Ocelové konstrukce v EN1998-1:2005

František Wald

2C09
Design for seismic and climate change

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European Erasmus Mundus Master Course

Sustainable Constructions
under Natural Hazards and Catastrophic Events

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

Motivation

- To summarise the current rules for seismic design of steel structures

Lecture outline

1. Benefits of steel structures
2. **Design criteria for steel structures**
3. **Detailing rules for steel structures**

Benefits of Steel Structures

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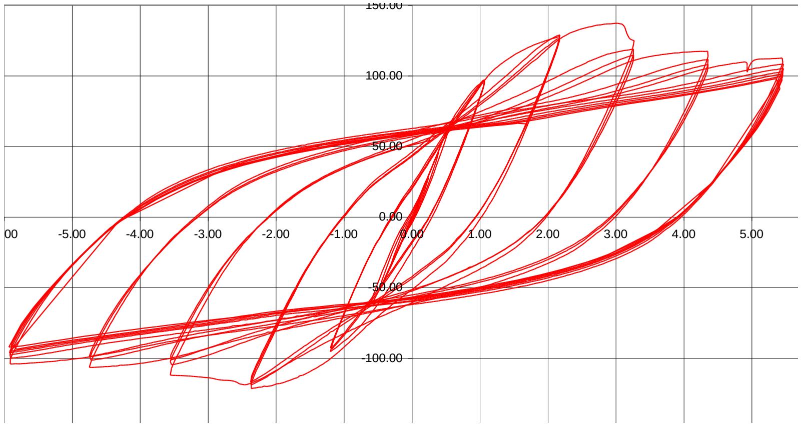
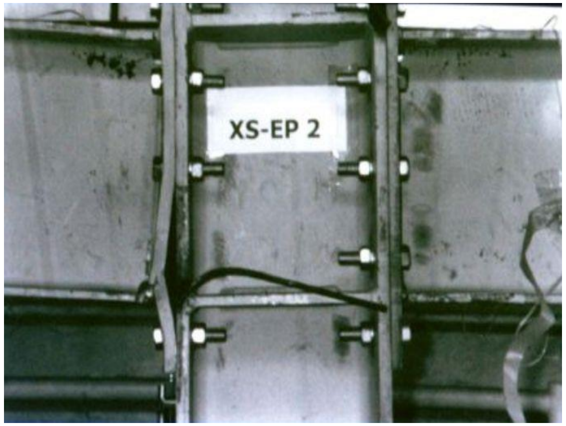
High ductility

The steel is characterized by the **ductility** that *is the capability to perform plastic deformations without failure*





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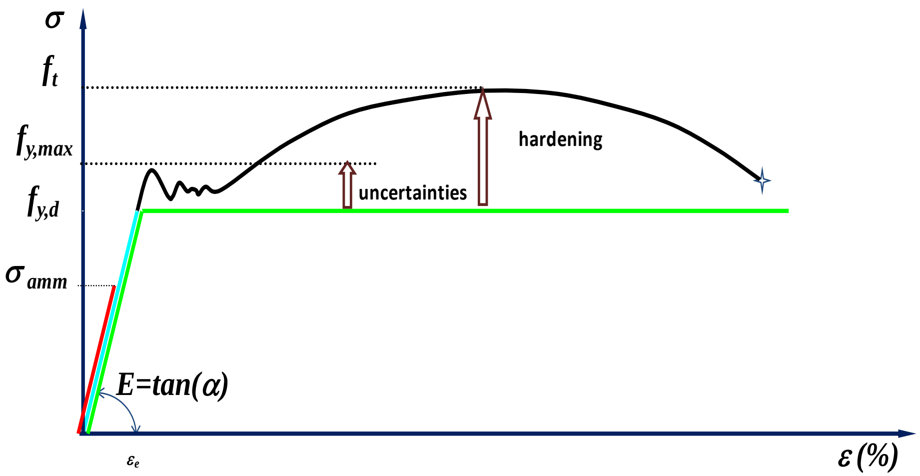
Ductility levels: **1. MATERIAL DUCTILITY**



Benefits of Steel Structures

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Ductility levels: 2. Local Ductility

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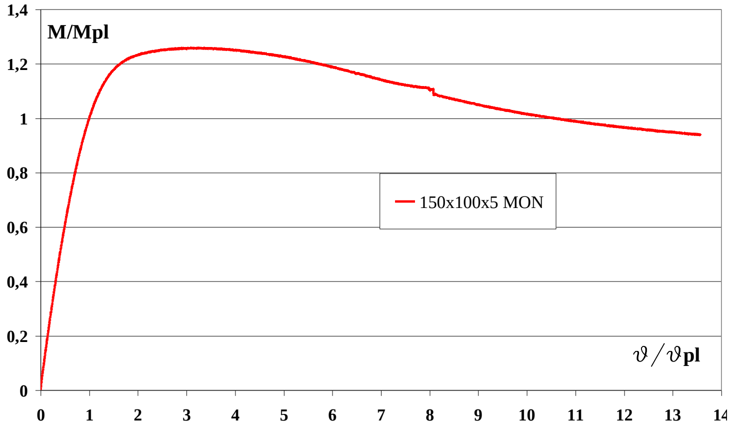

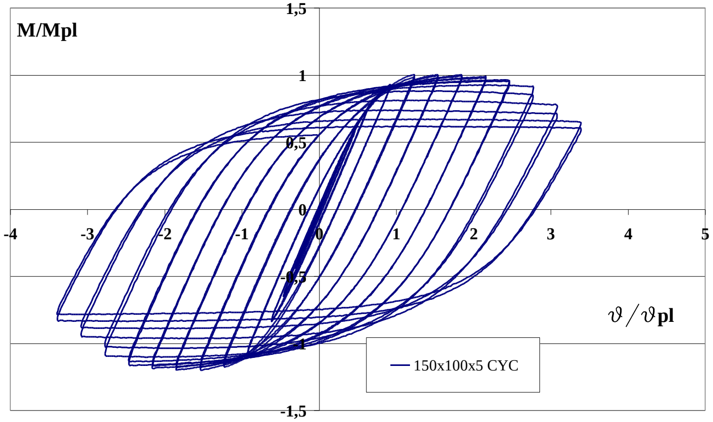

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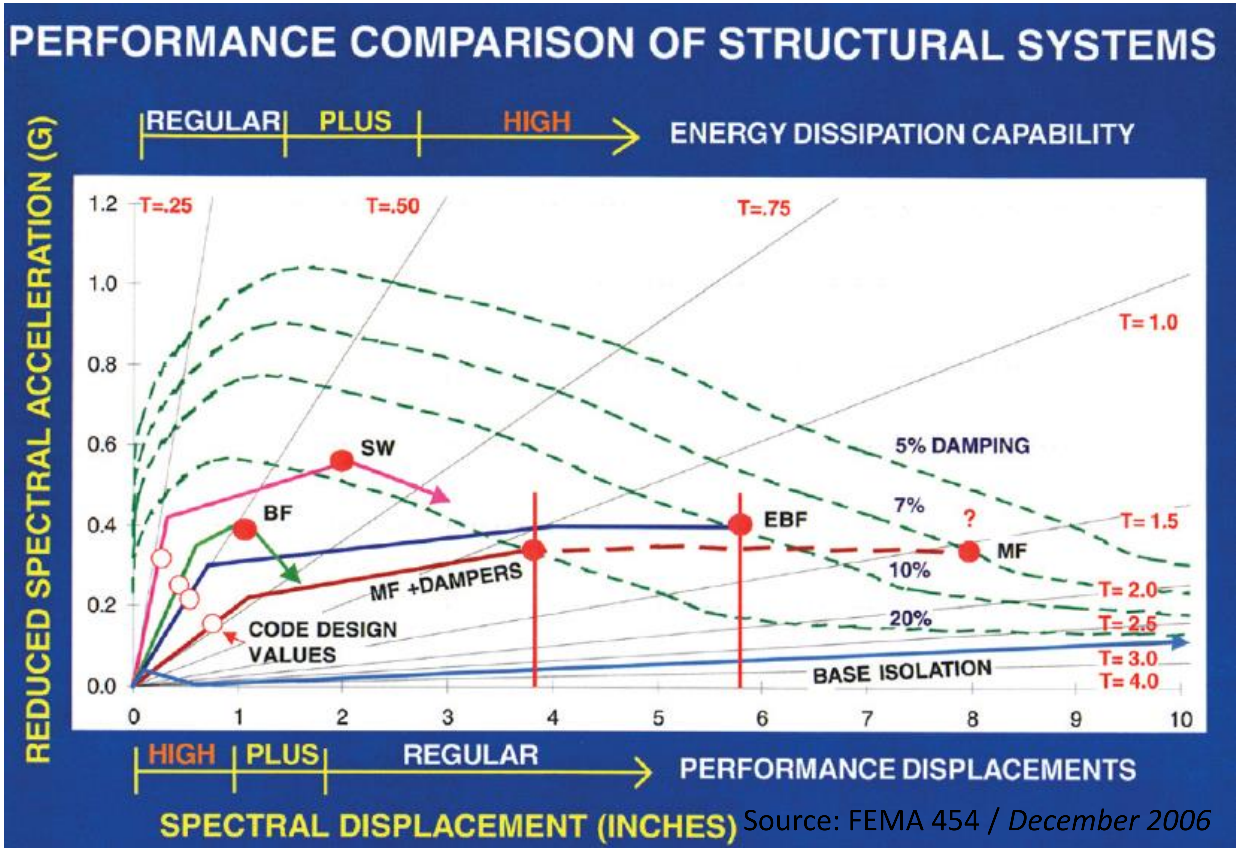
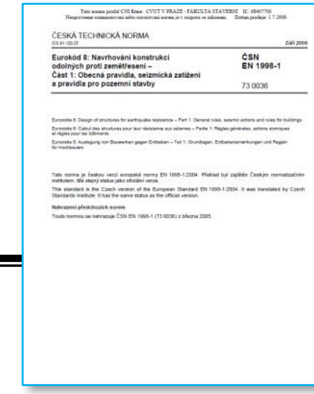
Ductility levels: 3. SYSTEM DUCTILITY

The great variability of structural typologies allows designing to get different seismic performances



Source: FEMA 454 / *December 2006*

EN1998-1:2008
Ch. 6 Steel Buildings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Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings

This standard is the Czech version of the European Standard EN 1998-1:2004. It was translated by Czech Standards Institute. It has the same status as the official version.

