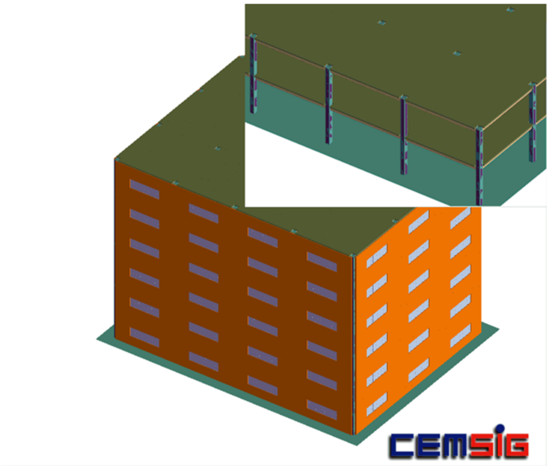
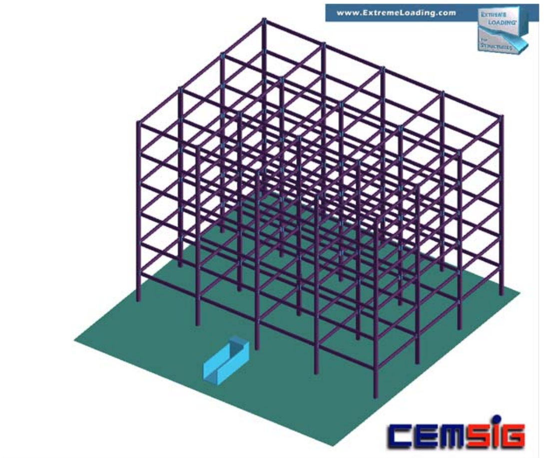
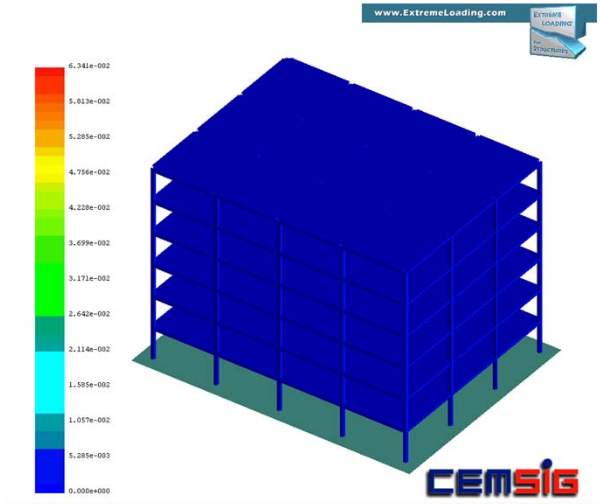
Robustness of structures. Generalities







Florea Dinu

Lecture 5: 02/04/2014

European Erasmus Mundus Master Course

Sustainable Constructions under Natural Hazards and Catastrophic Events

520121-1-2011-1-CZ-ERA MUNDUS-EMMC

Universitatea Politehnica Timişoara

Introduction and definitions

Definitions

- Progressive collapse
- Robustness
- Structural integrity
- Accidental loading, Exceptional loading
- Class of consequences
- Scenarios
- …

Progressive collapse & Robustness

Robustness - the ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent *disproportionate* to the original cause.

EN 1991-7

Progressive collapse - the spread of local damage, from an initiating event, from element to element resulting, eventually, in the collapse of an entire structure or a disproportionately large part of it; also known as *disproportionate collapse*.

ASCE 7-05

Robustness

Robustness required to resist to extreme events such as:
- explosion
- terrorist attack
- impact
- fire*
- earthquake*

events of low probability but sometimes disastrous consequences

The Cardington Fire Test © Hothan3

* fire or earthquake events not foreseen when initially designing the structure

Eurocode requirements

Eurocode EN 1990 Basis of Structural Design:

(4)P A structure shall be designed and executed in such a way that it will not be damaged by events such as:
- explosion,
- impact
- the consequences of human errors,

to an extent disproportionate to the original cause.

Eurocode and U.K. recommendations

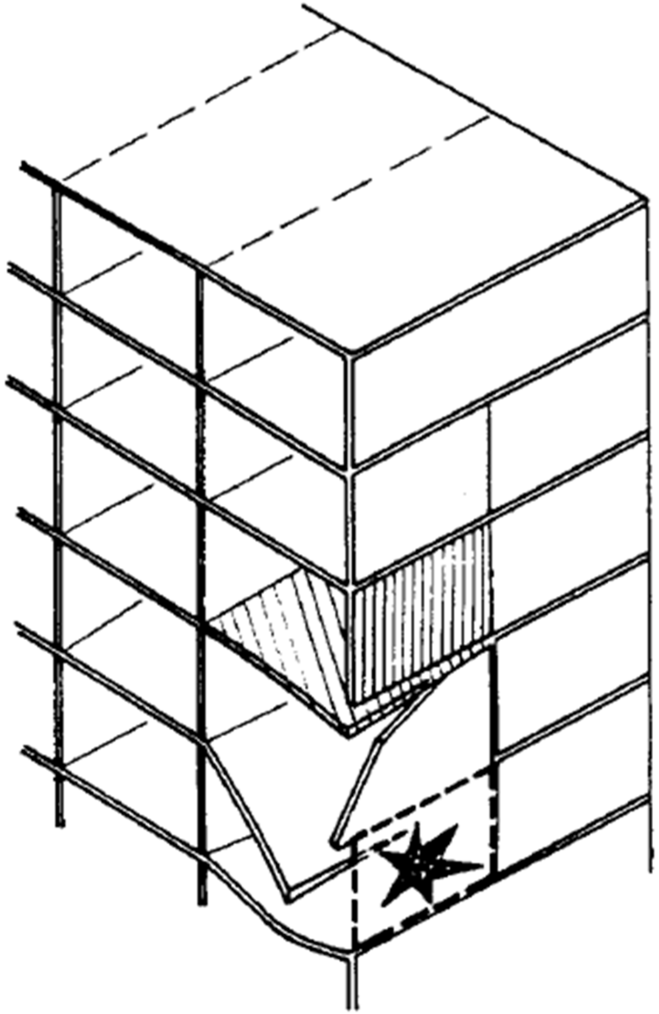
Rules in EN 1991-1-7 Accidental Actions and UK Codes of Practice:

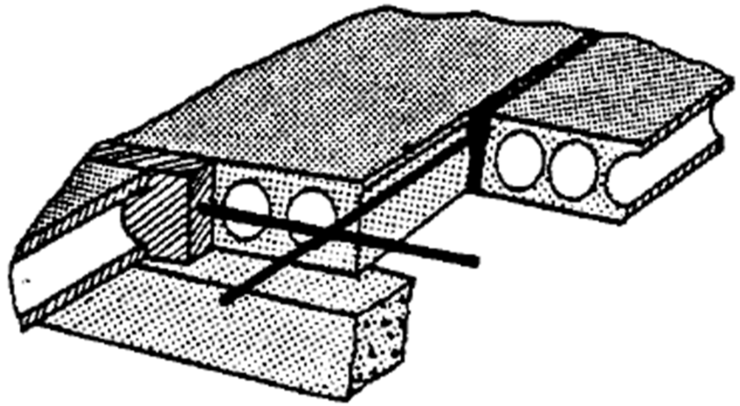
- introduce vertical ties,

- design key elements for a recommended accidental design action Ad= 34 kN/m2

- ensure that upon the notional removal of a supporting column, wall section or beam, the damage does not exceed 15% of the floor in each of 2 adjacent storeys

