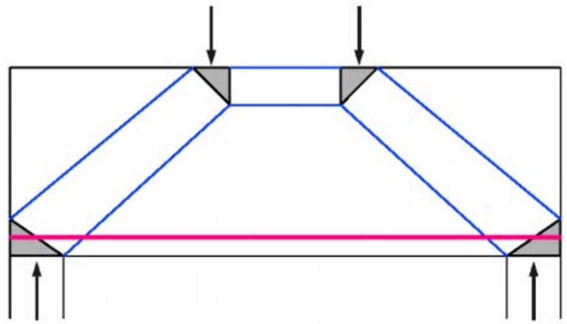

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INTRODUCTION

Two design methods for concrete

Conventional design:
- Determine moment diagram
- Specify steel in areas of tension

Strut and tie models:
- Define internal forces in tension and compression (ties and struts)
- Specify steel in areas of tension

1. Introduction / Introducere

- The Strut-and-Tie is an approach which **considers all load effects** (M, N, V, T) simultaneously

- The Strut-and-Tie Model (STM) approach is a useful design method for **concrete structures with shear critical elements** or **disturbed regions**

- The STM provides **appropriate and simplified truss models** to represents complex structural phenomenon

- Based on the existing techniques and rules, for a given situation **several STM could be developed** (is no unique STM!)

- The form of a **STM depends** on the element **geometry**, by the applied **loads** and their **position** and by the **static scheme**, conceived in a such way to respect all the specific rules related to the struts, ties and joints

2. History of the STM / Istoria procedeului modelului de bare

History of the STM

Walter Ritter (1899) Switzerland
Emil Mörsch (1902) Germany

→ Truss analogy was first introduced

Collins & Mitchell (1980) Canada
→ A design method for shear and torsion for regions of a structure where Bernoulli's hypothesis is applicable

Schlaich et al (1987, 1991) Germany
→ STM based on experimental data, rule of thumb (a broadly accurate guide or principle, based on practice rather than theory) and past design experiences, based on physical models which are more understandable
→ flexibility to the designers to reach cheapest or safest solutions

Collins and Mitchell (1991)
MacGregor (1992)

2. History of the STM / Istoria procedeului modelului de bare

STM was introduced in codes:

AASHTO (1994)
American Association of State Highway and Transportation Officials

ACI 318-02
American Concrete Institute

EC2 - 2004
Eurocode 2

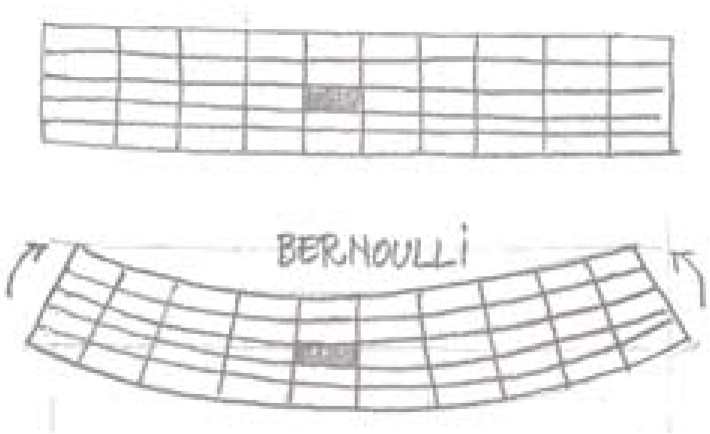
3. Regions in the structural elements / Zone în elemente structurale

Parts of a structural element are classified in two regions:

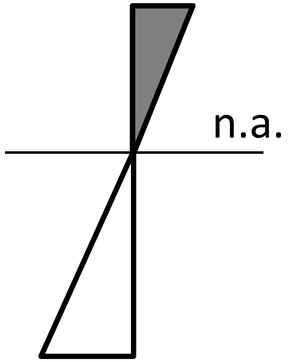
1) B-region (is known as **Bernoulli** or **Beam**)

→ Regions of a structure where Bernoulli's hypothesis is applicable ⇔ plane section remain plane after bending

→ facilitates the flexural design of reinforced concrete structures by allowing a linear strain distribution for all loading stages, including ultimate flexural capacity



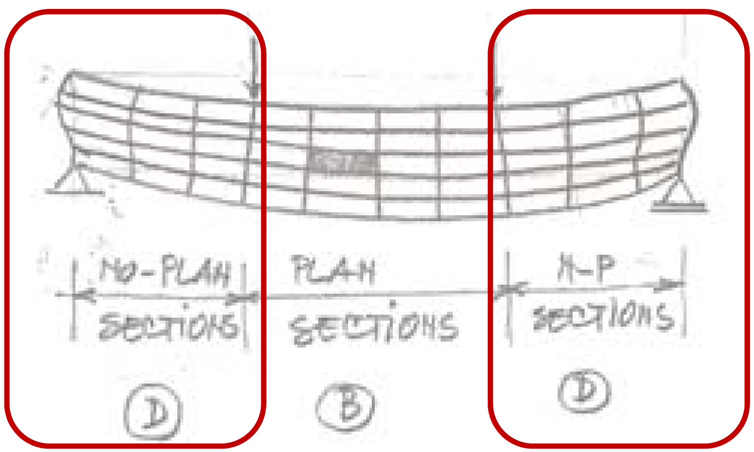
pure bending



3. Regions in the structural elements / Zone în elemente structurale

2) D-region (from **D**isturbance or **D**iscontinuity**)**

→ regions where the beam theory does not apply



bending & shear

3. Regions in the structural elements / Zone în elemente structurale

2) D-region (from **D**isturbance or **D**iscontinuity**)**
→ regions where the beam theory does not apply

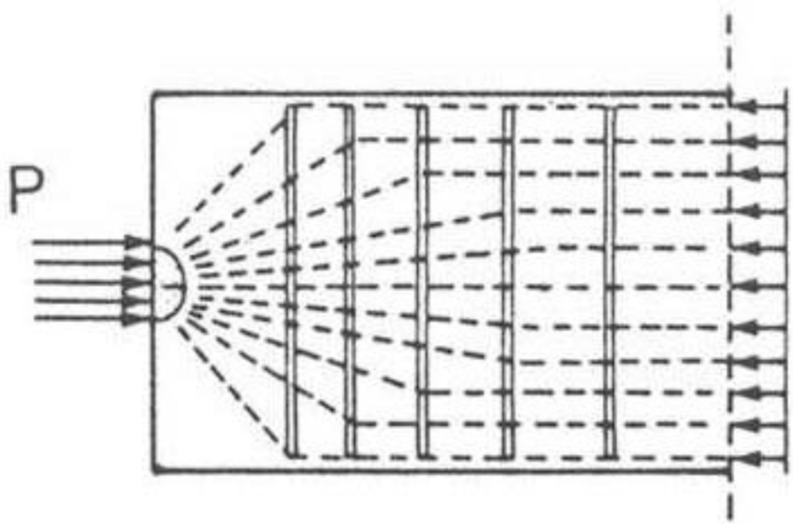
→ occur at regions of **geometrical** or **static discontinuity**, such as openings, changes in cross section or near concentrated loads and reactions.