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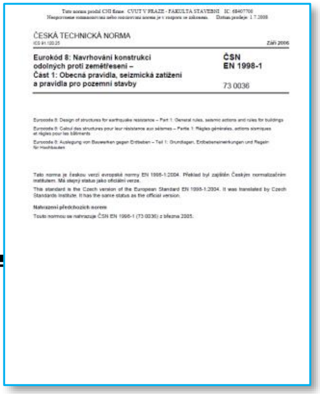
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DESIGN CONCEPT AND SAFETY VERIFICATIONS

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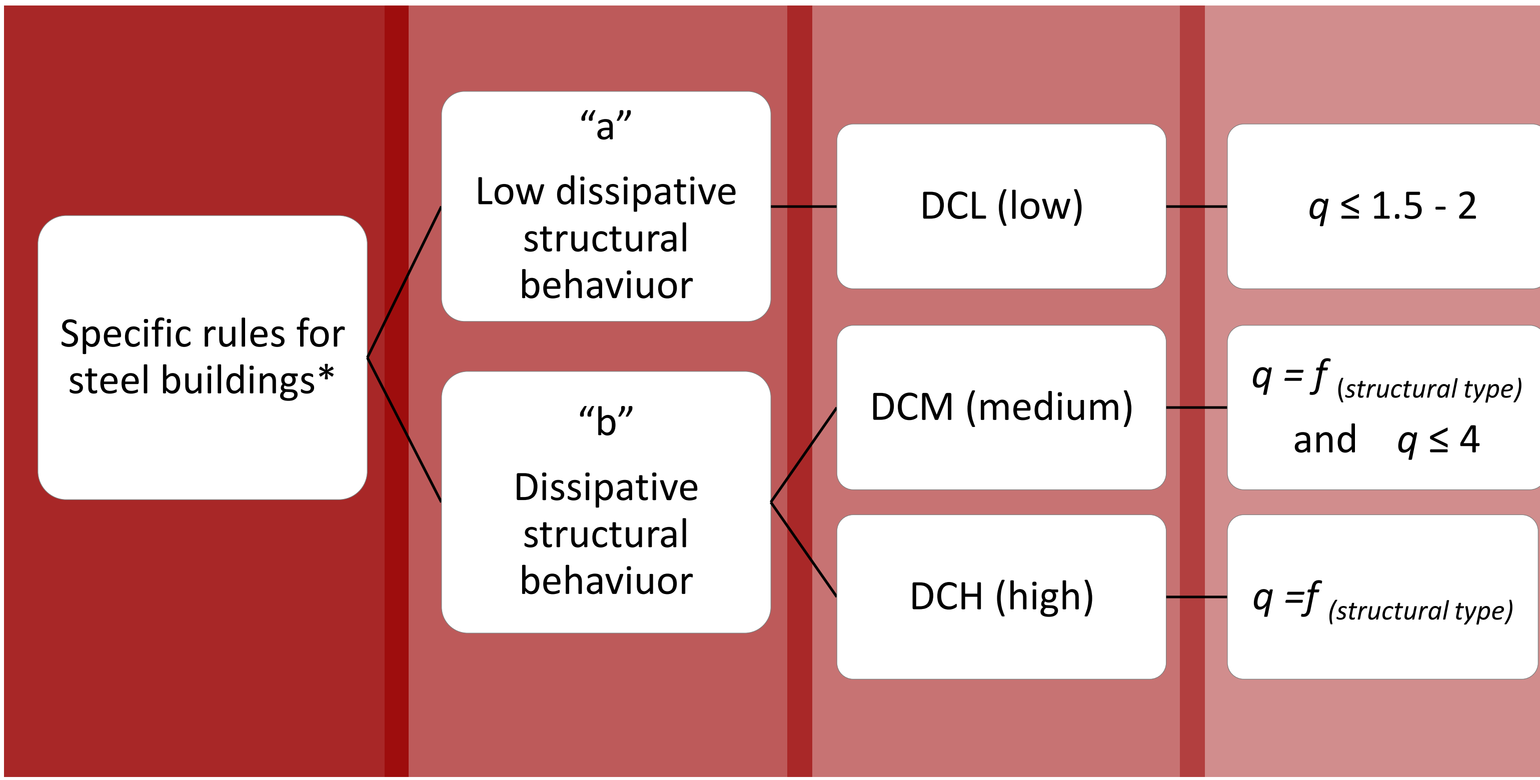
EN 1998-1 CH.6 | **DESIGN CONCEPTS** | **DUCTILITY CLASSES** | **BEHAVIOUR FACTORS**



* For the design of non dissipative steel structures see: EN1993

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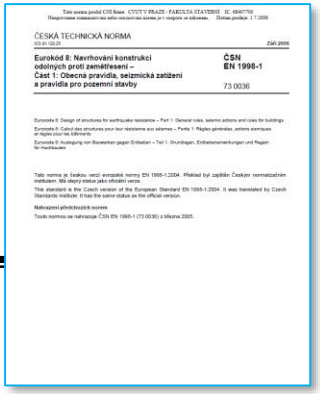
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Rules for Dissipative Structures

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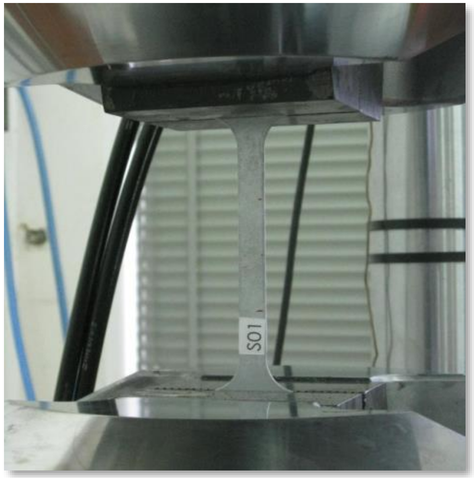
Material Properties

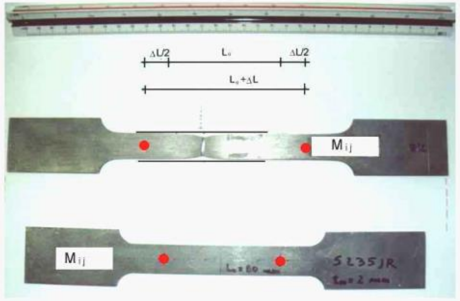
Estimate the actual yield strength of dissipative members/connections, which can be substantially larger than the nominal one.

$$f_{y,max} \leq 1{,}1\,\gamma_{ov}\,f_y$$

RECOMMENDED EC8 VALUE

γ_{ov} **= 1,25**





$f_{y,max}$ is actual maximum yield strength of the steel of dissipative zone

f_y : is nominal yield strength specified for the steel grade

γ_{ov} : is overstrenght factor

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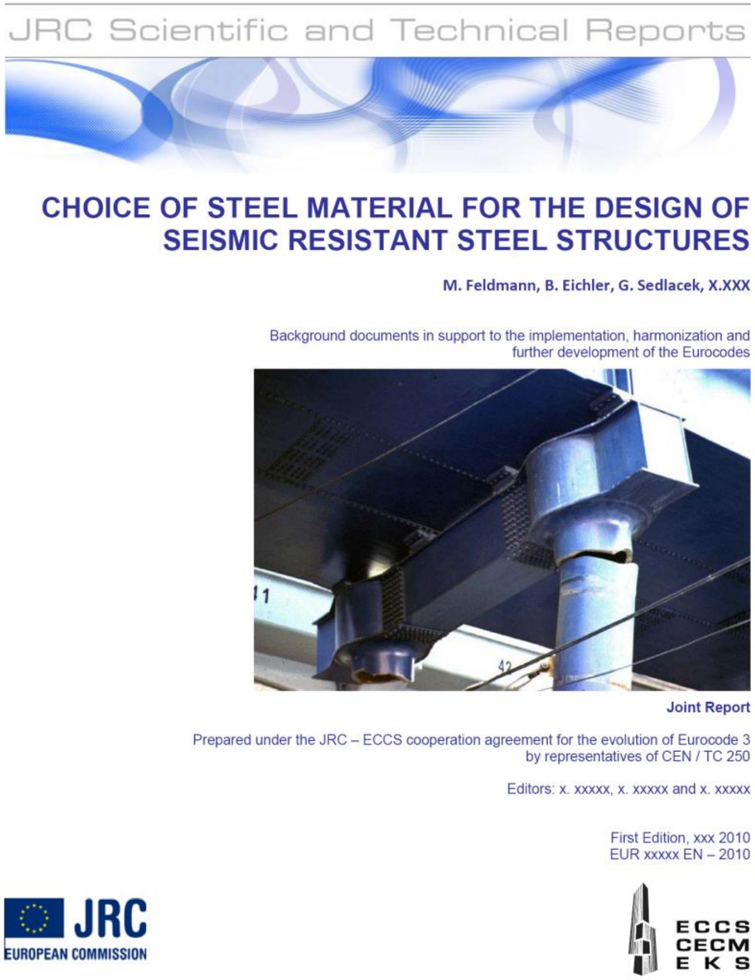
Material Toughness

The choice of material **to avoid brittle fracture** in view of toughness is another key issue in the seismic design of steel structures .

