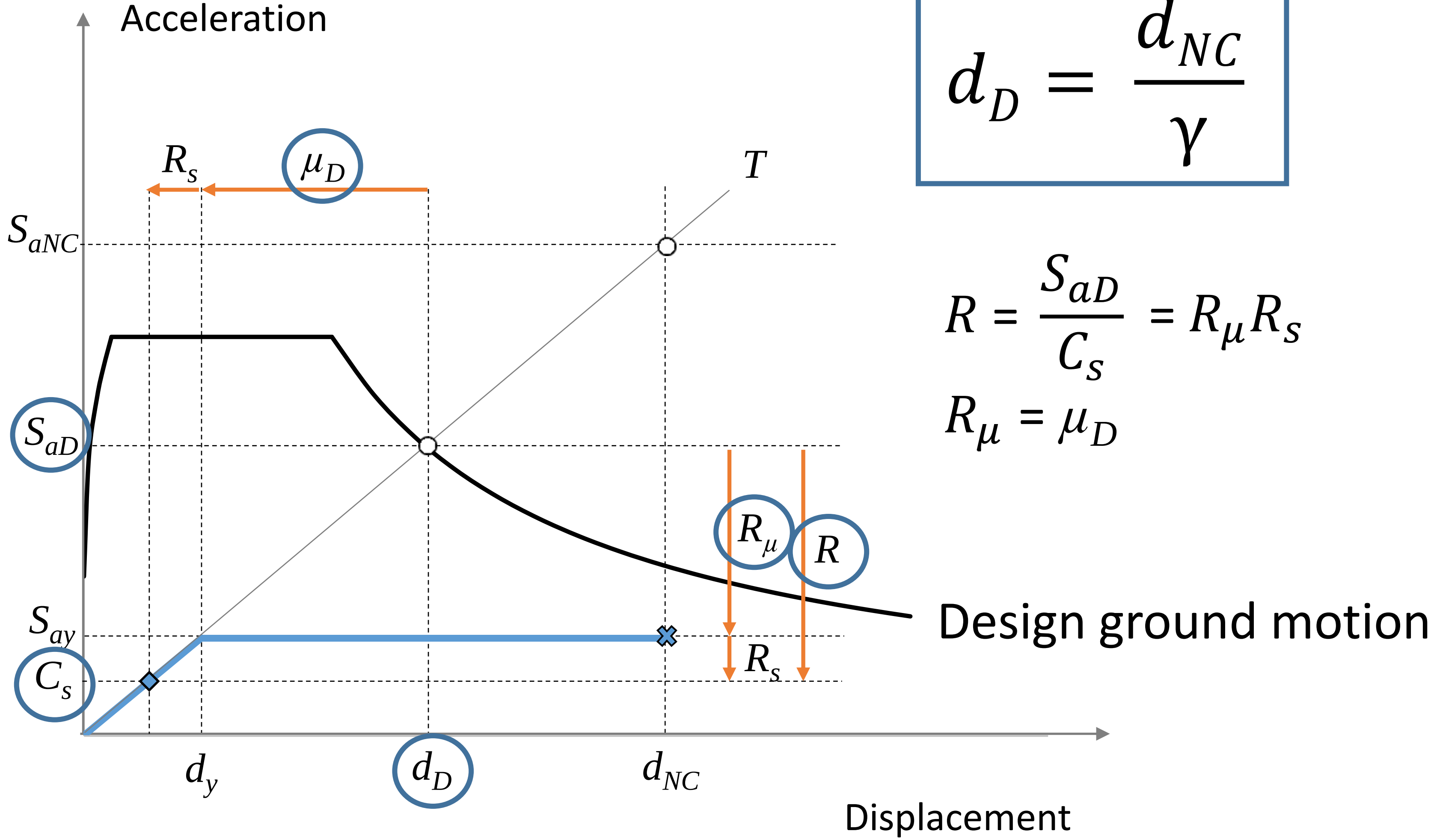
$$\gamma = \frac{S_{aNC}}{S_{aD}} = \frac{d_{NC}}{d_D}$$



$$d_D = \frac{d_{NC}}{\gamma}$$

Force reduction R factor

Behaviour factor q in EC8



$$d_D = \frac{d_{NC}}{\gamma}$$

$$R = \frac{S_{aD}}{C_s} = R_\mu R_s$$

$$R_\mu = \mu_D$$

Force reduction *R* factor

$$R = R_\mu R_s$$

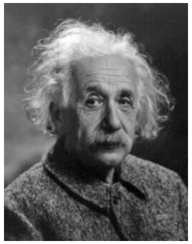
$$R_\mu \neq \mu_{NC} \quad !$$

$$R_\mu = \mu_D = \frac{\mu_{NC}}{\gamma}$$

Conclusion

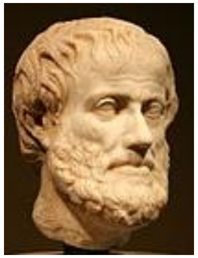
Analysis procedures available for all needs