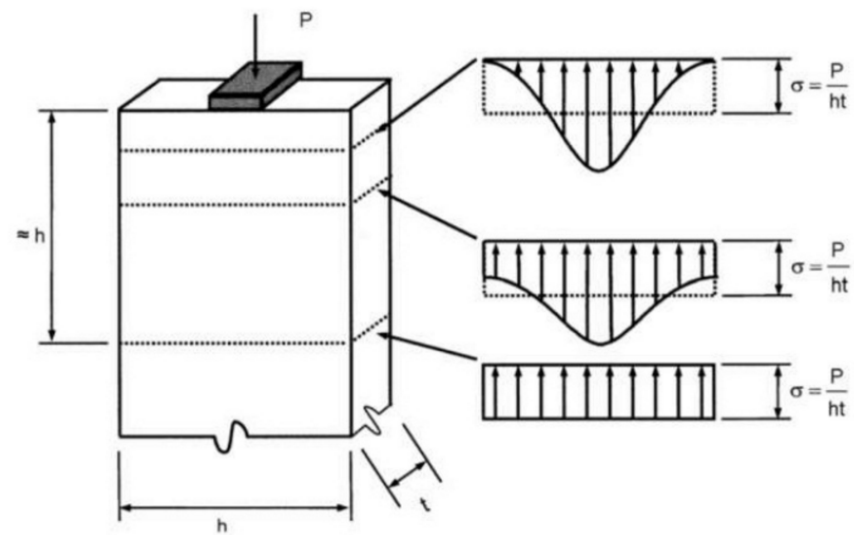
→ The strain distributions for this section will not be linear and the length is usually governed by St. Venant's principle

3. Regions in the structural elements / Zone în elemente structurale

St. Venant's Principle states

→ "The localized effects caused by any load acting on the body will dissipate or smooth out within regions that are sufficiently away from the location of the load…"





"The stress due to axial load and bending approach a linear distribution at a distance approximately equal to the maximum cross-sectional dimension of a member, h, in both directions, away from a discontinuity"

(Brown et al. 2006).

3. Regions in the structural elements / Zone în elemente structurale

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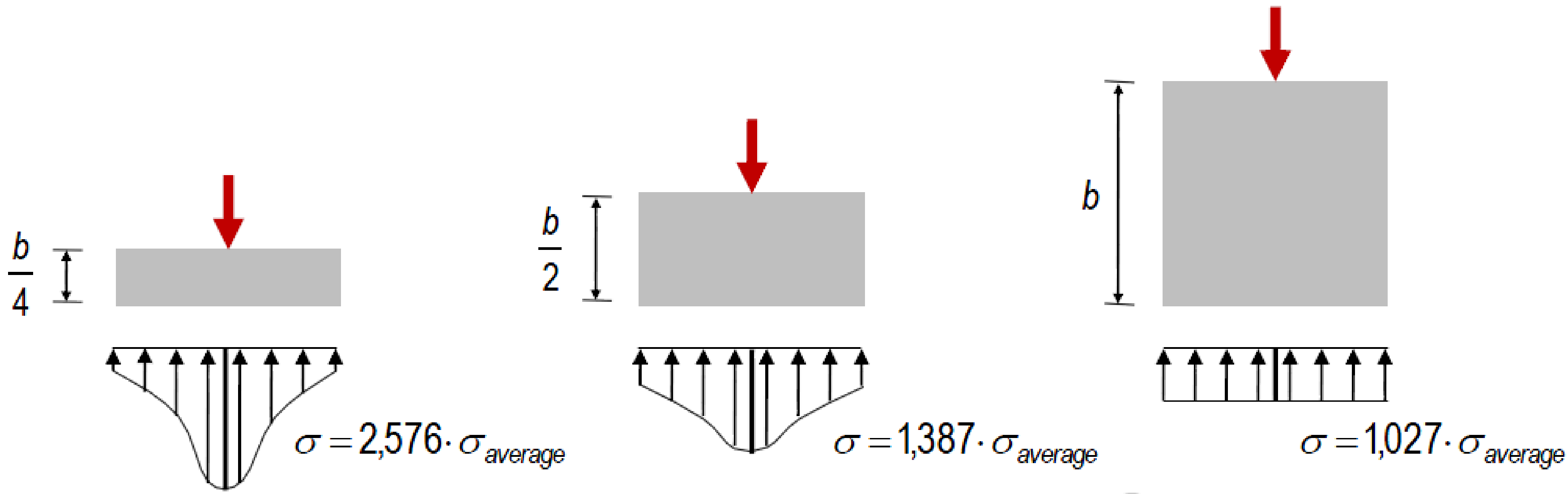

(Prof. Kovács I., DE)