EC8 requires that the toughness of the steels should satisfy the requirements for the seismic action at the **quasi-permanent value of the service temperature** according to see EN 1993-1- 10.

Recent studies have shown that the limitation given in Eurocode 8 is **safe-sided** for European earthquakes.


JRC Scientific and Technical Reports

CHOICE OF STEEL MATERIAL FOR THE DESIGN OF SEISMIC RESISTANT STEEL STRUCTURES

M. Feldmann, B. Eichler, G. Sedlacek, X.XXX

Background documents in support to the implementation, harmonization and further development of the Eurocodes

Joint Report

Prepared under the JRC – ECCS cooperation agreement for the evolution of Eurocode 3 by representatives of CEN / TC 250

Editors: x. xxxxx, x. xxxxx and x. xxxxx

First Edition, xxx 2010
EUR xxxxx EN – 2010

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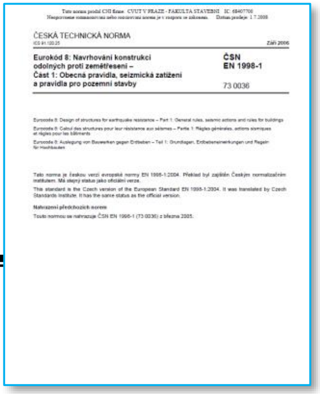
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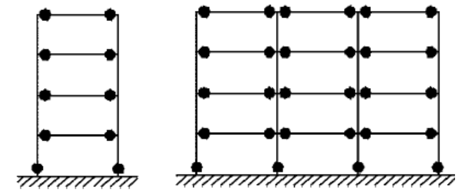
Rules for Dissipative Structures

Structural typologies and behaviour factors

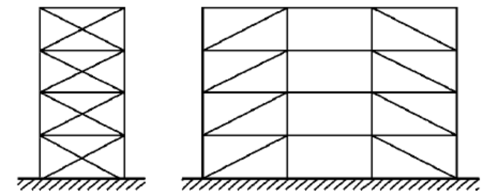
Code behaviour factors are mostly empirical, and are supposed to account for ductility, redundancy and overstrength of different structural typologies.

STRUCTURAL TYPE	Ductility Class	
	DCM	DCH
a) MRF	4	$5\alpha_u/\alpha_1$
b) CBF Diagonal bracings V-bracings	 4 2	 4 2,5
c) EBF	4	$5\alpha_u/\alpha_1$
d) Inverted pendulum	2	$2\alpha_u/\alpha_1$
e) Concrete cores/walls	See section 5	
f) MRF + CBF	4	$4\alpha_u/\alpha_1$
g) MRF + infills Unconnected infills	2	2
Connected infills	See section 7	
Isolated infills	4	$5\alpha_u/\alpha_1$

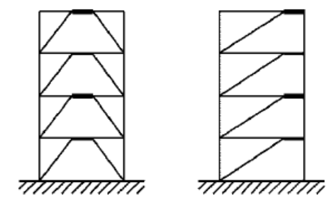
Moment Resisting Frames (MRF)



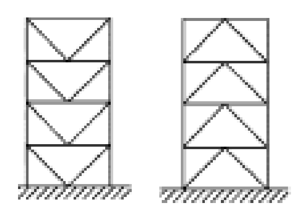
Diagonal braced frames (CBF)

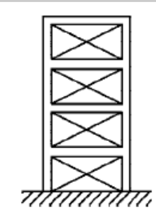


Eccentric braced frames (EBF)



V Bracing (CBF) **MRF + CBF**





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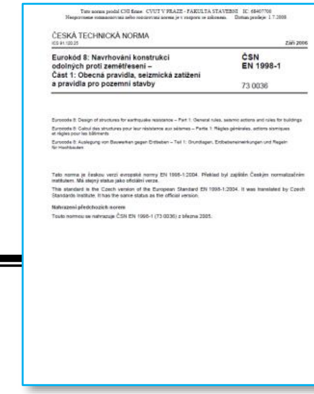
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DUCTILITY REQUIREMENTS: RULES FOR DISSIPATIVE MEMBERS AND FOR CONNECTIONS

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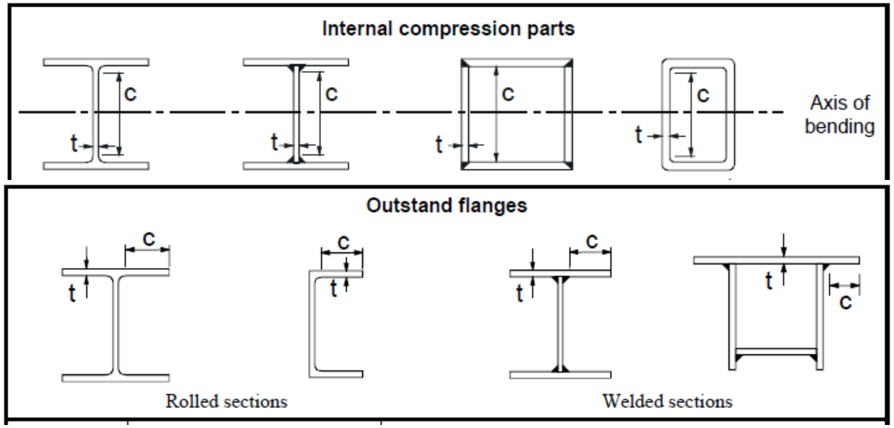
Element in compression of dissipative zones

Sufficient local ductility of members which dissipate energy in **compression** or **bending** shall be ensured by restricting the width-thickness ratio b/t according to the cross-sectional classes specified in EN 1993-1-1

Local slenderness b/t and local ductility



Requirements on cross-sectional class of dissipative elements depending on Ductility Class and reference behaviour factor

Ductility class	Reference value of behaviour factor q	Required cross-sectional class
DCM	$1,5 < q \leq 2$	class 1, 2 or 3
	$2 < q \leq 4$	class 1 or 2
DCH	$q > 4$	class 1

Element in tension of dissipative zones

For tension members or parts of members in tension, the ductility requirement of EN 1993-1-1 should be met.

Where capacity design is requested, the design plastic resistance $N_{pl,Rd}$ should be less than the design ultimate resistance of the net section at fasteners holes $N_{u,Rd}$ so the following expression should be satisfied:

$$\frac{A_{res}}{A} \geq 1{,}1 \cdot \frac{\gamma_{M2}}{\gamma_{M0}} \cdot \frac{f_{yk}}{f_{tk}}$$

A_{res} is net resistant area

A is gross area

γ_{M0} is safety factor for the resistance of the members without holes

γ_{M2} is safety factor for the resistance of the members with holes

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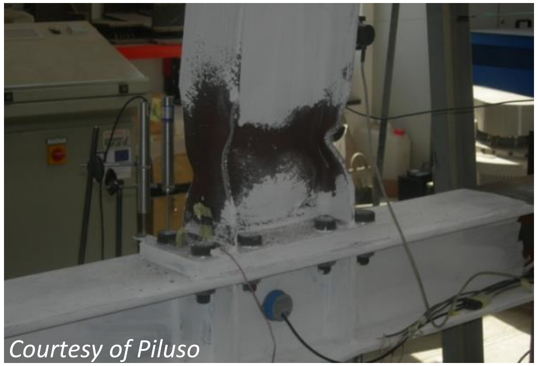
Connections

CAPACITY DESIGN PRINCIPLES

Dissipative zones may be located in the structural members or in the connections.

If dissipative zones are located in the structural members, the connections of the dissipative parts to the rest of the structure shall have sufficient overstrength to allow the development of cyclic yielding in the dissipative parts.


Courtesy of Piluso

When dissipative zones are located in the connections, the connected members shall have sufficient overstrength to allow the development of cyclic yielding in the connections


Courtesy of Piluso

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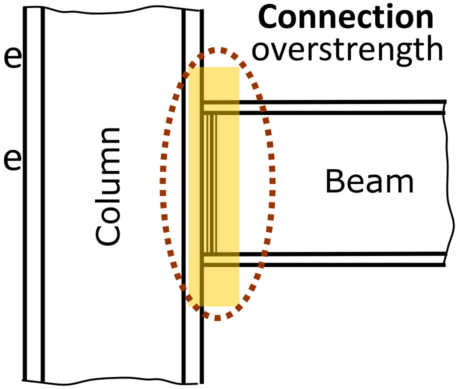
Non dissipative connections in dissipative zones



The design of connections shall be such as to satisfy the overstrength criterion.
For fillet weld or bolted non dissipative connections, the following expression should be satisfied:

The hardening factor is assumed constant

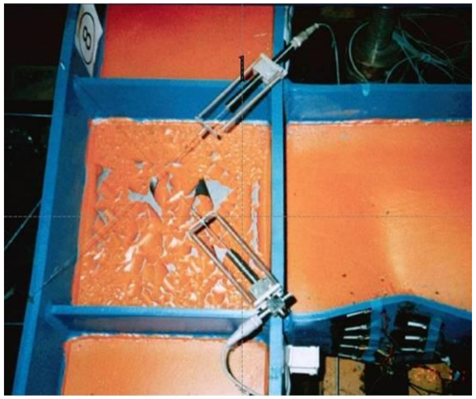
$$R_d \geq 1{,}1\,\gamma_{ov}\,R_{fy}$$

R_d : resistance of the connection in accordance with EN 1993

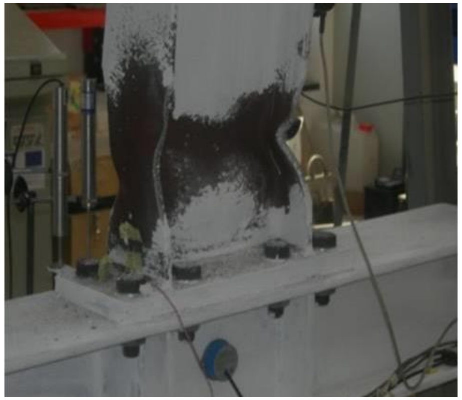
R_{fy} : plastic resistance of the connected dissipative member