U.K. recommendations



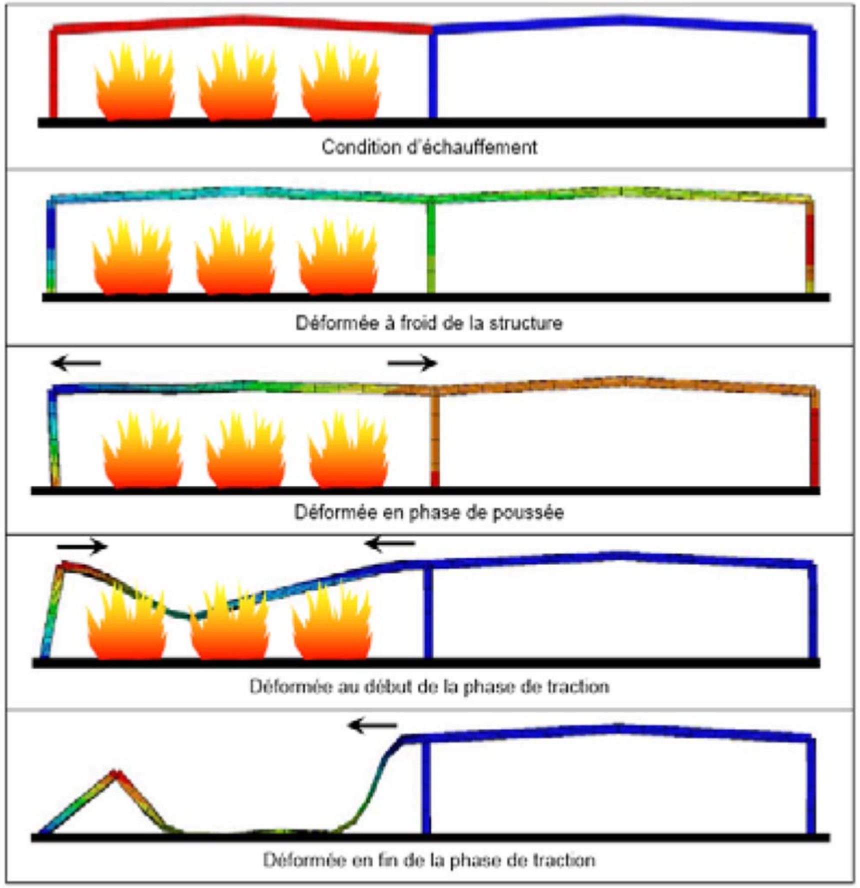


- Collapse at Ronan Point, Canning Town, England, 16th May 1968:
  - caused by a gas explosion in the corner of the 18th floor
  - progressive collapse (precast concrete slab elements)

First provisions: HMSO (1976). Statutory Instrument, No. 1676: Building and Buildings, London

Aims

- Save lives
- Reduce the risks for interventions (fire brigades, civil protection, …)
- Limit collateral damages


Condition d'échauffement
Déformée à froid de la structure
Déformée en phase de poussée
Déformée au début de la phase de traction
Déformée en fin de la phase de traction

Risk: progressive collapse

RONAN POINT, 1968

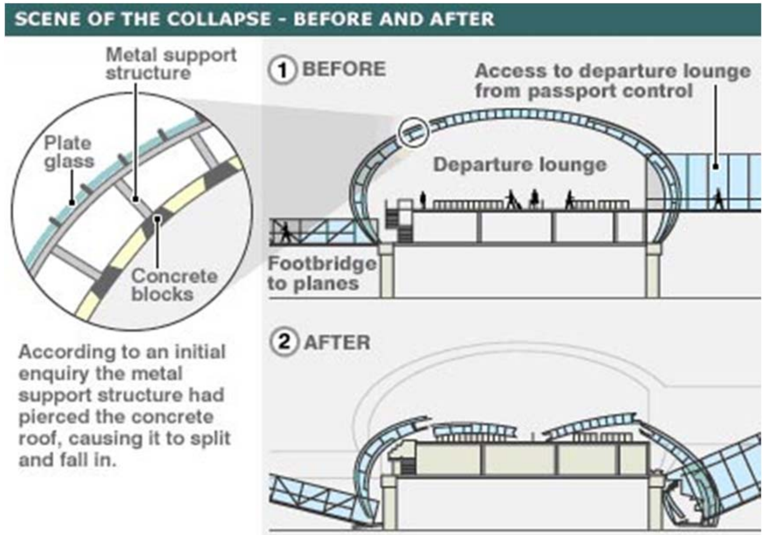
WTC, 2001

OKLAHOMA CITY, 1995

Ice Stadium Bad Reichenhall © Feuerwehr Berchtesgaden

Kattowitz © dpa

Wrong steel-concrete connection details at Charles-de-Gaulle Airport new terminal, 2004



Structural requirements

- Under design loads:
  - Resistance
  - Stiffness
  - Stability
  - Ductility

of the whole structure and of its structural elements with a predefined level of safety