3. Regions in the structural elements / Zone în elemente structurale

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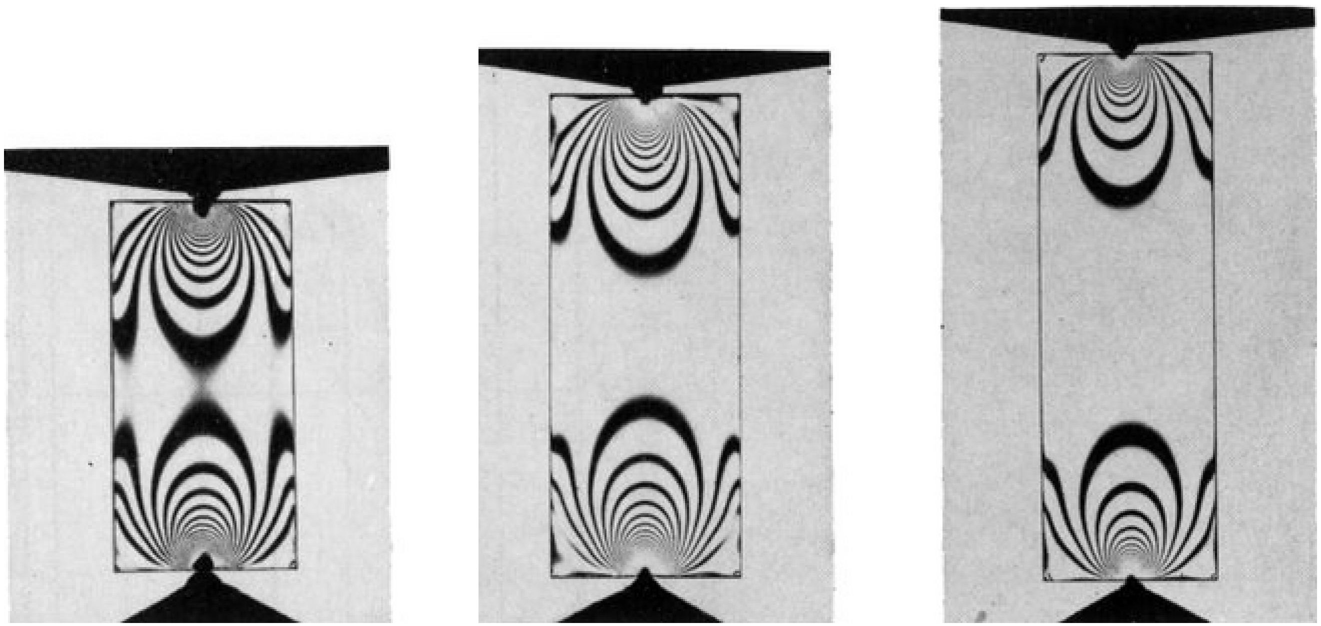

→ Disturbance extends over a length equal to the largest dimension of the cross section area

(Prof. Clipii T.)

3. Regions in the structural elements / Zone în elemente structurale

St. Venant's Principle states

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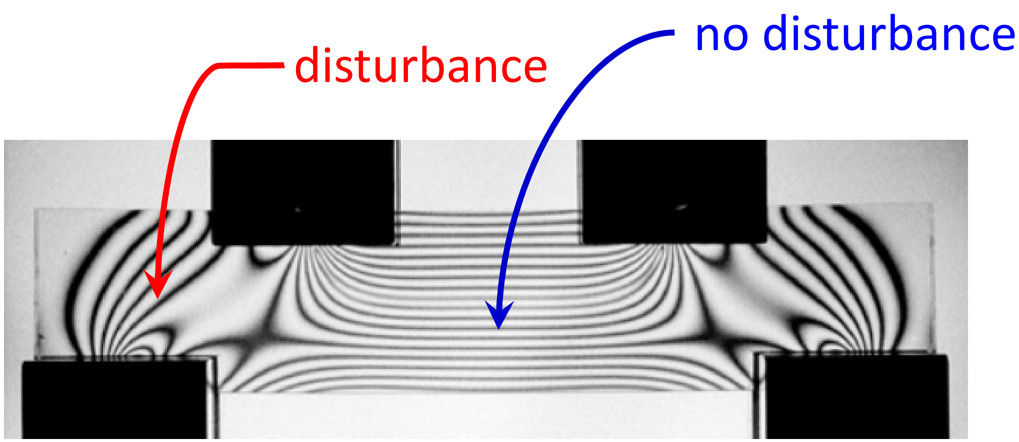

(Prof. Clipii T.)

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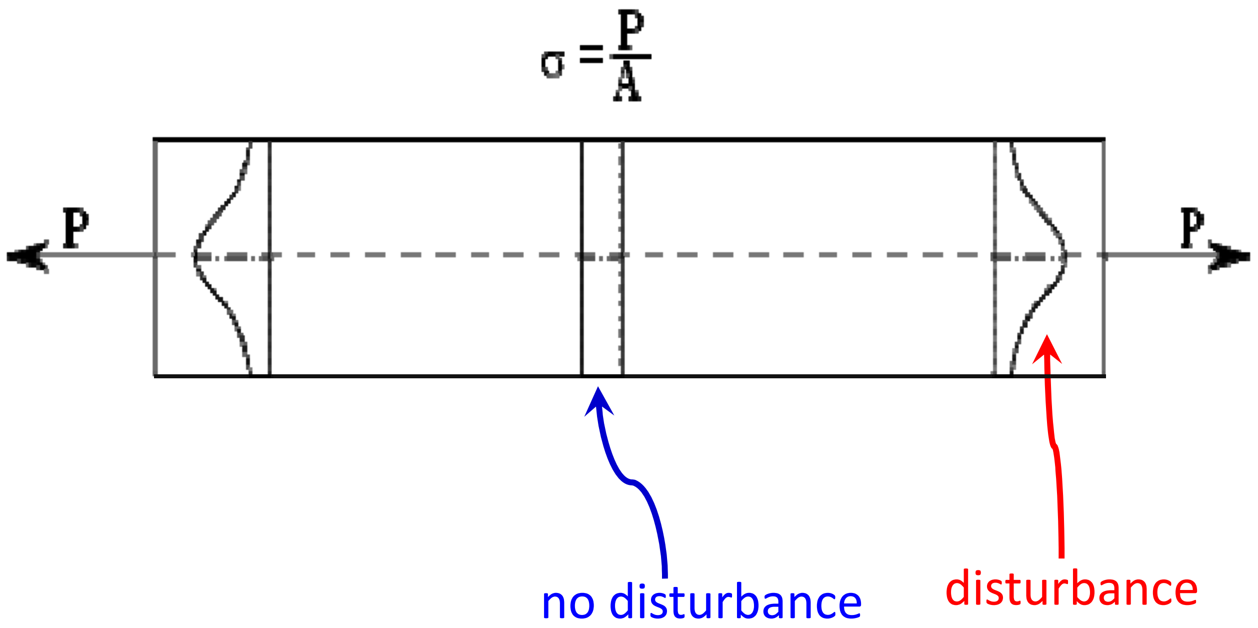