γ_{ov} : overstrenght factor

The hardening factor should be related to cross section classification



WELDED CONNECTION



BOLTED CONNECTION

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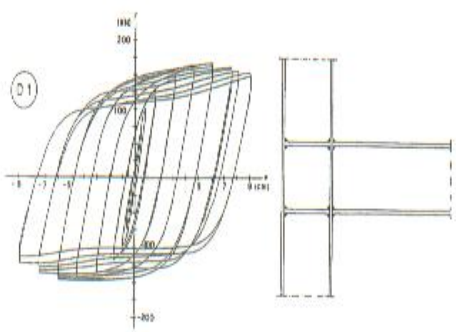
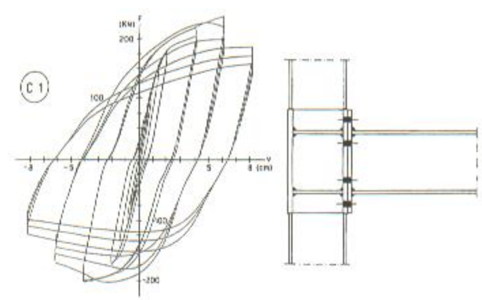
Provisions for dissipative connections

EN 1998:2008 allows the formation of plastic hinges in the connections in case of partial-strength and/or semi-rigid joints, provided that :

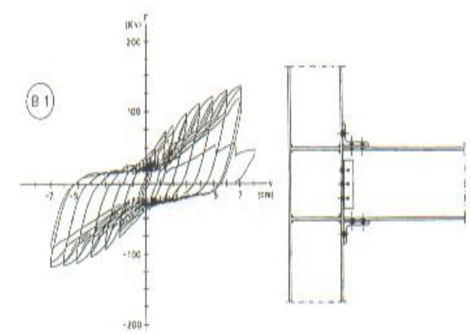
Joint cyclic rotation capacity should be at least **0.035 rad** in case of Ductility class high **DCH** or **0.025 rad** in case of Ductility class medium **DCM**



Welded joint



End plate joint



Angle cleat joint

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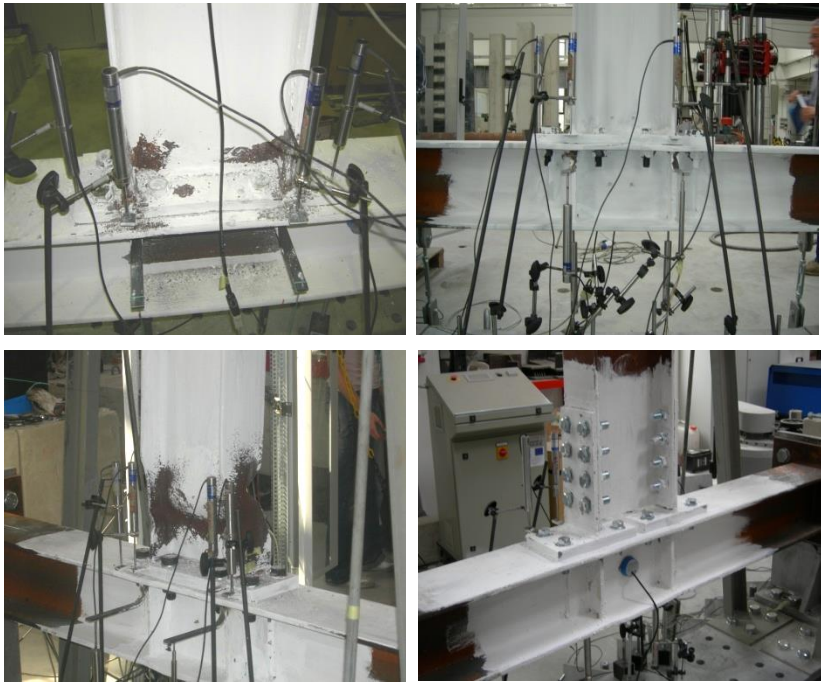
Dissipative connections

How computing Joint cyclic rotation capacity ?

EN 1998-1 (2004) requires design supported by specific **experimental testing**, resulting in impractical solutions within the typical time and budget constraints of real-life projects.

Experimental tests



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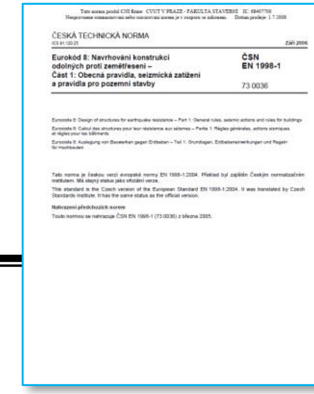
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Structural Typologies for Steel Buildings

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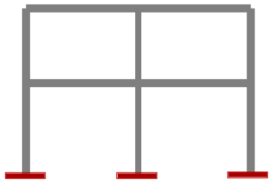
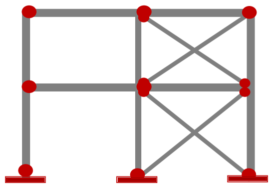
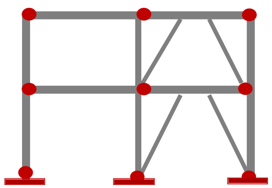
○ **Moment Resisting Frames (MRF)**
horizontal forces are resisted by members acting in an essentially flexural manner



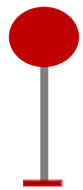
○ **Frames with Concentric Bracings (CBF)**
horizontal forces are mainly resisted by members subjected to axial forces



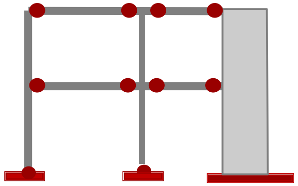
○ **Frames with Eccentric Bracings (EBF)**
horizontal forces are mainly resisted by seismic links by cyclic bending or cyclic shear



○ **Inverted Pendulum structures**
dissipative zones are located at the bases of columns



○ **Structures with concrete cores or concrete walls**
are those in which horizontal forces are mainly resisted by these cores or walls



Seismic Design of Steel Structures

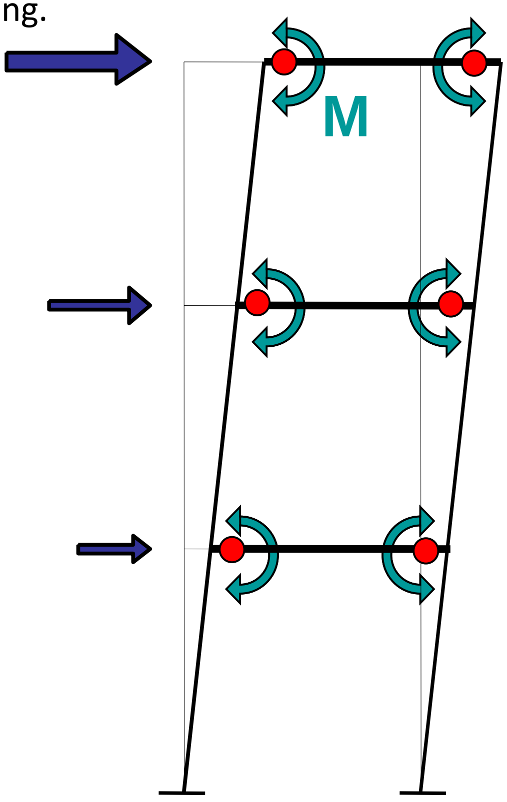
1. Benefits of steel structures
2. Design criteria for steel structures
3. Detailing rules for steel structures

Moment resisting frames (MRF)

Detailing Rules for Moment resisting frames

Moment Resisting Frames

The horizontal forces are mainly resisted by members acting in essentially flexural manner. Energy is thus dissipated by means of cyclic bending.



Detailing Rules for Moment resisting frames

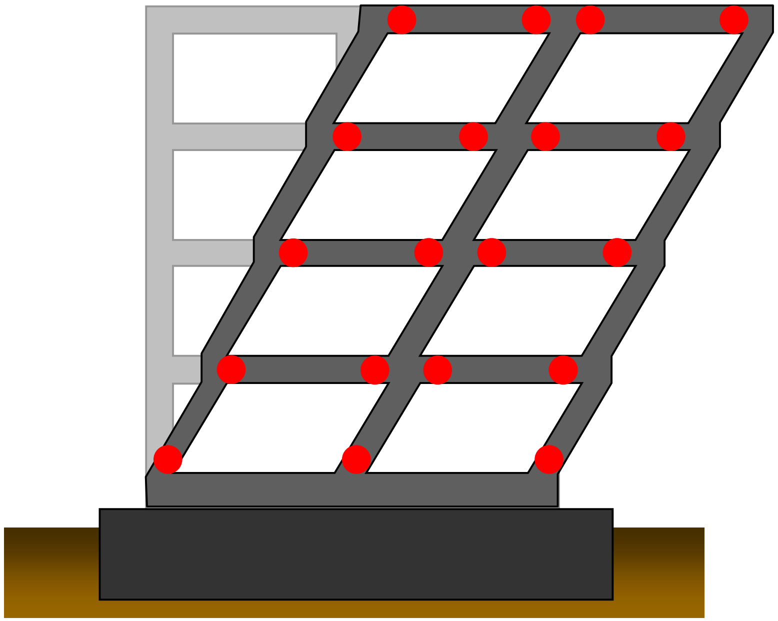
List of contents:

Design Concept

Global mechanism:
Plastic hinges in **beams** not in columns

The dissipative zones should be mainly located in plastic hinges in the beams or in the beams-to-columns joints