- Under exceptional loads
  - Structural integrity

of the whole structure (or a large part) to avoid *progressive* collapse

Exchequer Court bombing,
St Mary's Axe, London 1992

Structural integrity

No structural integrity

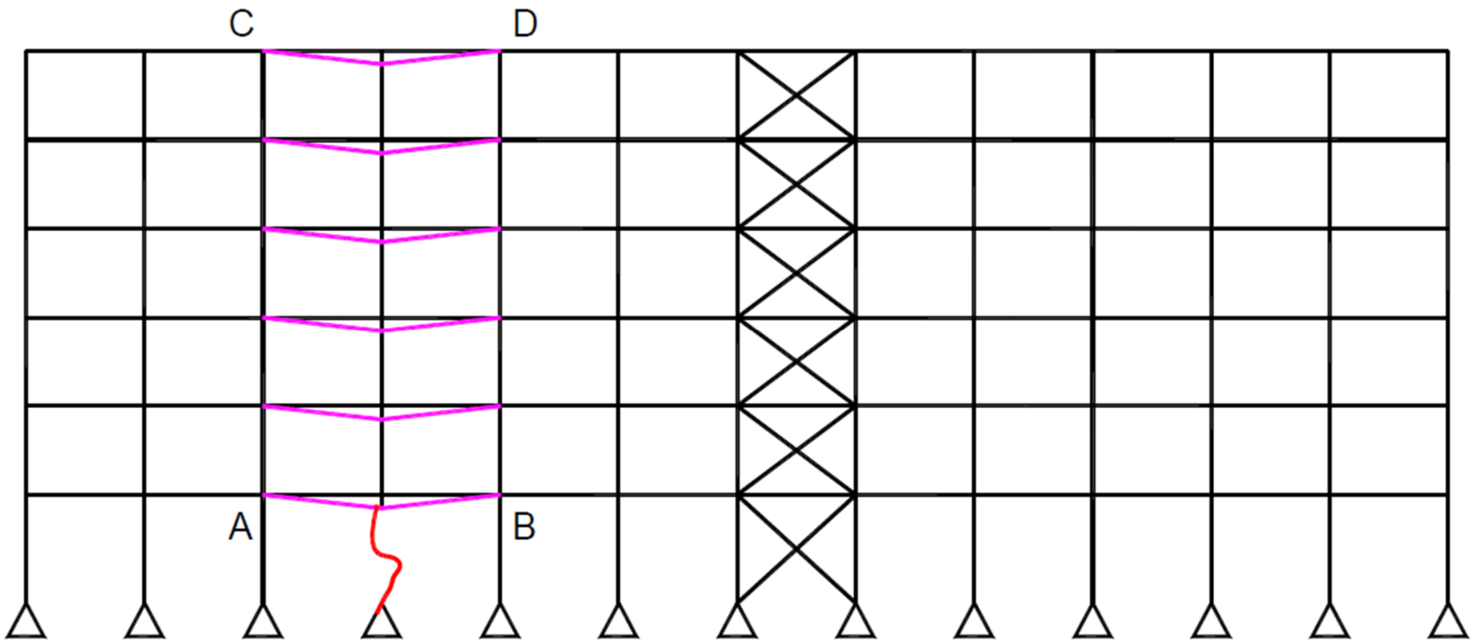
Partial structural integrity

Structural integrity

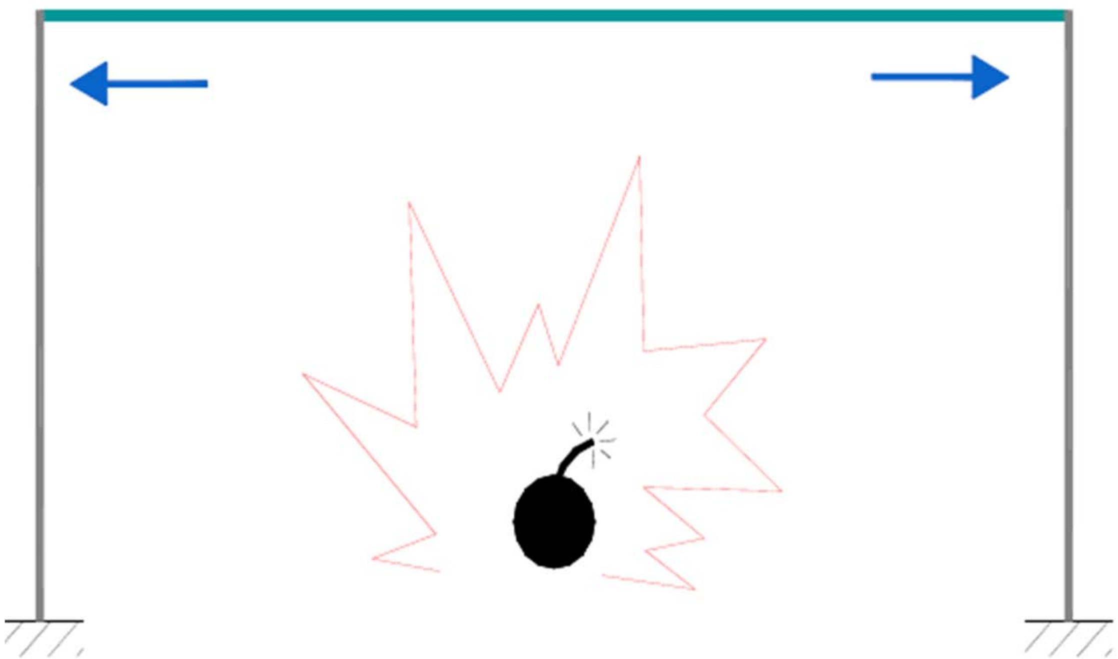
Beyond limit states

- Under service loads SLS
- Under factored (design) loads ULS
- Under exceptional loads:
  - No control on deformations and displacements
  - Second order effects ==> deformed new stable stage to reach

Beyond limit states



Beyond limit states



Loading situations

- Resistance and proper behavior required under design loads
  ==> traditional design

- Robustness required under exceptional loads (events)*
  ==> extra structural requirements

* distinguish from 'accidental' loads

Example:

Significant seismic action (0.3 - 0.4g) for a building in Romania:
==> design load

Similar seismic action for a building in a non seismic (or low seismicity) region (eg. Belgium):
==> exceptional load

Exceptional loading:

- Load with a very low probability of occurrence
- Too low probability to be directly taken into account in the design

Loading situations

- Snow,
- Wind (storm, …),
- Earthquakes
- Tsunami,
- …

Natural hazard

- Impacts,
- Explosions, …
- …

Human induced hazard

Loading situations

- Snow,
- Wind (storm, …),
- Earthquakes
- Tsunami,
- …

- Impacts,
- Explosions, …
- …

Different types:

- **static**
- **dynamic**
- **impact**
- **cyclic**
- **…**

Conclusions

- In contrast to ultimate, serviceability and durability limit states, only general requirements and very few detailed rules exist

- Recent incidents show high relevance and importance

- Structures such as power and manufacturing plants, banks, administrative, finance and healthcare office buildings and bridges are key elements of modern infrastructure for which robustness requirements have more and more to be satisfied

Conclusions

Robustness as structural ability to allow sufficient resistance against failure for unplanned and unforeseen exceptional events, i.e. which have not been considered in the initial design

Ice Stadium Bad Reichenhall © Feuerwehr Berchtesgaden

- Structural integrity should be maintained and progressive collapse should be avoided
- Global structure should remain stable under any conditions, even one part is removed or heavily damaged