3. Regions in the structural elements / Zone în elemente structurale

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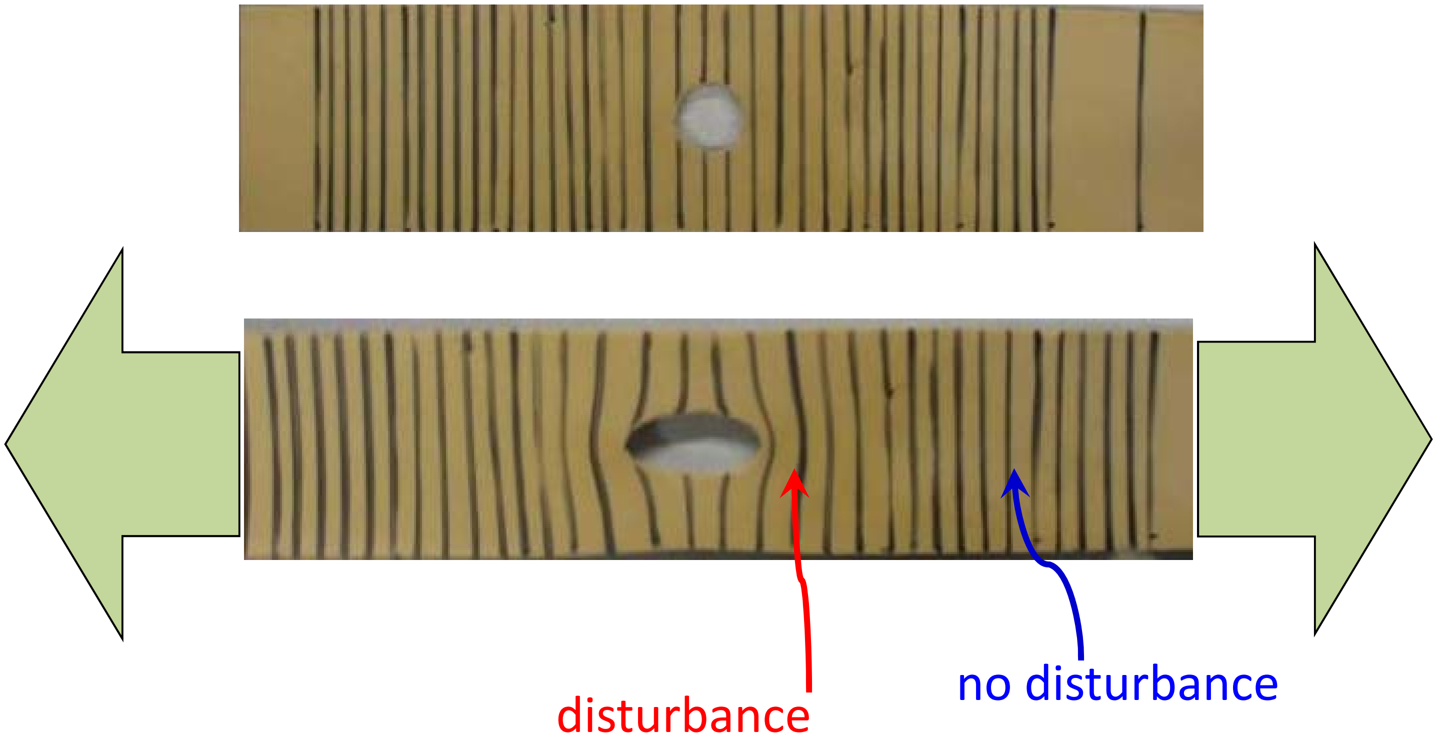


(Prof. Clipii T.)

1. INTRODUCTION

2. HISTORY OF THE STM

3. REGIONS IN THE STRUCTURAL ELEMENTS

4. SAMPLES OF DISCONTINUITIES

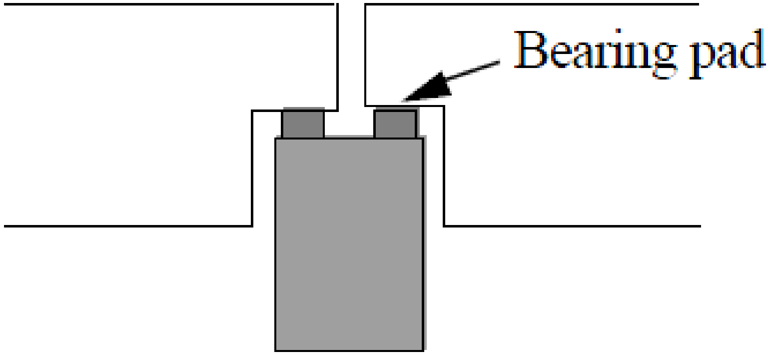
5. DESIGN OF B & D REGIONS

6. STM EXAMPLES

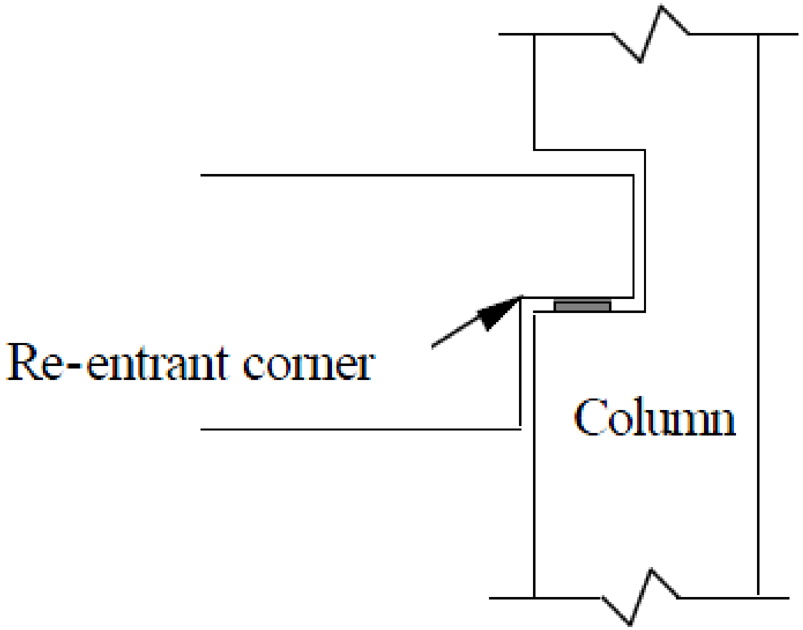
4. Samples of discontinuities / Exemple de discontinuități