Dissipative zone in columns may be located:
- at the base of the frame
- at the top of the column in the upper story of multi storey building



Detailing Rules for Moment resisting frames

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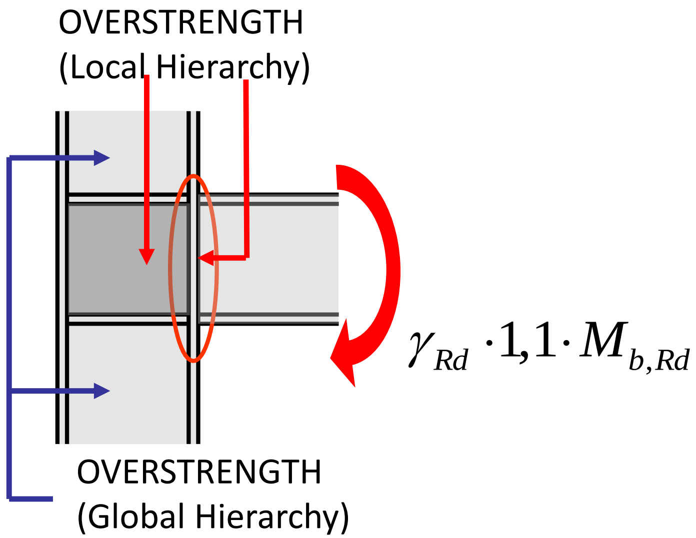
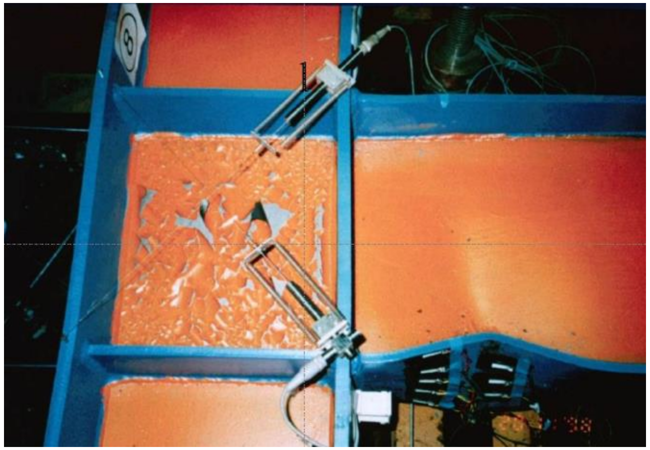
Basic Principles

Global capacity design:
Allows the formation of the global dissipative mechanisms

Local capacity design:
Allows the formation of local plastic mechanisms and ensures the transfer of full plastic forces
Concerns mainly connections





Detailing Rules
for Moment resisting frames

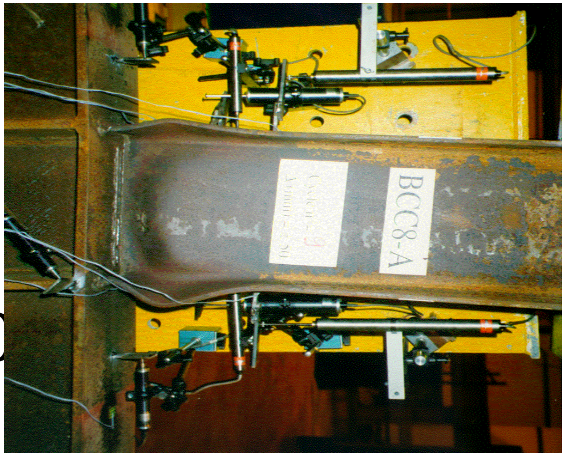
Beams

For plastic hinges in the beams it should be verified that the full plastic moment resistance and rotation capacity are not decreased by compression and shear force. At the location of the expected plastic hinge it should be verified:

$$M_{Ed} / M_{pl,Rd} \leq 1,0$$

$$N_{Ed} / N_{pl,Rd} \leq 0,15$$

$$\left(V_{Ed,G} + V_{Ed,M}\right) / V_{pl,Rd} \leq 0,50$$



where:

M_{Ed} , N_{Ed} , V_{Ed} design values of bending moment, axial force and shear force

$M_{pl,Rd}$, $N_{pl,Rd}$, $V_{pl,Rd}$ design plastic moment, axial forces, and shear resistance

$V_{Ed,G}$ design value of shear force due to non seismic actions

$V_{Ed,M}$ is the design value of the shear force due to two plastic moments $M_{pl,Rd}$ with the same sign at the location of plastic hinges

Detailing Rules
for Moment resisting frames

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Columns

Columns shall be verified considering the most unfavourable combination of the axial force and the bending moment assuming the following design values:

$$N_{Ed} = N_{Ed,G} + 1{,}1 \cdot \gamma_{0V} \cdot \Omega \cdot N_{Ed,E}$$

$$M_{Ed} = M_{Ed,G} + 1{,}1 \cdot \gamma_{0V} \cdot \Omega \cdot M_{Ed,E}$$

$$V_{Ed} = V_{Ed,G} + 1{,}1 \cdot \gamma_{0V} \cdot \Omega \cdot V_{Ed,E}$$

The column shear force shall satisfy the relation:

$$V_{Ed} / V_{pl,Rd} \leq 0{,}50$$

where:

$M_{Ed,G}$, $N_{Ed,G}$, $V_{Ed,G}$ are the design values of the effect of the non seismic actions

$M_{Ed,E}$, $N_{Ed,E}$, $V_{Ed,E}$ are the design value of the effects of seismic actions

γ_{0V} is the overstrength factor

Ω is the minimum value of $\Omega_i = M_{pl,Rd,i} / M_{Ed,i}$ of all beams in which dissipative zones are located

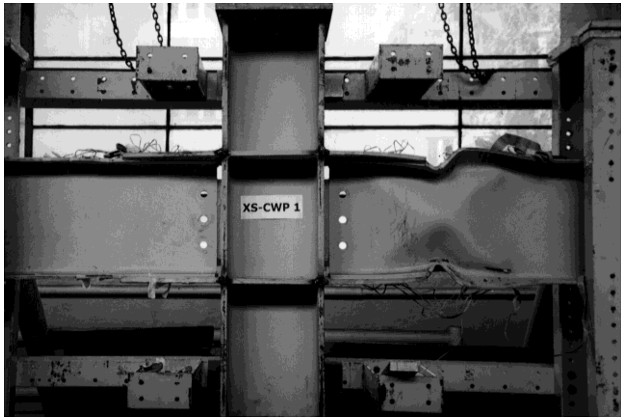
Detailing Rules for Moment resisting frames

List of contents:

Capacity Design (Beam-Column)

In order to allow the development of the global collapse mechanism it has to be ensured the local capacity design.

In frame buildings the following condition should be satisfied at all beam to column joints:



$$\sum M_{Rc} \geq 1,3 \cdot \sum M_{Rb}$$

where:

ΣM_{Rc} is the sum of the design values of the moments of resistance of the columns framing the joint. The minimum value of column moments of resistance within the range of column axial forces produced by the seismic design situation should be used in the previous expression

$\Sigma M_{,Rb}$ is the sum of the design values of the moments of resistance of the beams framing the joint. When partial strength connections are used, the moments of resistance of these connections are taken into account in the calculation of $\Sigma M_{,Rb}$

Detailing Rules for Moment resisting frames

List of contents:

Beam-Column connections

If the structure is designed to dissipate energy in the beams, the beam to column connections of the whole frame must provide adequate overstrength to permit the formation of the plastic hinges at the ends of the beams.
So the following relationship must be achieved:

$$M_{j,Rd} \geq 1{,}1 \cdot \gamma_{0V} \cdot M_{b,pl,Rd}$$

where:

$M_{j,Rd}$ is the bending moment resistance of the connection

$M_{b,pl,Rd}$ is the bending moment resistance of the connected beam

γ_{0V} is the overstrength factor

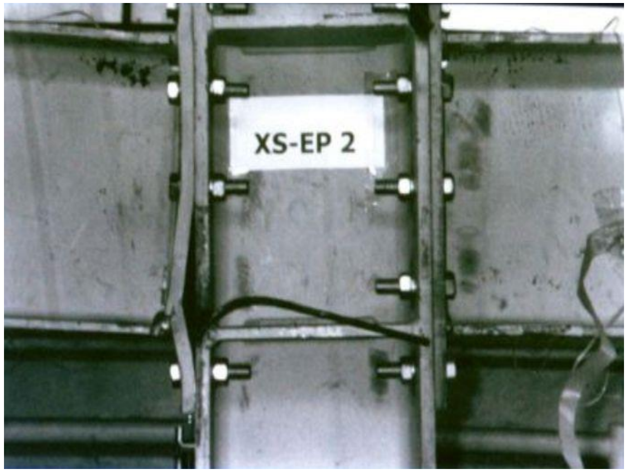
Detailing Rules
for Moment resisting frames

List of contents:

Nodal Web Panels

In beam to column connections the web panels of the columns must provide adequate overstrength to permit the development of the expected dissipative mechanism, avoiding their plasticization or shear buckling.