Ways and Means

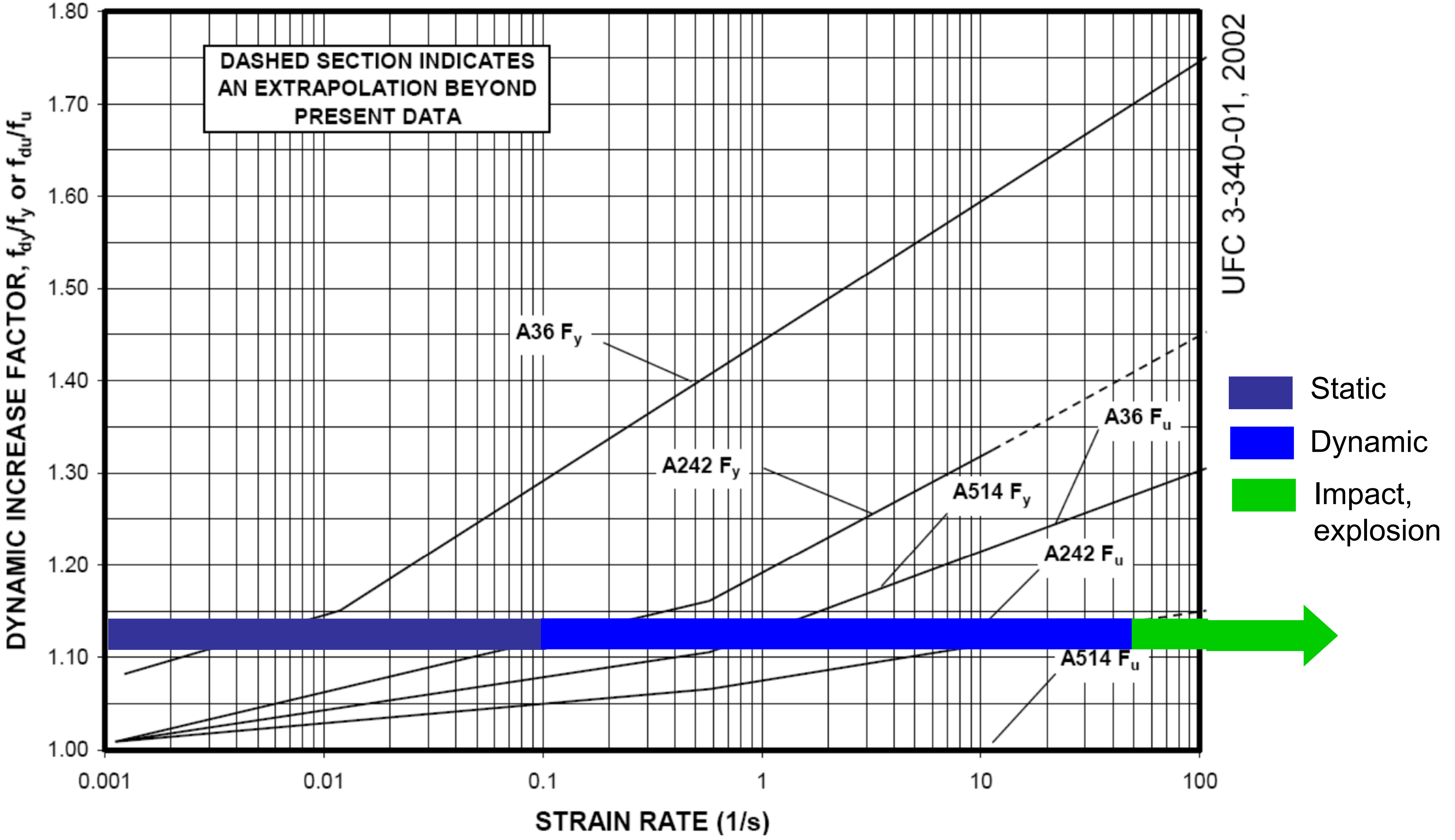
Various aspects to consider

Complex problems to face:

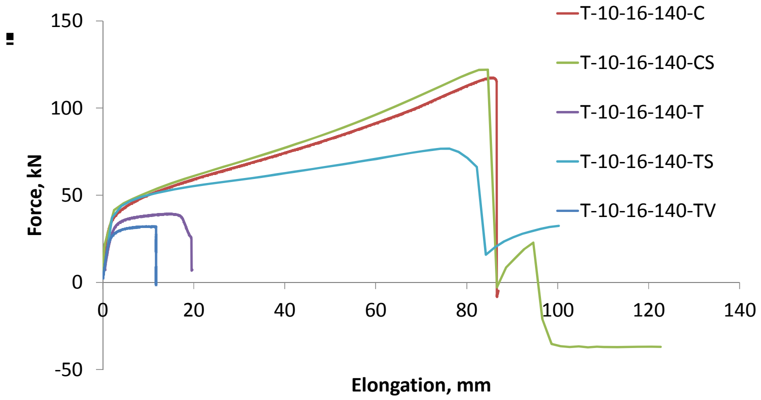
-Material characteristics depend on temperature or dynamic behaviour

- Actions: dynamic, temperature dependent

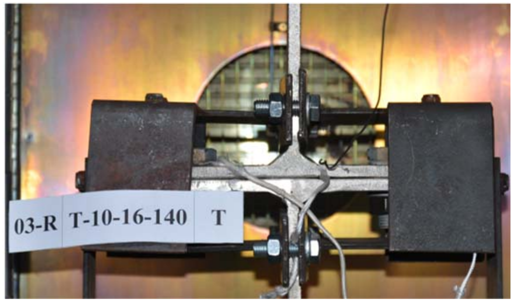
- Evaluation of a residual resistance time or of a residual bearing capacity



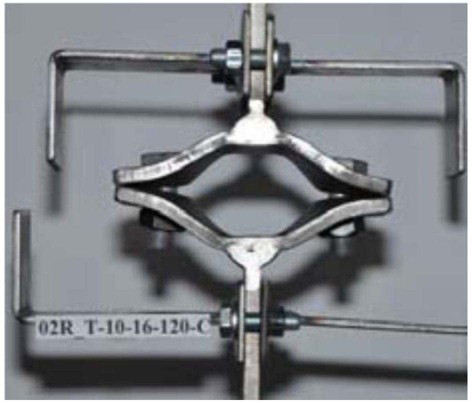
Strain Rate Factors for Structural Steel