SAMPLES OF DISCONTINUITIES - GEOMETRIC DISCONTINUITIES

1. Cross section modification → dapped-end



Beam to Beam



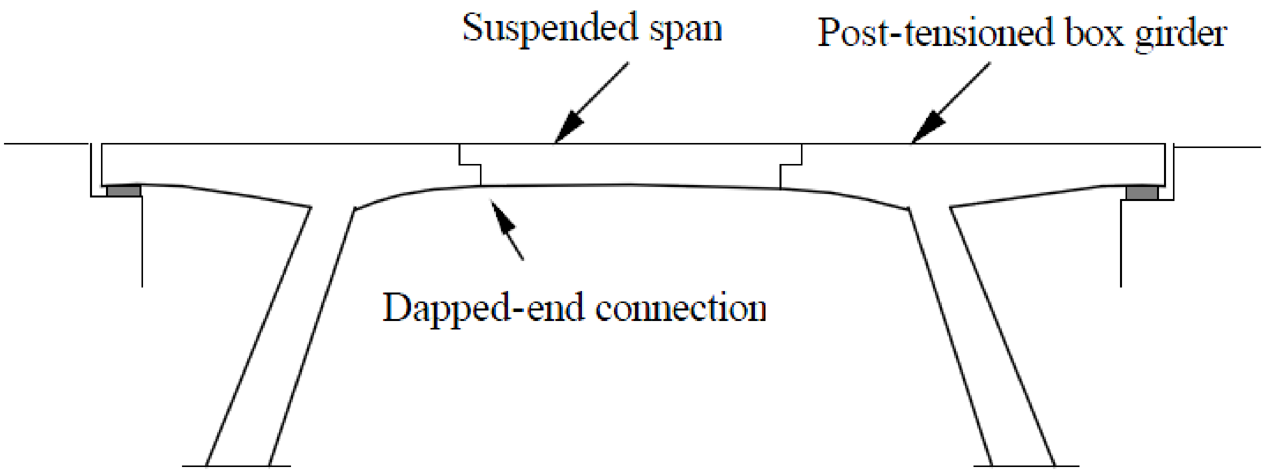
Beam to Column

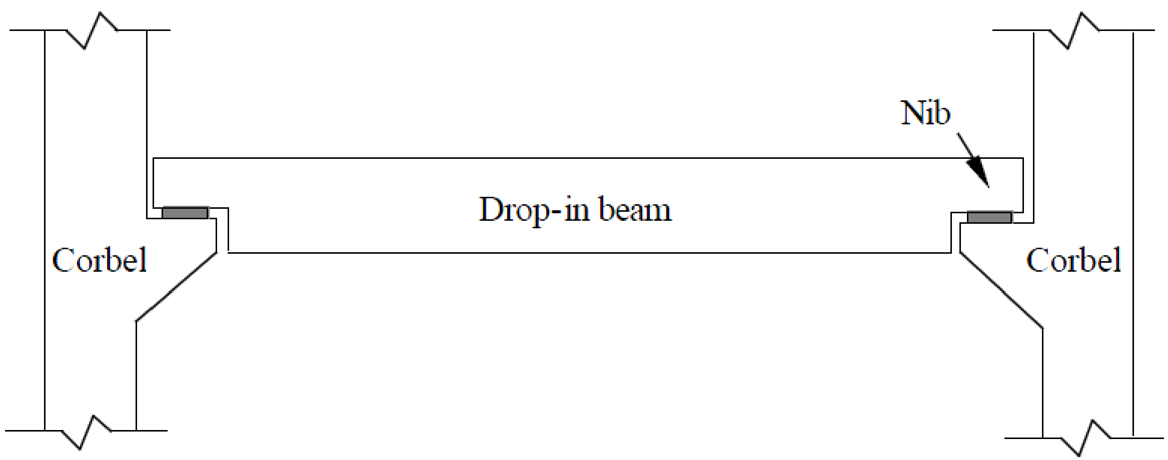
(Prof. Clipii T.)

4. Samples of discontinuities / Exemple de discontinuități

SAMPLES OF DISCONTINUITIES - GEOMETRIC DISCONTINUITIES

1. Cross section modification → dapped-end



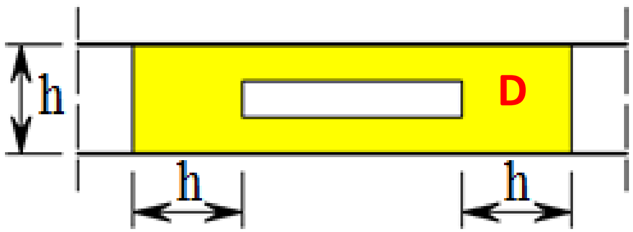


(Prof. Clipii T.)

4. Samples of discontinuities / Exemple de discontinuități

SAMPLES OF DISCONTINUITIES - <u>GEOMETRIC DISCONTINUITIES</u>

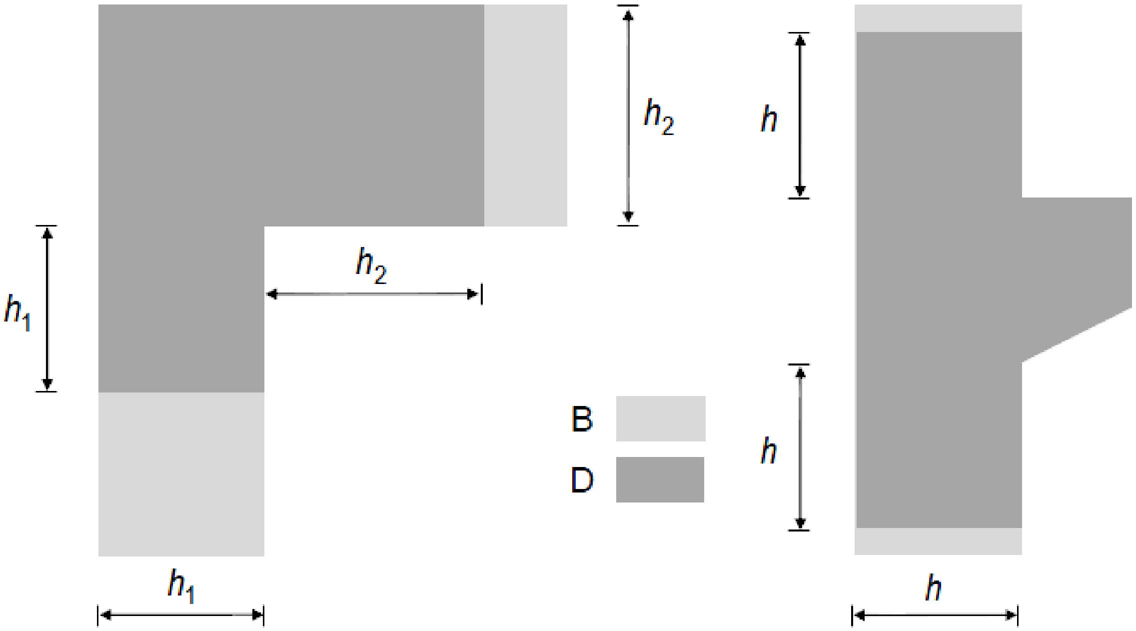
2. Opening in the web → building services