This requirement is satisfied if:



$$V_{vp,Ed} / \min\left(V_{vp,Rd} ; V_{vb,Rd}\right) < 1$$

where:

$V_{vp,Ed}$ is the design shear force in the web panel due to the action effects

$V_{vp,Rd}$ is the shear resistance of the web panel

$V_{vb,Rd}$ is the shear buckling resistance of the web panel

Column-Foundation connections

The beam to Foundation connection has to be designed in such a way to have adequate overstrength with respect to the column.
In particular, the bending moment resistance of the connection must achieve the following relationship:

$$M_{C,Rd} \geq 1{,}1 \cdot \gamma_{0V} \cdot M_{c,pl,Rd}\left(N_{Ed}\right)$$

where:

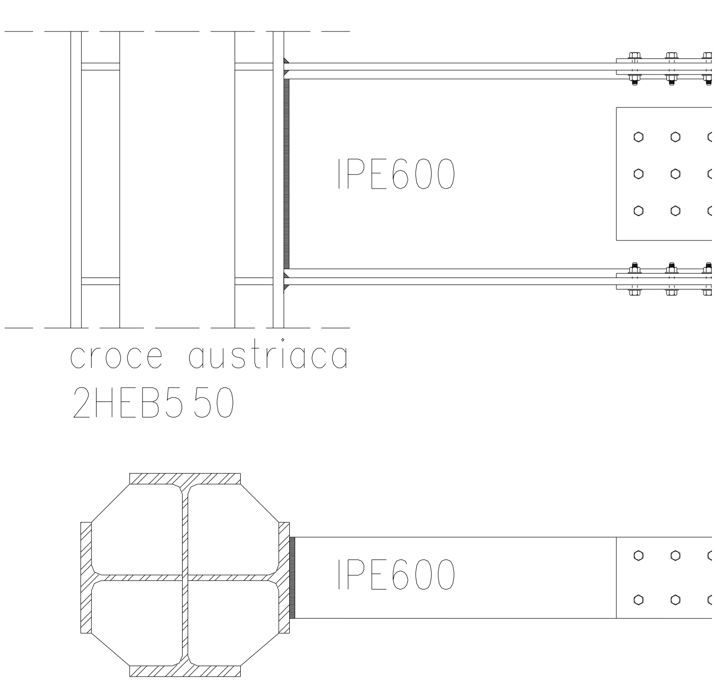
$M_{c,pl,Rd}$ is the design plastic bending moment of the column, taking into account the axial force N_{Ed} acting in the column, that give the worst condition for the base connection

γ_{0V} is the overstrength factor

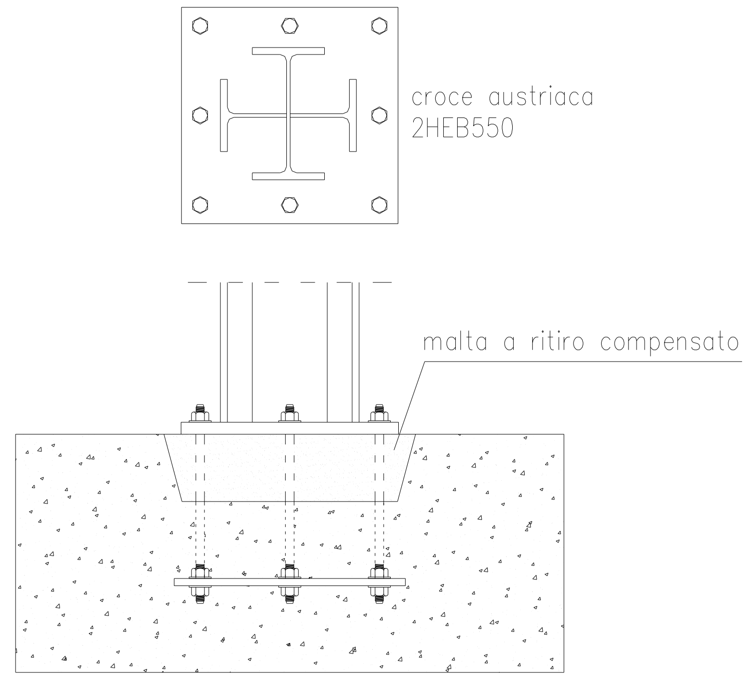
Detailing Rules
for Moment resisting frames

List of contents:

Connections: typical joints



Beam to Column



Column to Foundations

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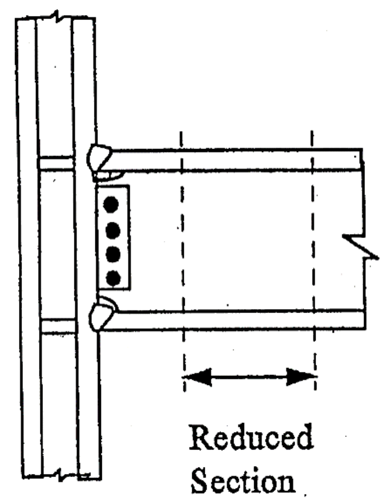
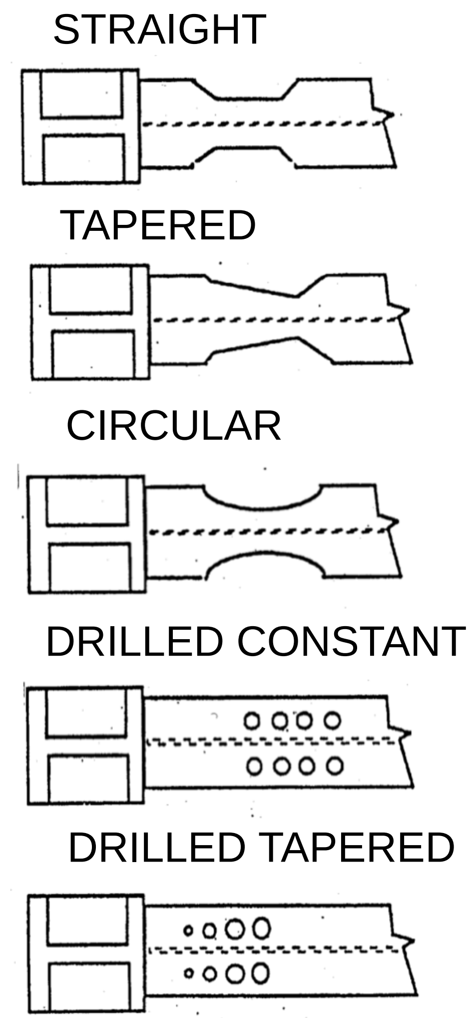
Sustainable Constructions under Natural Hazards and Catastrophic Events

Innovative solutions
for Moment resisting frames

DOG BONE

The reduced section of the beam is intended to force the formation of the plastic hinge away from the face of the column, and it forces the large stresses and inelastic strains further into the beam.





Seismic Design of Steel Structures

1. Benefits of steel structures
2. Design criteria for steel structures
3. Detailing rules for steel structures

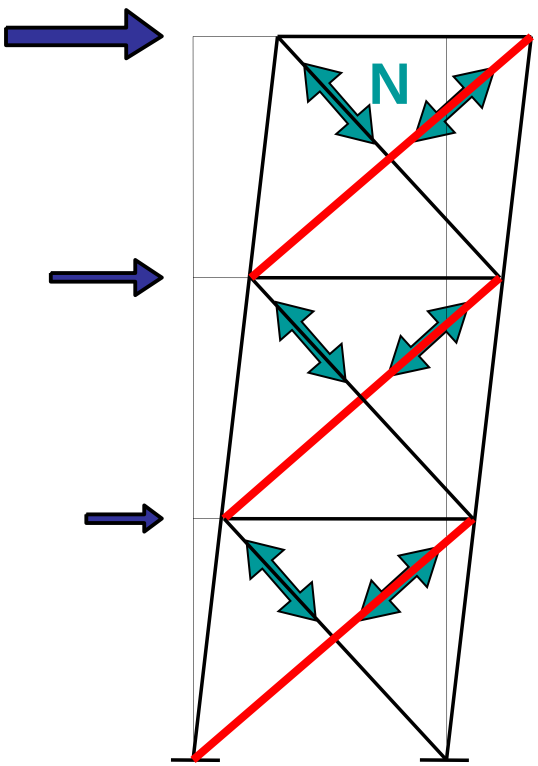
Concentric Braced Frames (CBF)

Detailing Rules
for Concentric Braced Frames (CBF)

List of contents:

Concentric Braced Frames

The horizontal forces are resisted by diagonal members acting in tension.



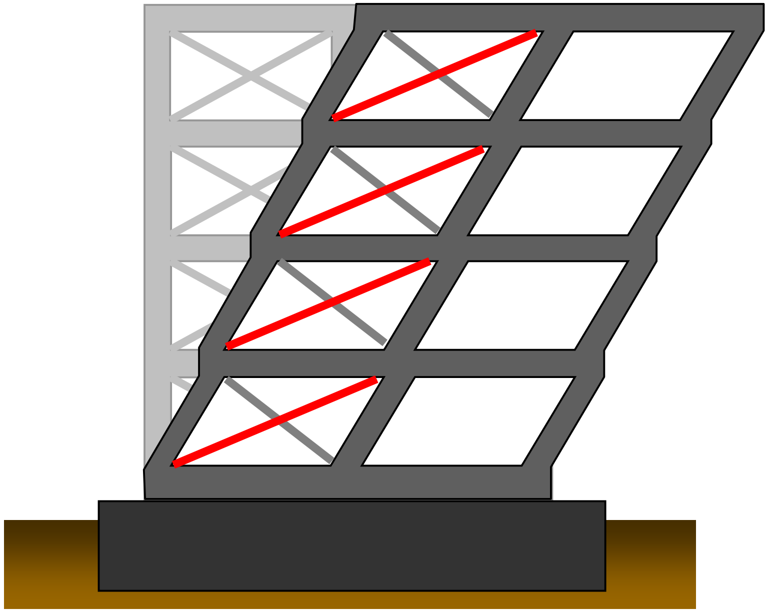
Detailing Rules
for Concentric Braced Frames (CBF)

List of contents:

Design Concept

Global mechanism:
The dissipative elements are the bracings in tension.

Concentric braced frames shall be designed so that yielding of the diagonals in tension will take place before failure of the connections and before yielding or buckling of the beams or columns.