Initial



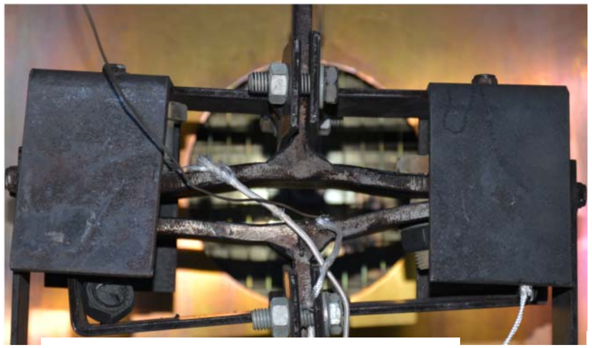
Initial, T=542°C

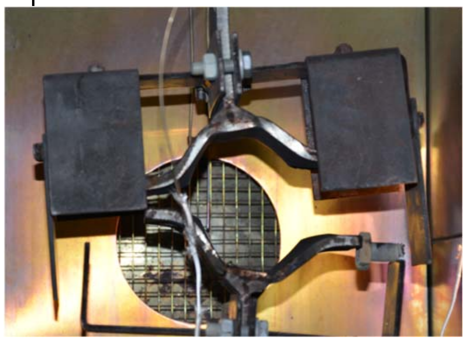


cvasistatic

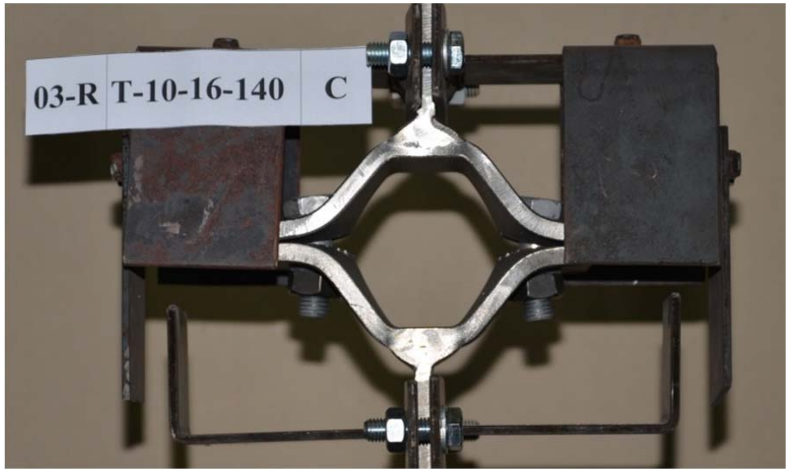

v_1 = 10 mm/sec

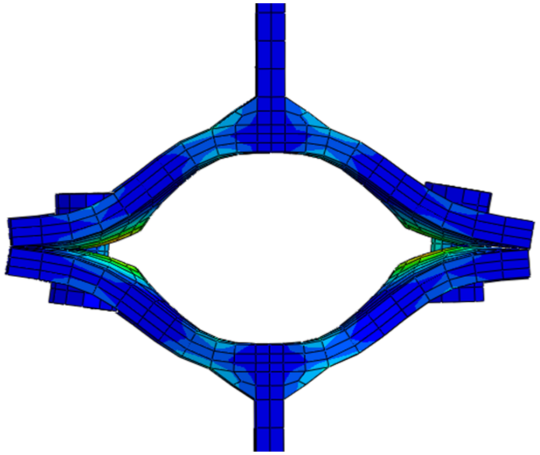
v2 = 15 mm/sec

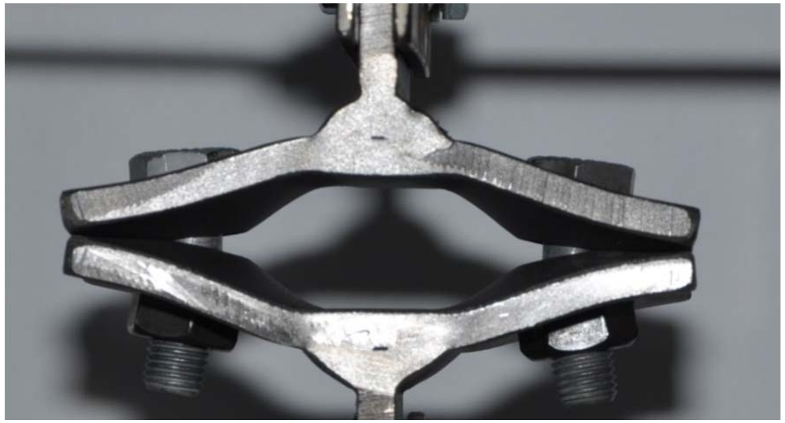

cvasistatic, T=542°C

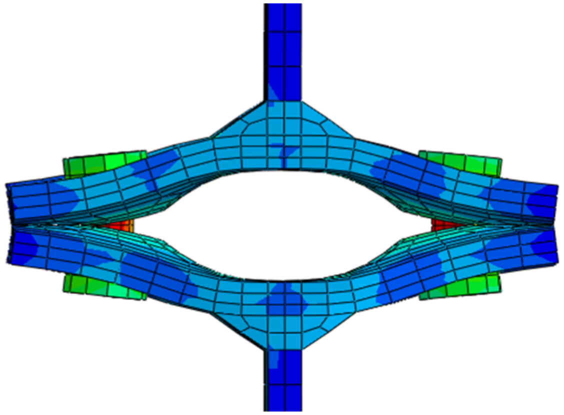

v1 = 10 mm/sec, T=542°C


v2 = 15 mm/sec, T=542°C


03-R
T-10-16-140
C







Ways and Means

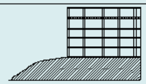
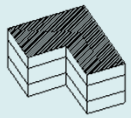
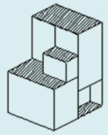
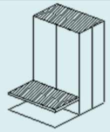
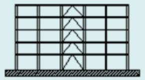
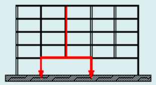
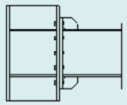
Various aspects to consider

Complex problems to face:

- Exceptional events unknown
- Scenarios unknown

==> risk analysis to define possible exceptional events and scenarios according to the structure and its use (comments on a recent experience)

Multi-hazard design matrix (adapted from FEMA 577)

	Site and building characteristics		Hazard: Seismic	Hazard: Flood	Hazard: Wind	Hazard: Fire	Hazard: Explosion	Interaction
1	Elevated building site		-	+	0	0	+	Highly beneficial for floods and external bomb explosion, not significant for wind or fire
2	Re-entrant corner plan forms		-	0	-	0	-	Stress concentration at corners, irregular behavior in case of earthquakes; localized wind pressures, amplification of shock wave in case of external blast
3	Very irregular buildings		-	0	-	-	-	Indirect load paths, stress concentrations in earthquakes, explosions. Localized high wind pressure, aggravates evacuation in case of fire
4	Large roof overhangs		-	0	-	-	-	Vulnerable to earthquakes (vertical motion), wind and also adjacent external blast. Mai pose risk also in case of fire evacuation
5	Steel structural frame		+	+	+	-	+	When properly detailed, is recommended in seismic and high-wind zones. Good in flood with proper detailing. Vulnerable to fire if is not protected or well detailed and designed. Low vulnerability in case of blast and explosion, offers multiple paths.
6	Indirect load path		-	0	-	-	-	Very vulnerable for seismic, wind and explosion hazards because poor structural integrity increases likelihood of collapse. Fire may further weaken structure.
7	Ductile detailing of structure and connections		+	0	+	+	+	Provides good plastic response. The structure has large ductility and is more resistant to collapse in case of extreme loading

Note: The following convention has been used in the table:
\+ indicates a desirable condition or beneficial interaction between the designated component/system and hazard
0 indicates little or no significant interaction between the designated component/system and hazard
\- indicates an undesirable condition or the increased vulnerability of a designated component/system to a hazard

Consequence Class

Consequences Class	Description	Examples of buildings and civil engineering works	
CC3	**High** consequence for loss of human life, *or* economic, social or environmental consequences **very great**	Grandstands, public buildings where consequences of failure are high (e.g. a concert hall)	Significant demand in terms of robustness
CC2	**Medium** consequence for loss of human life, economic, social or environmental consequences **considerable**	Residential and office buildings, public buildings where consequences of failure are medium (e.g. an office building)	
CC1	**Low** consequence for loss of human life, *and* economic, social or environmental consequences **small or negligible**	Agricultural buildings where people do not normally enter (e.g. storage buildings), greenhouses	Low or no demand in terms of robustness

Various philosophies to follow

- Indirect methods:
  - No scenario considered
  - Just design requirements to fulfill
- Direct methods:
  - Specific load resistance method
  - Alternative load path method

 Specific load resistance method (version 1)

• Key elements ensuring the structural integrity

• These elements should remain unaffected by the event

 Specific load resistance method (version 2)

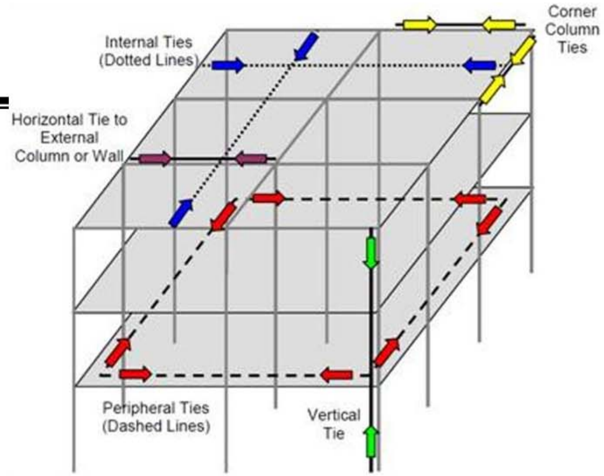
• Key elements ensuring the structural integrity

• These elements rapidly collapse in order to avoid the propagation of the damages to the rest of the structure