4. Samples of discontinuities / Exemple de discontinuități

SAMPLES OF DISCONTINUITIES - GEOMETRIC DISCONTINUITIES

3. Structural joints, intersections → cantilevers, frame joints

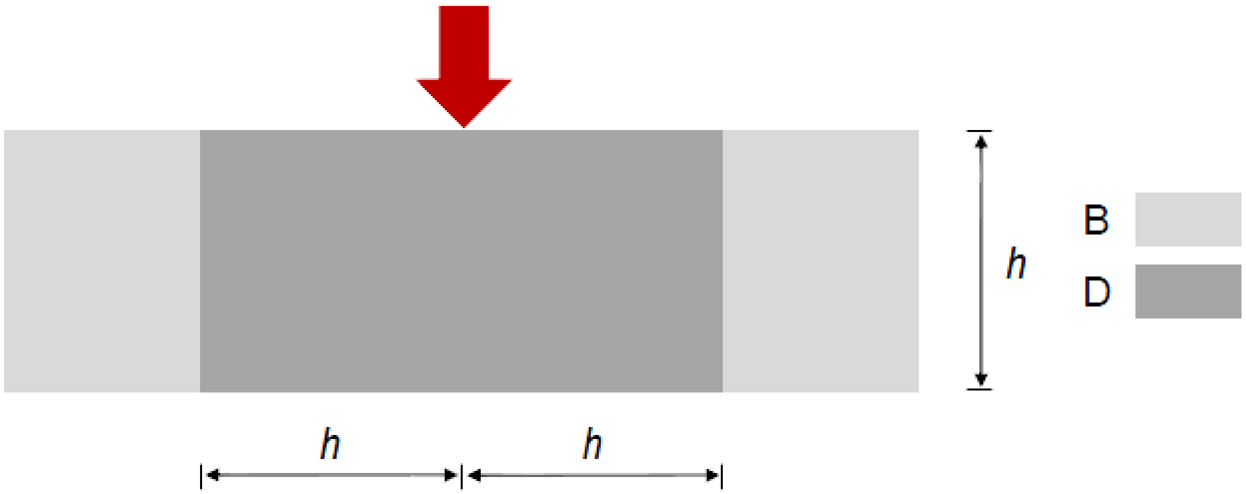


(Prof. Kovács I., DE)

4. Samples of discontinuities / Exemple de discontinuități

SAMPLES OF DISCONTINUITIES - STATIC DISCONTINUITIES

1. Concentrate loads

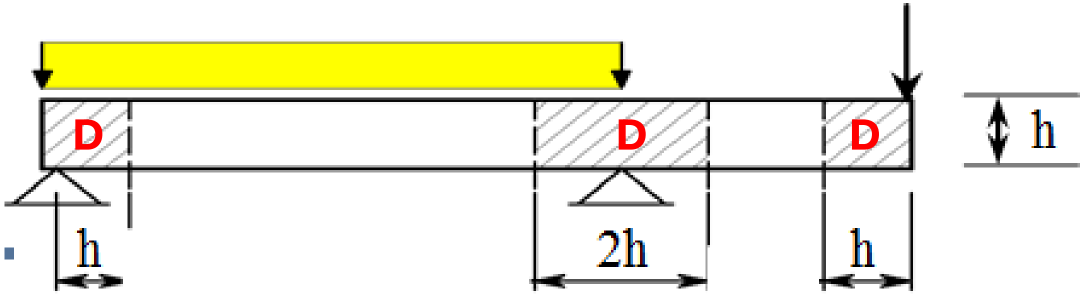


(Prof. Kovács I., DE)

4. Samples of discontinuities / Exemple de discontinuități

SAMPLES OF DISCONTINUITIES - STATIC DISCONTINUITIES

2. Support zones



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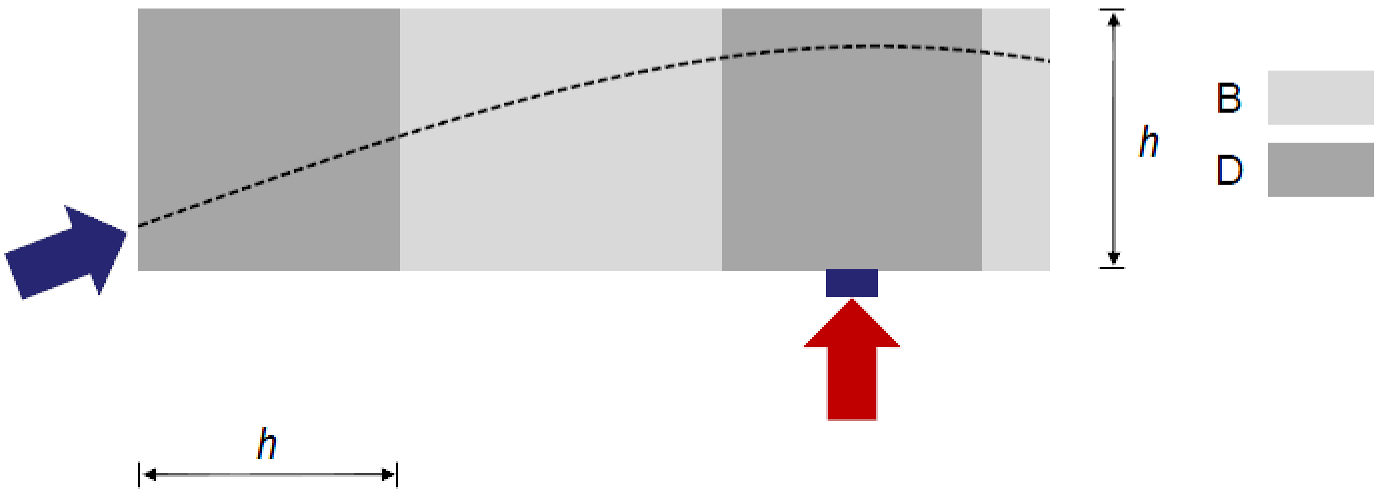
4. Samples of discontinuities / Exemple de discontinuități