Everything should be made as simple as possible, but not simpler



A. Einstein

It is the mark of an educated mind to rest satisfied with the degree of precision which the nature of the subject admits and not to seek exactness where only an approximation is possible.

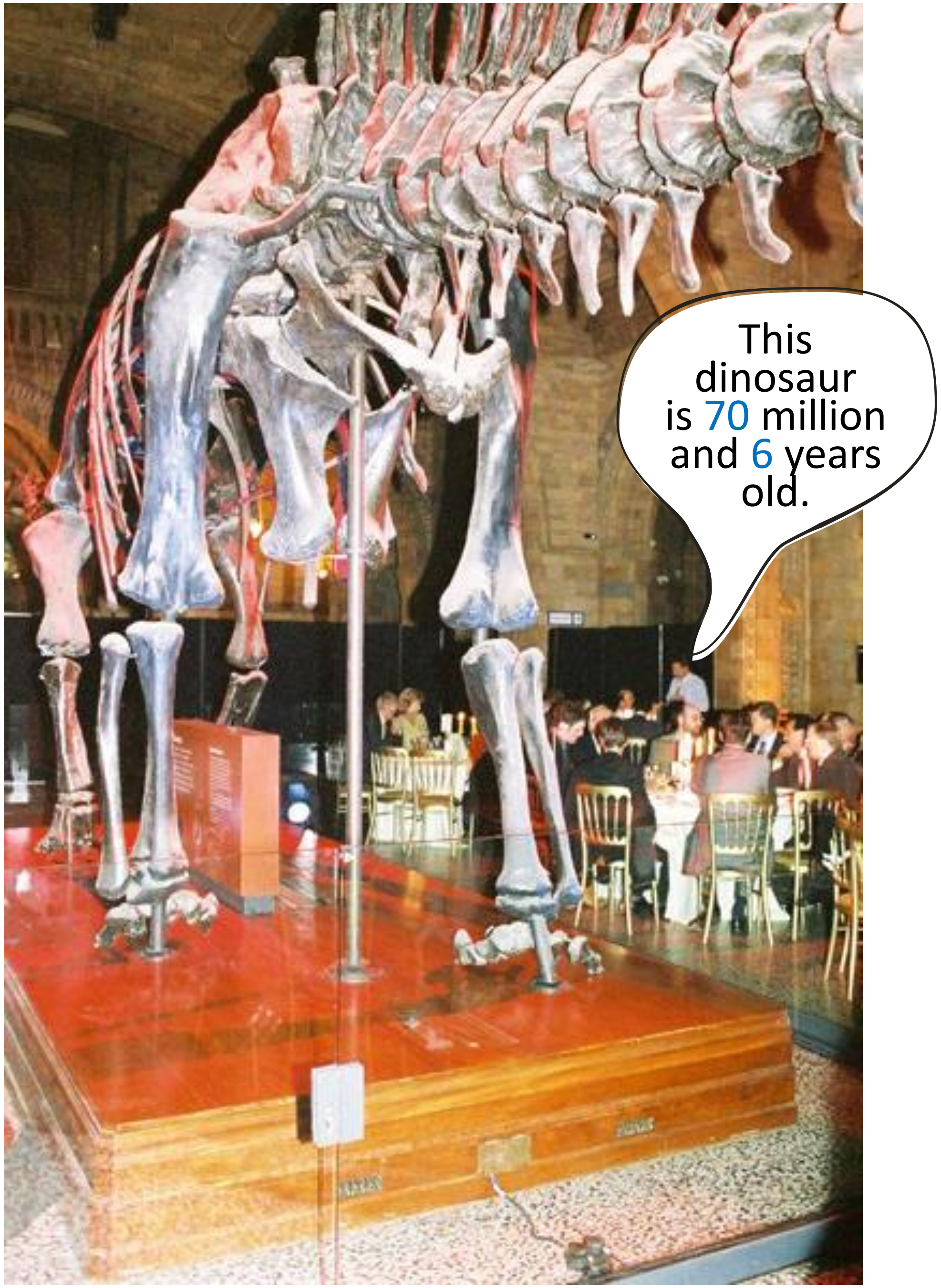