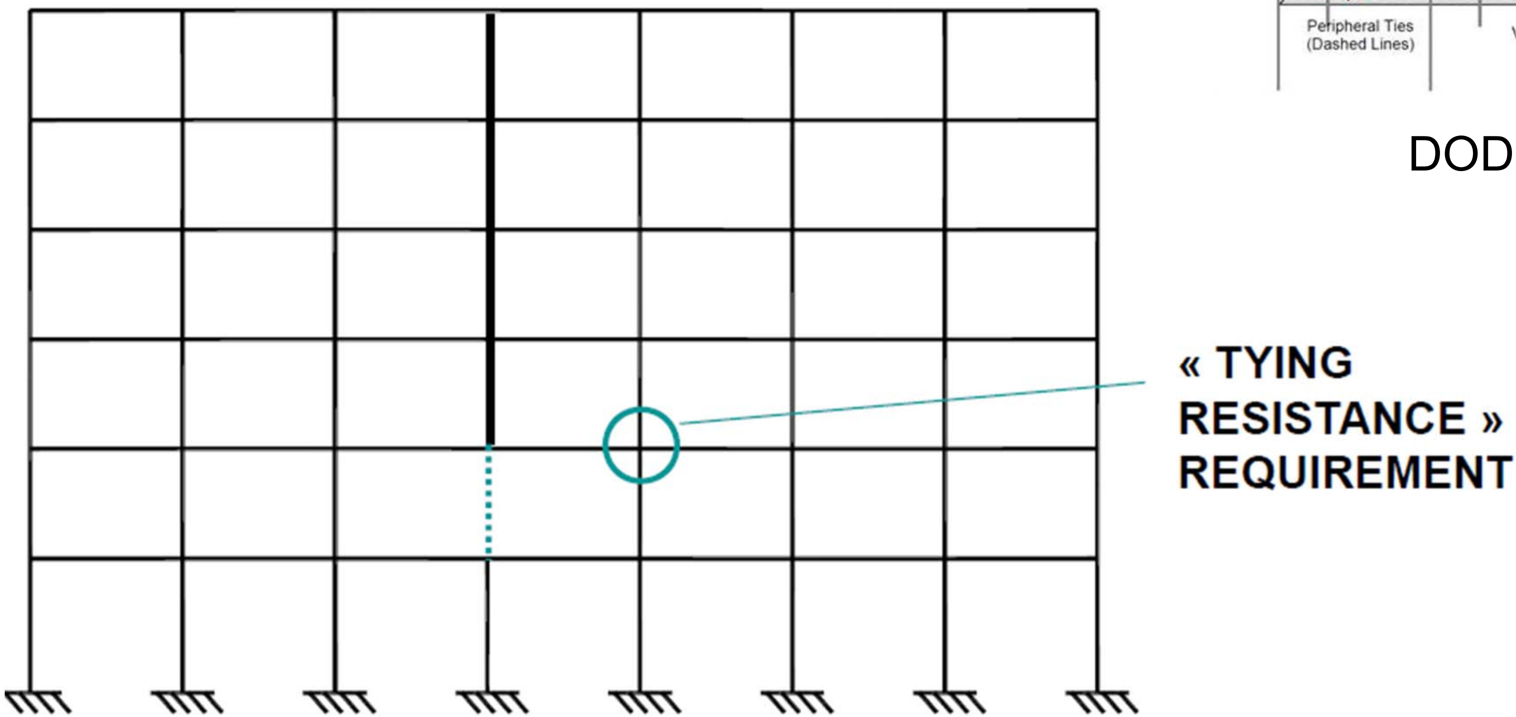
 Alternative load path method:

- Identification of damages associated to scenarios
- Load paths identified in the damaged structure
- Structural integrity checked