SAMPLES OF DISCONTINUITIES - STATIC DISCONTINUITIES

3. Prestressing-end zone

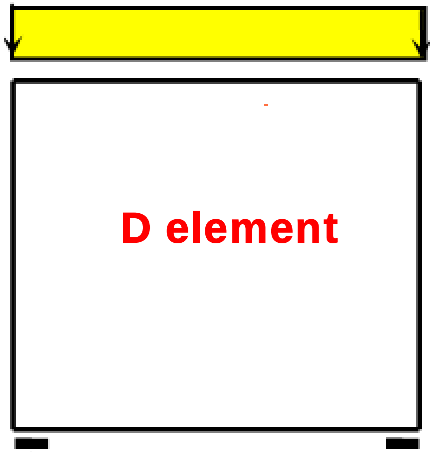


(Prof. Kovács I., DE)

4. Samples of discontinuities / Exemple de discontinuități

SAMPLES OF DISCONTINUITIES - STATIC DISCONTINUITIES

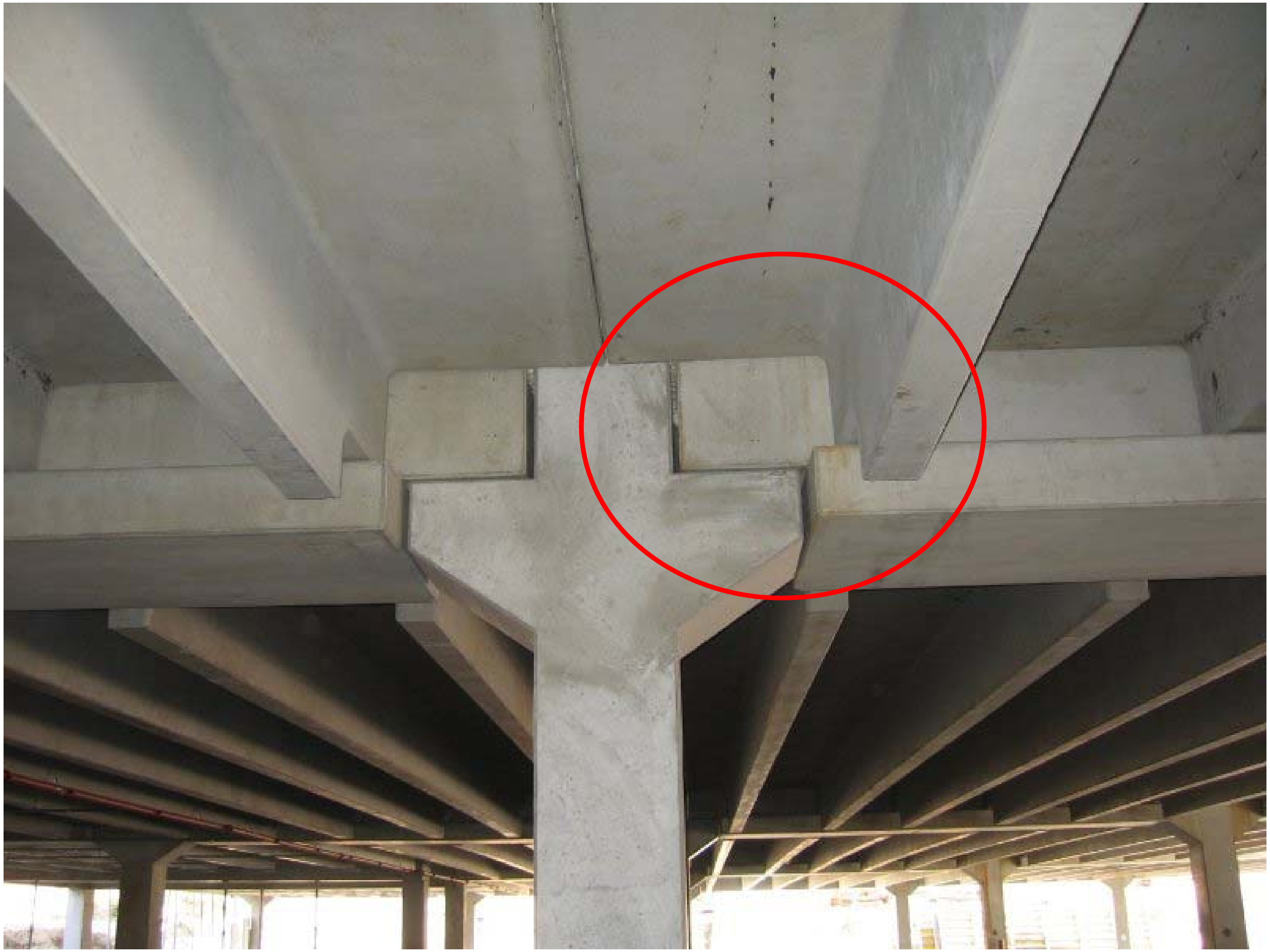
4. Deep beams



Deep beam

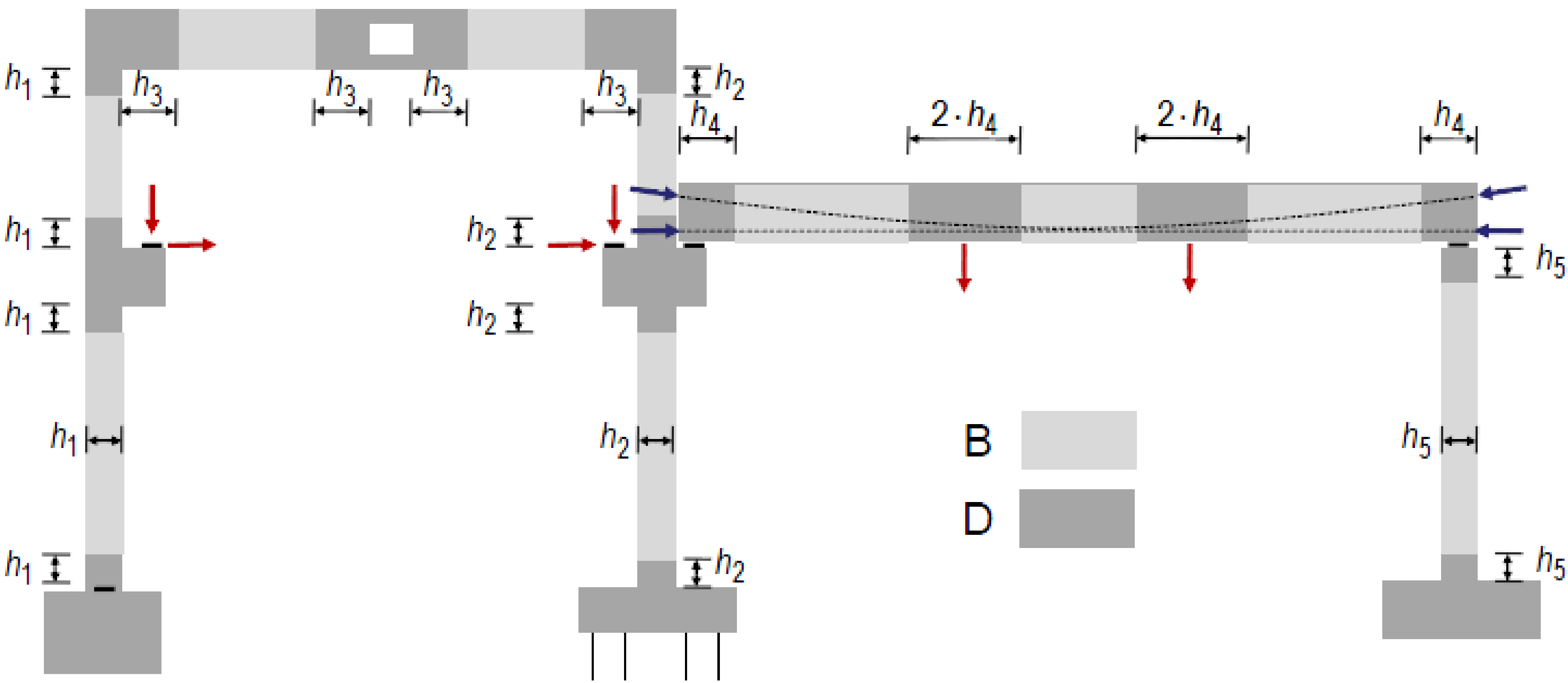
(Prof. Clipii T.)