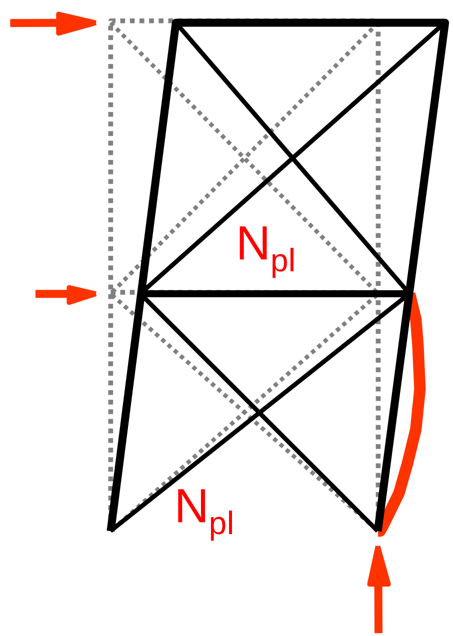


Detailing Rules
for Concentric Braced Frames (CBF)

List of contents:

Basic Principles

Global capacity design:
Allows the formation of the global dissipative mechanisms



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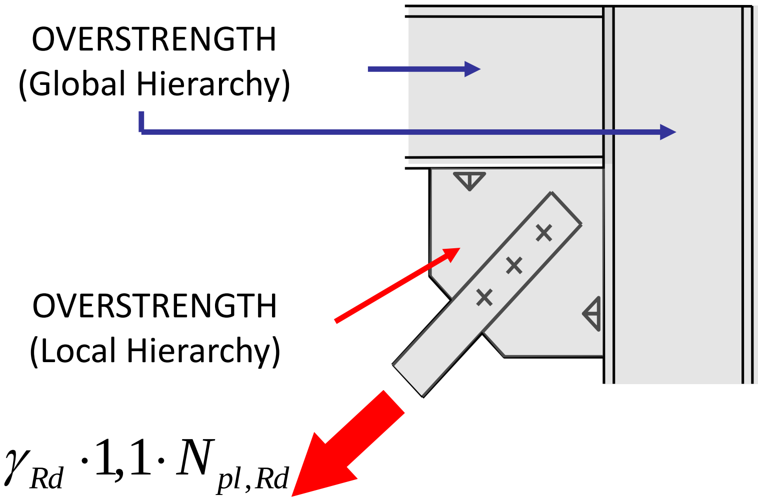
Sustainable Constructions under Natural Hazards and Catastrophic Events

Detailing Rules
for Concentric Braced Frames (CBF)

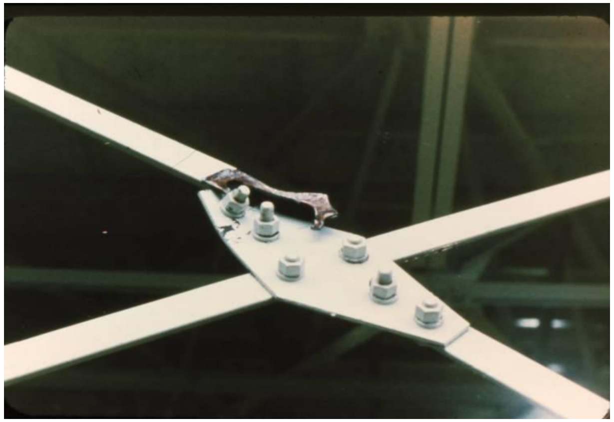
List of contents:

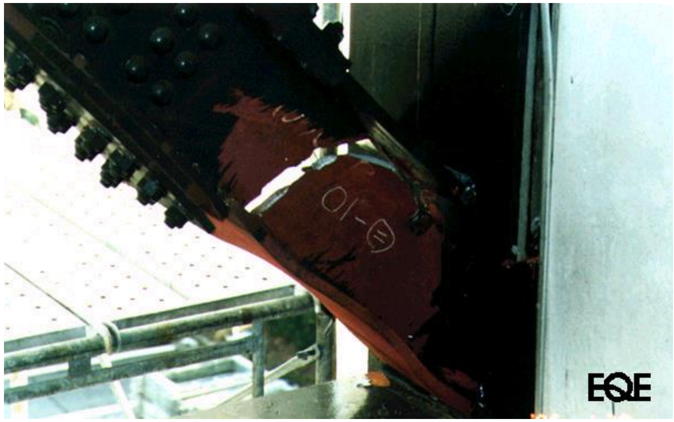
Basic Principles

Local capacity design:
Allows the formation of local plastic mechanisms and ensures the transfer of full plastic forces
Concerns mainly connections



$$\gamma_{Rd} \cdot 1{,}1 \cdot N_{pl,Rd}$$



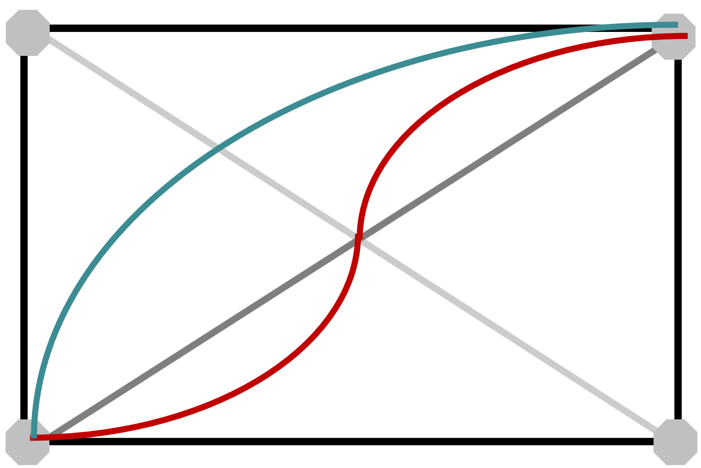


Detailing Rules
for Concentric Braced Frames (CBF)

List of contents:

Diagonal Bracings

Slenderness :
The non-dimensional slenderness of diagonals is the ratio between the geometrical slenderness λ and the elastic critical slenderness λ_y



IN PLANE

$$\lambda_{ip} = \frac{0.5 \cdot L_d}{\rho_{ip}}$$

OUT OF PLANE

$$\lambda_{op} = \frac{L_d}{\rho_{op}}$$

NON-DIMENSIONAL SLENDERNESS $\bar{\lambda} = \frac{\lambda}{\lambda_y}$ with $\lambda_y = \pi\sqrt{\frac{E}{f_y}}$

Detailing Rules
for Concentric Braced Frames (CBF)

List of contents:

Diagonal members

In structures of more than two storeys the non-dimensional slenderness of diagonal members should be

$$1{,}3 \leq \overline{\lambda} \leq 2$$

in frames with X bracings.

The overstrength factor to apply the capacity design criteria is

$$\Omega_i = \frac{N_{pl,Rd,i}}{N_{Ed,i}}$$

Calculated over all the diagonals of the braced system. In order to satisfy a homogeneous dissipative behaviour of the **diagonals**, it should be checked that the maximum value does not differ from the minimum value by more than **25%**.

Detailing Rules
for Concentric Braced Frames (CBF)

List of contents:

Beams and Columns

Beams and columns with axial forces should meet the following minimum resistance requirement

$$N_{Ed} / N_{pl,Rd}(M_{Ed}) \leq 1$$

where

$$N_{Ed} = N_{Ed,G} + 1{,}1 \cdot \gamma_{0V} \cdot \Omega \cdot N_{Ed,E}$$

and $N_{pl,Rd}$ is the design buckling resistance of the beam or the column in accordance with EN 1993, taking into account the interaction of the buckling resistance with the bending moment defined as its design value in the seismic design situation

$$M_{Ed} = M_{Ed,G} + 1{,}1 \cdot \gamma_{0V} \cdot \Omega \cdot M_{Ed,E}$$

Detailing Rules
for Concentric Braced Frames (CBF)

List of contents:

Connections

The connections of diagonal members to the structure have to provide adequate overstrength to permit the development of the expected dissipative mechanism.

For fillet weld or bolted non dissipative connections, the following expression should be satisfied

$$R_{j,d} \geq \gamma_{0V} \cdot 1{,}1 \cdot R_{pl,Rd} = R_{U,Rd}$$

where:

$R_{j,d}$ is the design resistance of the connection;

$R_{pl,Rd}$ is the plastic resistance of the connected dissipative member based on the design yield stress of the material

$R_{U,Rd}$ is the upper bound of the plastic resistance of the connected dissipative member;

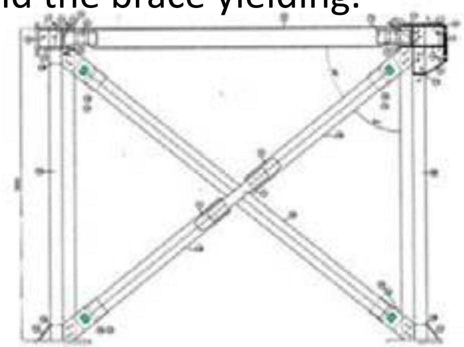
γ_{0V} is the overstrength factor

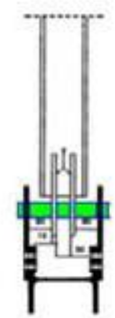
List of contents:

SEMI-RIGID JOINTS

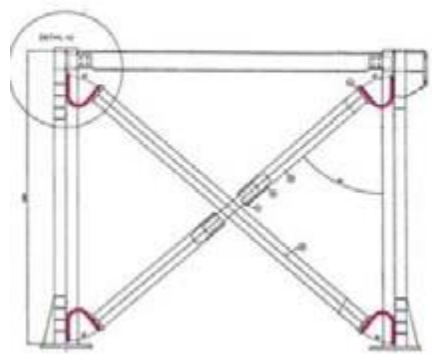
The solution consists in replacing traditional joints with special dissipative joints. They are semi-rigid joints (pin-connections and U-connections) designed with a lower resistance with respect to the one corresponding to the diagonal member instability, to avoid the brace yielding.