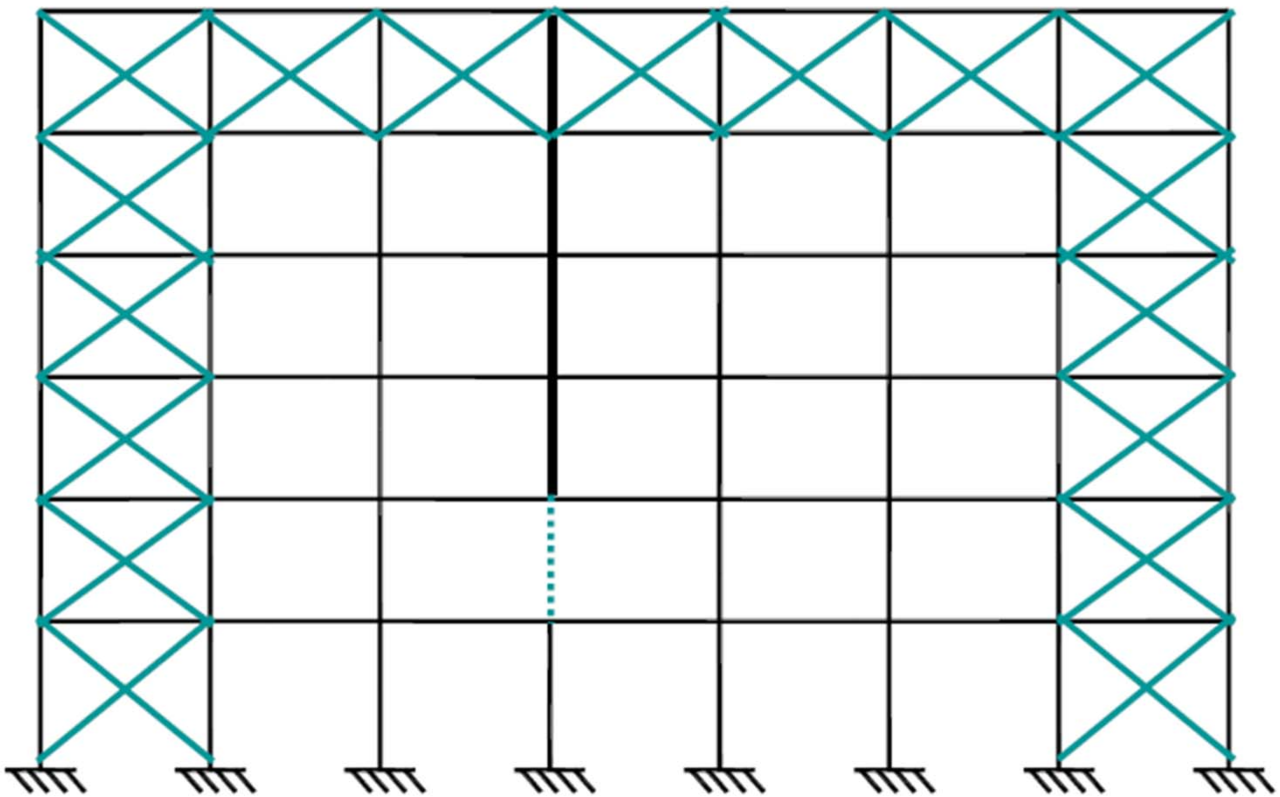
Indirect methods



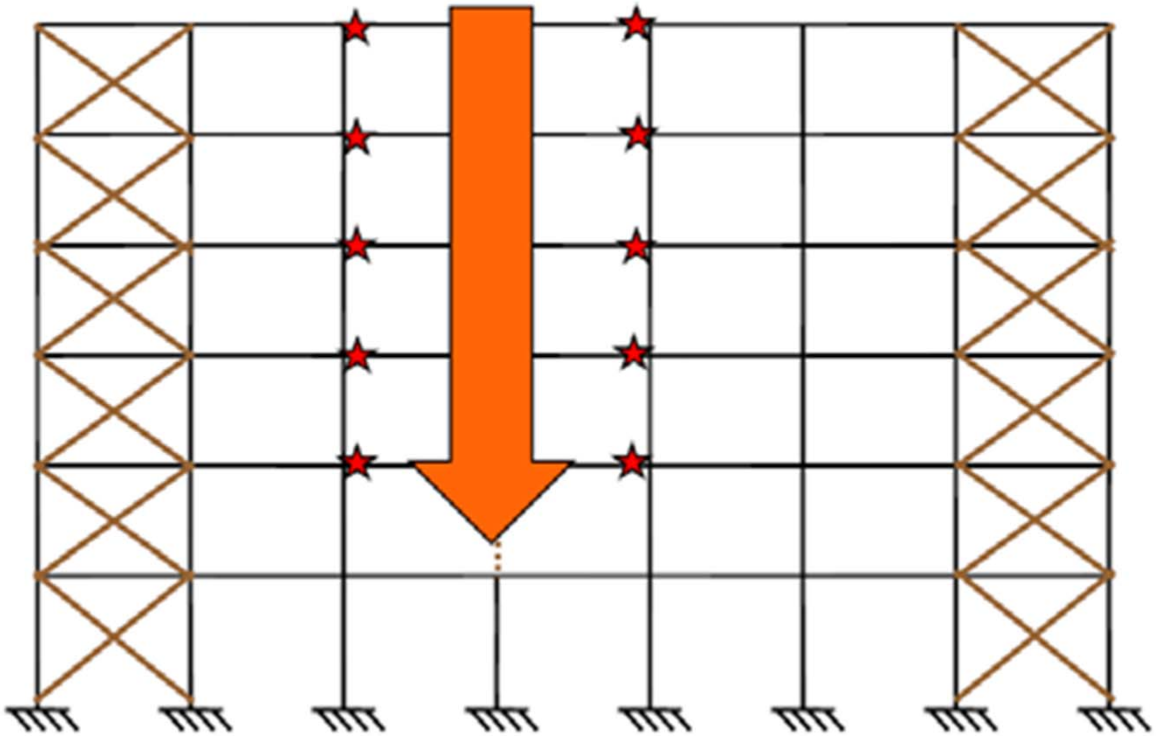
DOD, 2005



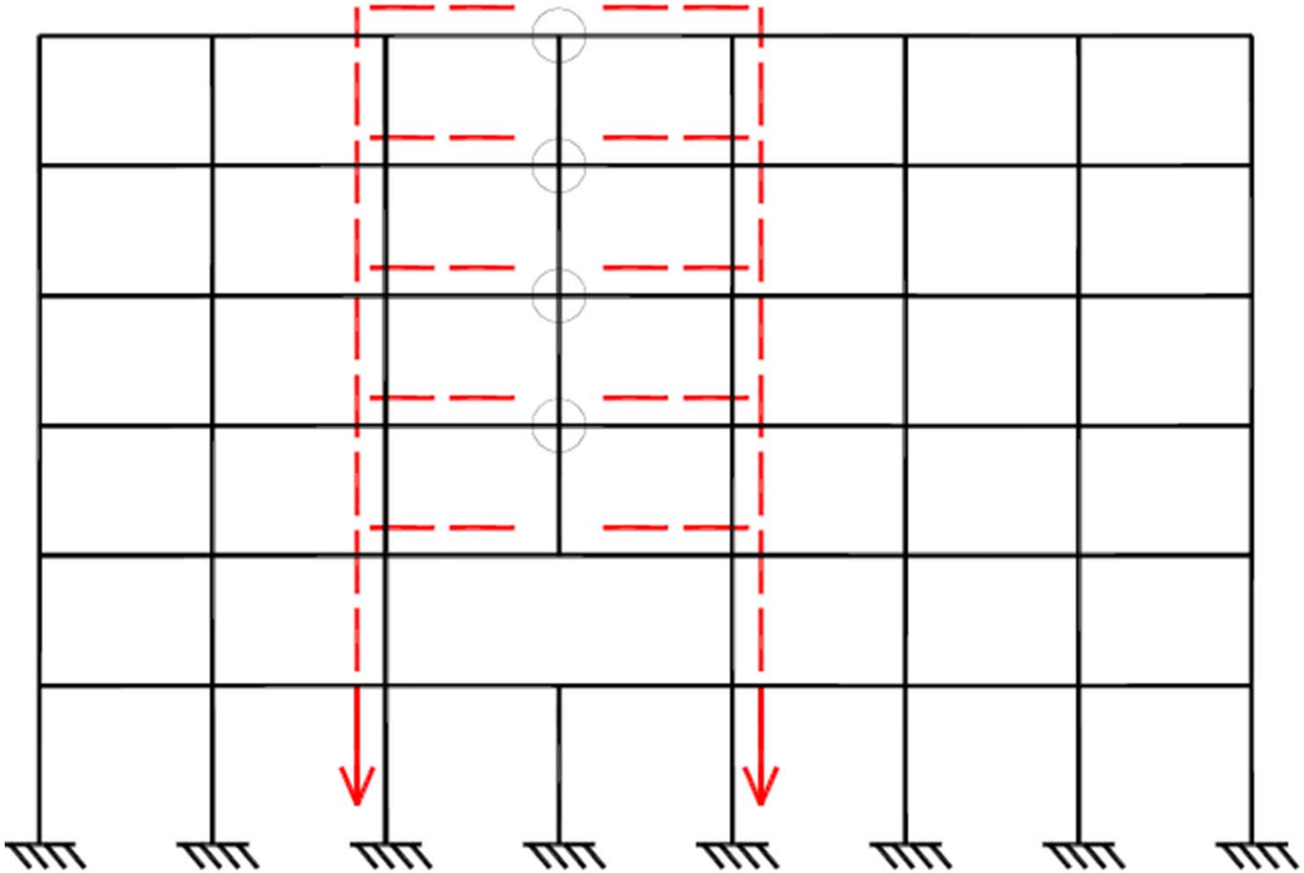
Specific load resistance (V1)



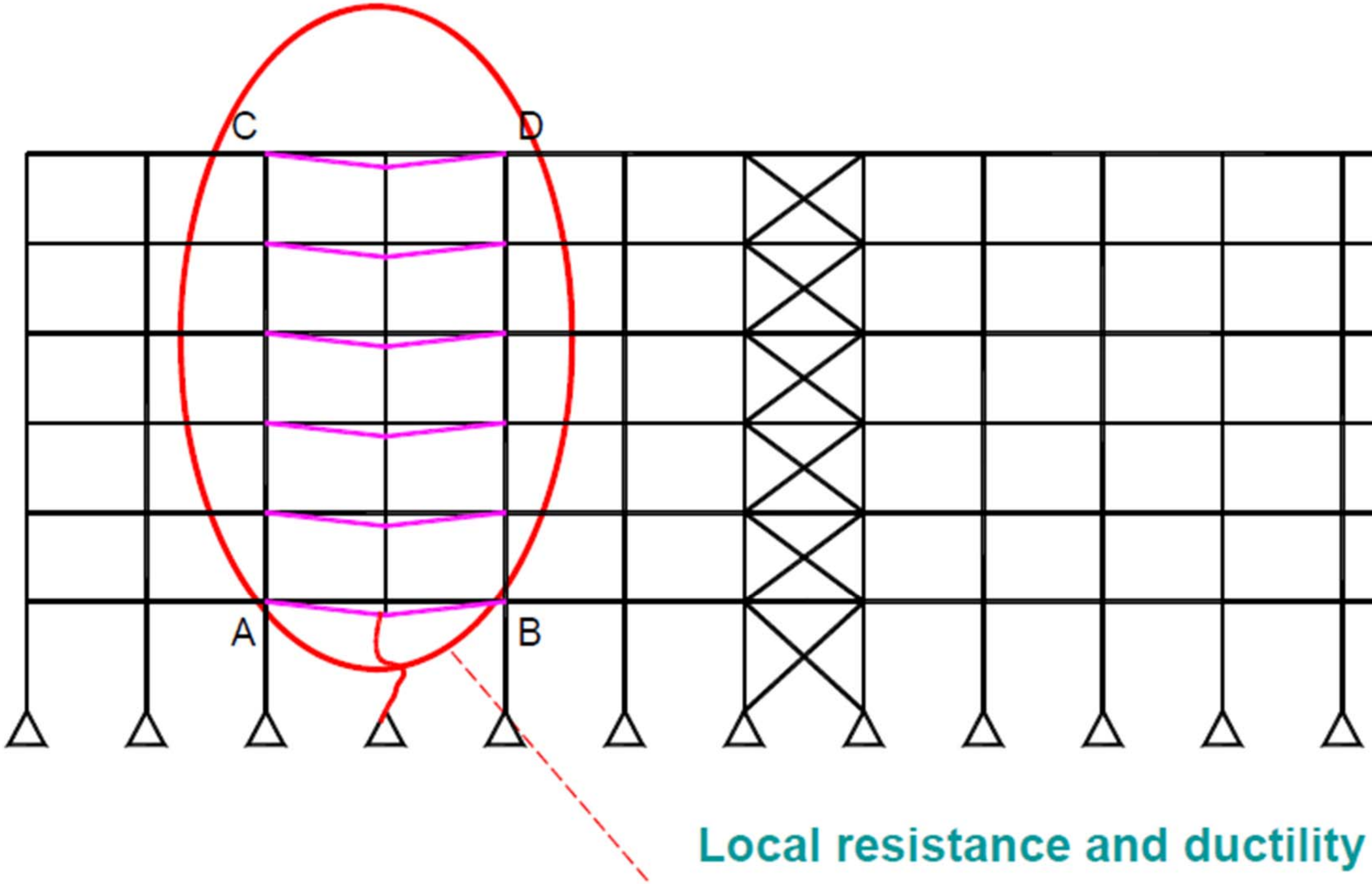
Specific load resistance (V2)