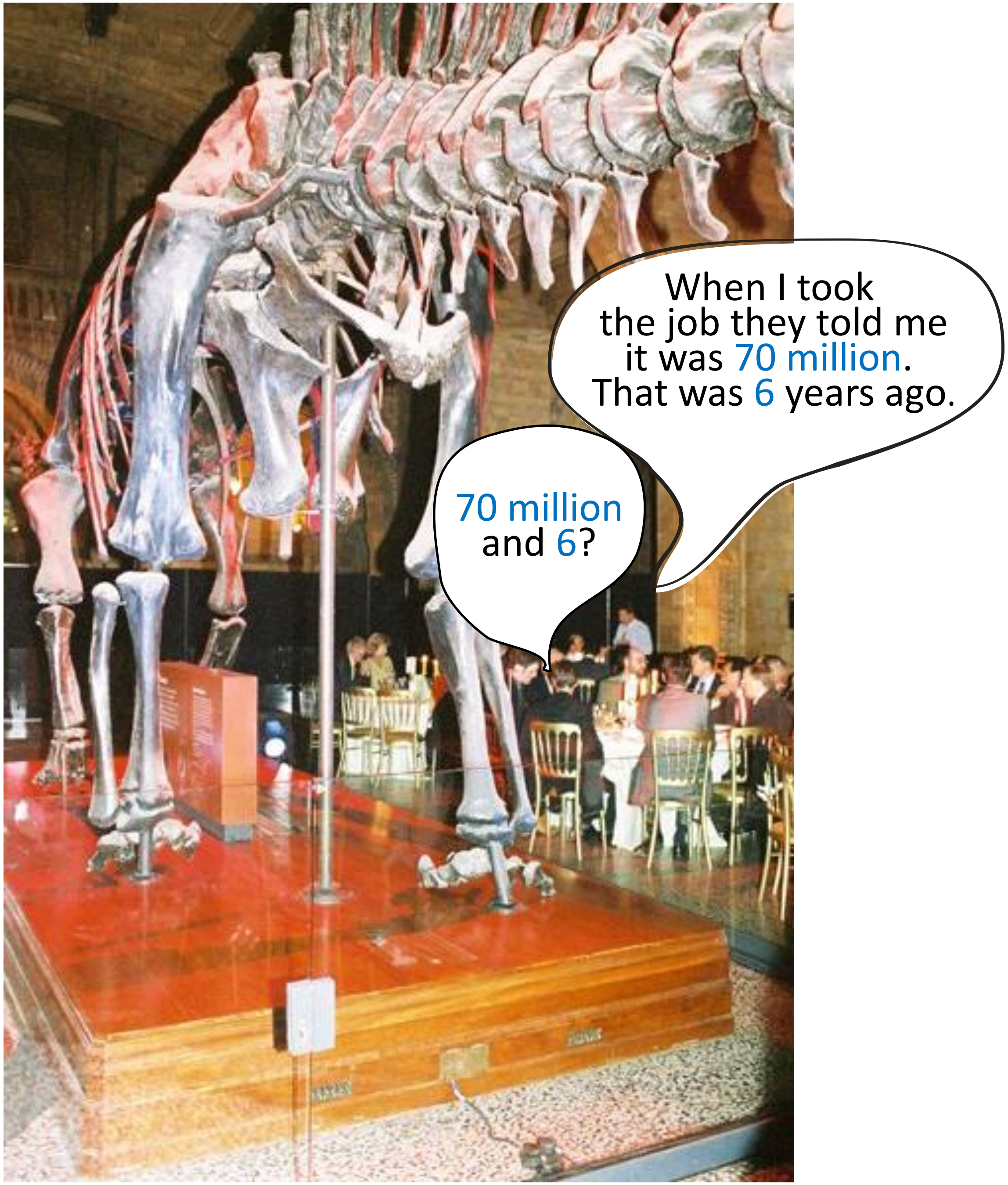
Aristotle (Nicomachean Ethics, Book One, Chapter 3)

(borrowed from P. Gülkan)

12^{th}ECEE, London 2002

Natural history museum


This dinosaur is 70 million and 6 years old.


When I took the job they told me it was 70 million. That was 6 years ago.
70 million and 6?