Pin-connection





U-connection

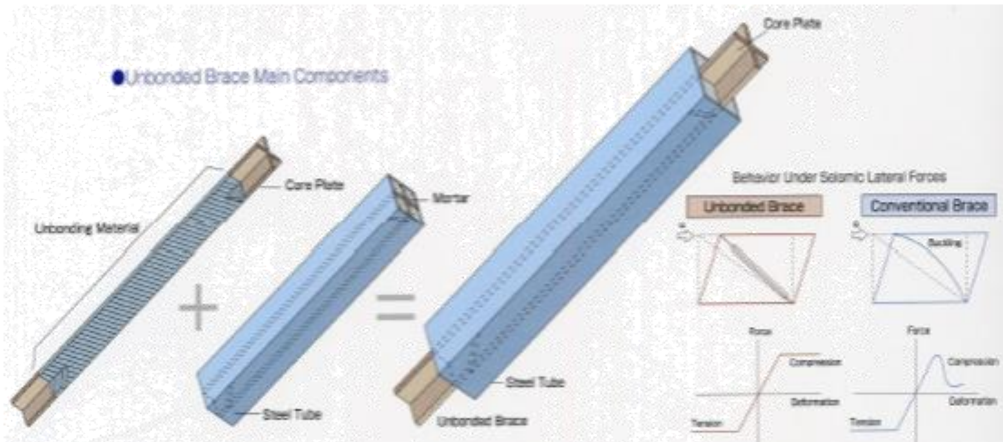


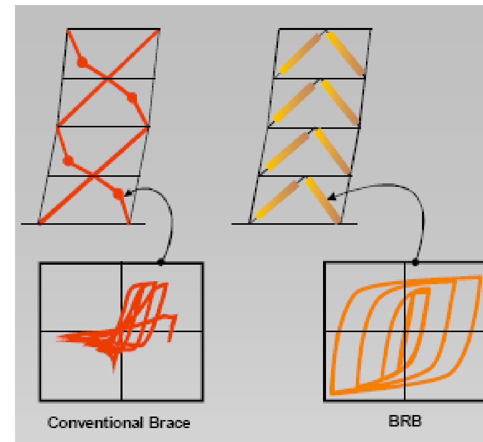
Source: INERD Project, Plumier, 2001-2004

Detailing Rules
for Concentric Braced Frames (CBF)

List of contents:

BUCKLING RESTRAINED BRACES (BRB)



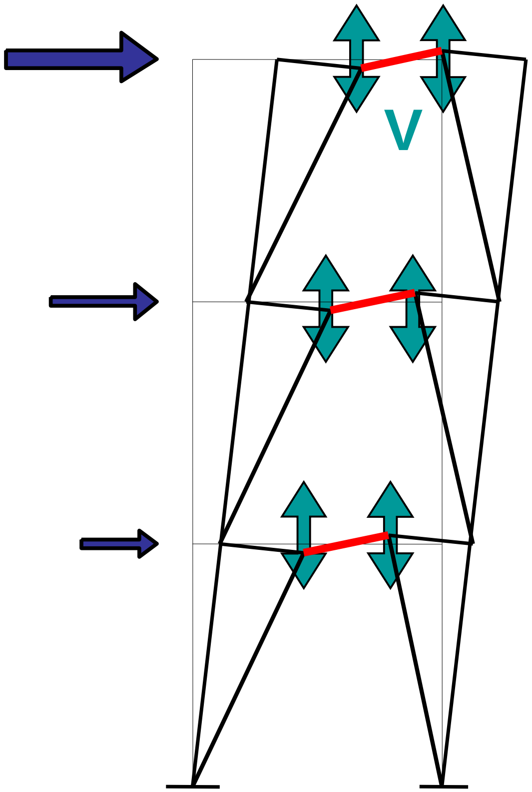


Detailing Rules
for Eccentric Braced Frames (EBF)

List of contents:

Eccentric Braced Frames

The horizontal forces are resisted by specific elements called "**seismic links**" acting in bending and/or shear.



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Sustainable Constructions under Natural Hazards and Catastrophic Events

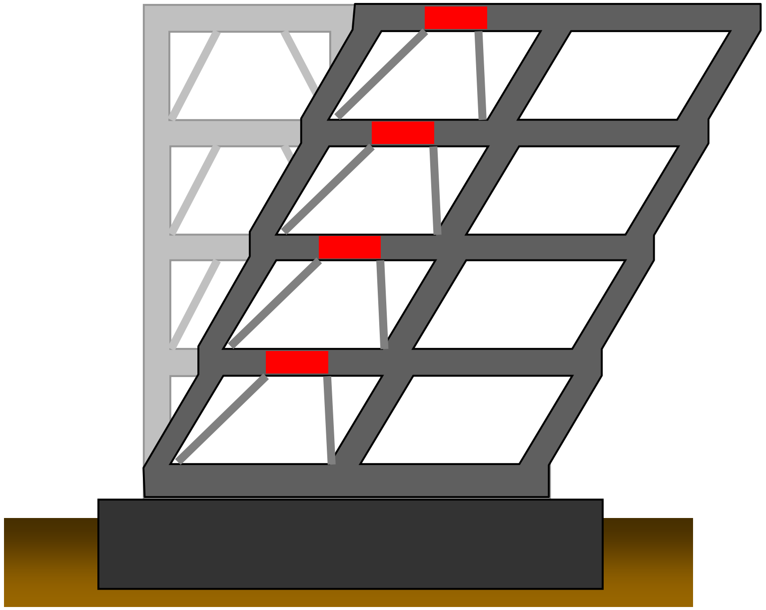
Detailing Rules
for Eccentric Braced Frames (EBF)

List of contents:

Design Concept

Global mechanism
The dissipative elements are the seismic links.

Frames with eccentric bracings shall be designed so that specific elements or parts of elements called "seismic links" are able to dissipate energy by the formation of plastic bending and/or plastic shear mechanisms, before failure of the connections and before yielding or buckling of the beams, columns and diagonal members.



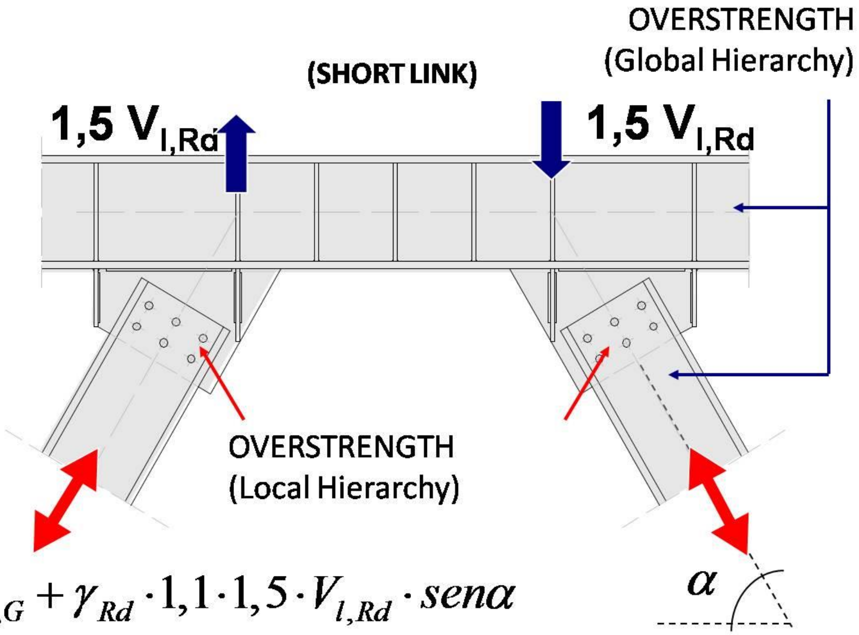
Detailing Rules
for Eccentric Braced Frames (EBF)

List of contents:

Basic Principles

Global capacity design:
Allows the formation of the global dissipative mechanisms

Local capacity design:
Non dissipative elements and connections are designed with adequate overstrength respect to dissipative zones (link)



$$N_{Ed,G} + \gamma_{Rd} \cdot 1{,}1 \cdot 1{,}5 \cdot V_{l,Rd} \cdot sen\alpha$$

Summary

EN1998-1:2008 Ch. 8

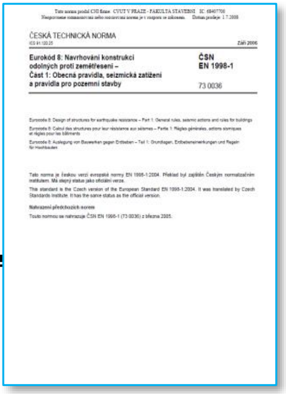
6.2 Materials

6.3 **Structural types and behavior factors**

6.4 Structural analysis

6.5 **Design criteria and detailing rules**

Summary



ČESKÁ TECHNICKÁ NORMA

ICS 91.120.25 — Září 2006

Eurokód 8: Navrhování konstrukcí odolných proti zemětřesení – Část 1: Obecná pravidla, seizmická zatížení a pravidla pro pozemní stavby

ČSN EN 1998-1

73 0036

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

Tato norma je českou verzí evropské normy EN 1998-1:2004. Překlad byl zajištěn Českým normalizačním institutem. Má stejný status jako oficiální verze.

This standard is the Czech version of the European Standard EN 1998-1:2004. It was translated by Czech Standards Institute. It has the same status as the official version.

Nahrazení předchozích norem

Touto normou se nahrazuje ČSN EN 1998-1 (73 0036) z března 2005.

List of contents:

Benefits of steel structures

Design criteria for steel structures

Detailing rules for steel structures

CONTENTS of EN1998-1:2008 Ch. 6 Steel buidings

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