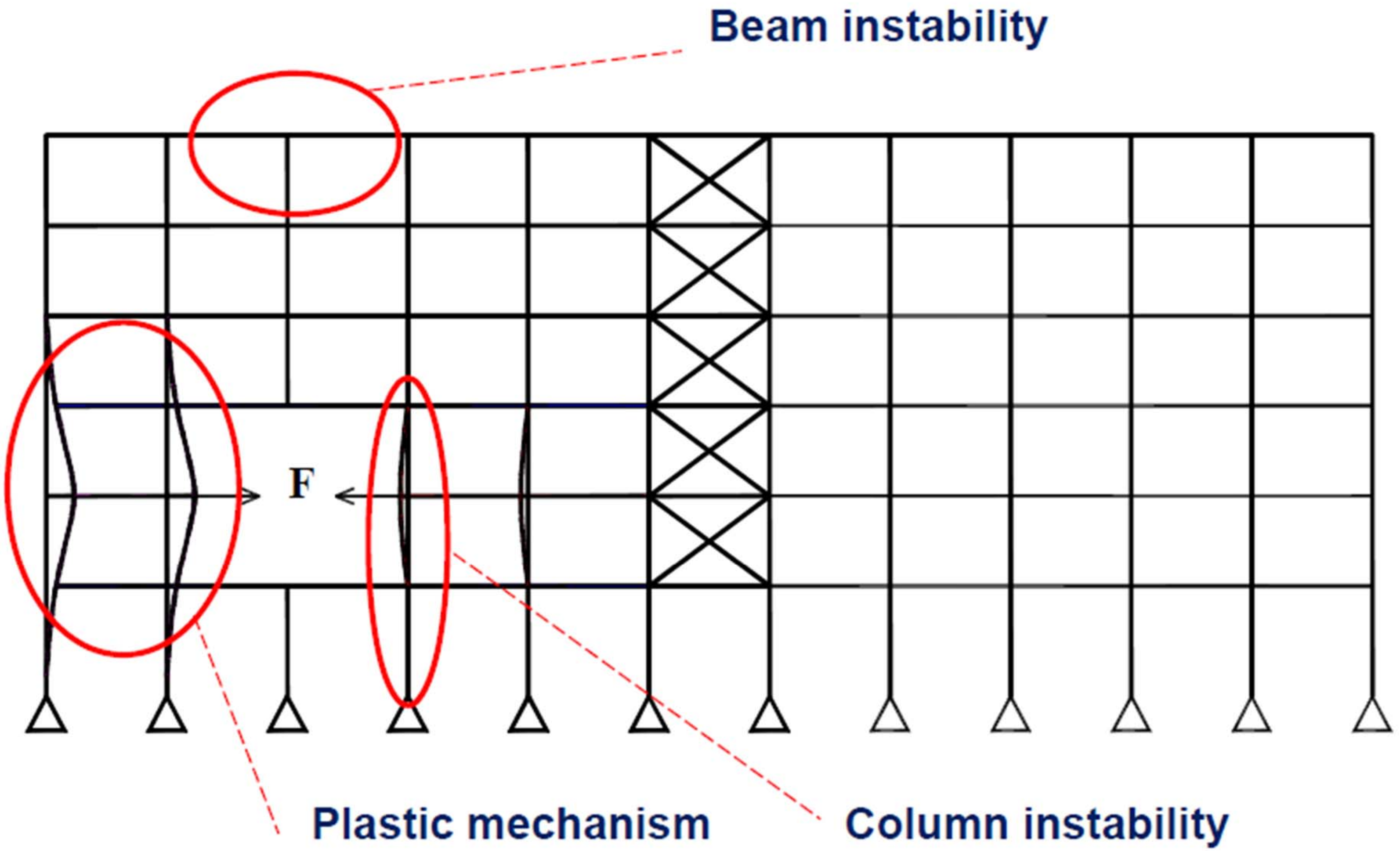
Alternative load path



Alternative load path

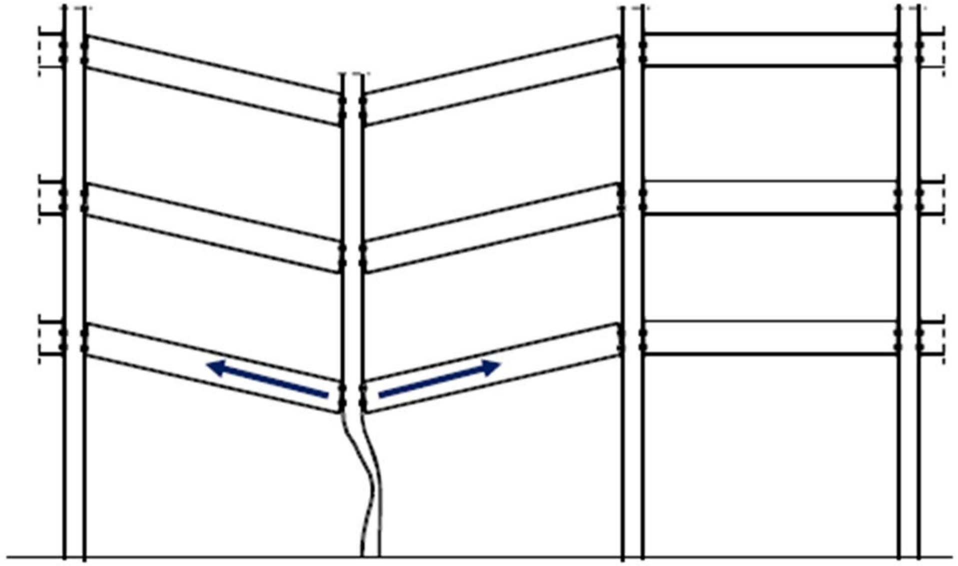


Alternative load path



Alternative load path

- Economical approach
- Requirements:
  - tying resistance
  - ductility criteria
  - redundancy
  - …



Different approaches

Most of these approaches will be described and illustrated in details in the next lectures

This lecture was prepared for the 1st Edition of SUSCOS (2012/14) by J.-F. Demonceau & J.-P. Jaspart, ULg

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