SAMPLES OF DISCONTINUITIES - STATIC and GEOMETRIC DISCONTINUITIES



4. Samples of discontinuities / Exemple de discontinuități

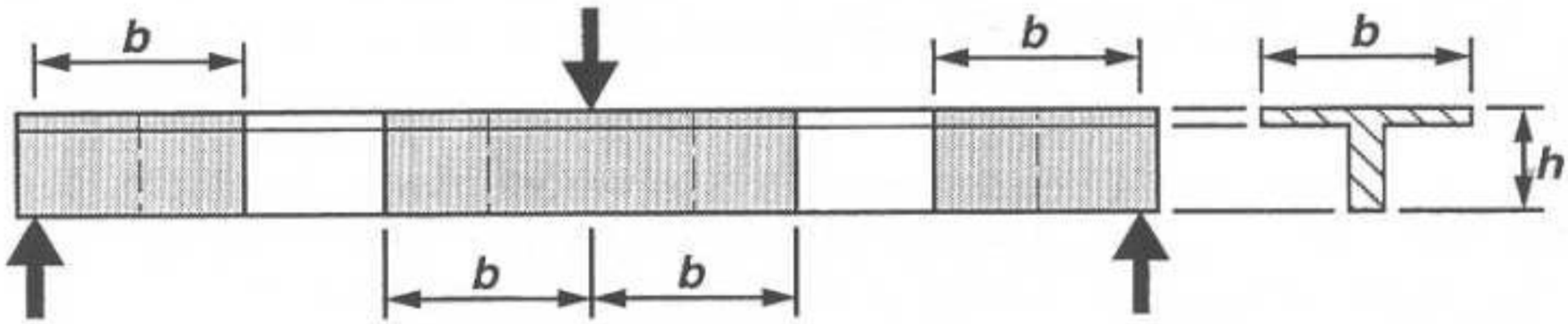
D-REGIONS



(Prof. Kovács I., DE)

4. Samples of discontinuities / Exemple de discontinuități

D-REGIONS



b) Flanged member

Design of B & D Regions

- The design of B (Bernoulli or Beam) region is well understood and the entire flexural behavior can be predicted by simple calculation

- Even for the most recurrent cases of D (Disturbed or Discontinuity) regions (such as deep beams or corbels), engineers' ability to predict capacity is either poor (empirical) or requires substantial computation effort (finite element analysis) to reach an accurate estimation of capacity!!!

D – region is safe if:

- the greatest compressive stress on the bearing support is < $0,6f_{cd}$

- all tensile forces are resisted by reinforcement

- sufficient development lengths are provided for the reinforcement

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STM in Eurocode 2

→ provides very little guidance in using STM, which covers mainly the effective concrete strength provisions for the various strut-and-tie elements.

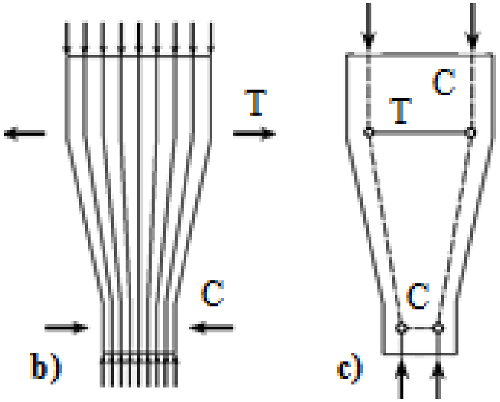
→ provides guidance for establishing the effective concrete strength values to use in the struts and nodes for a specific internal force condition and arrangement

Table 1. EC2 design concrete compressive strength provisions for STM elements

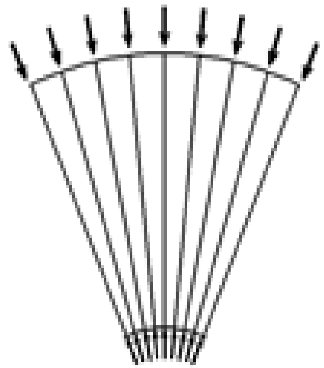
STM Element	Effective concrete strength	
Strut	Without transverse tension f_{cd}	With transverse tension $0.6\,v' f_{cd}$
Node	Compression node without ties (C-C-C) $v' f_{cd}$	Compression node with ties in one direction (C-C-T) $0.85\,v' f_{cd}$

where f_{cd} is the design concrete strength; $v' = 1 - f_{ck}/250$; f_{ck} is the concrete cylinder strength.

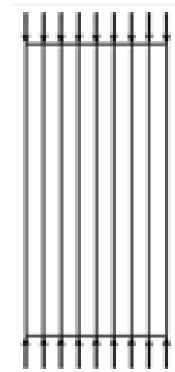
5. Design of B & D Regions / Calculul zonelor B și D



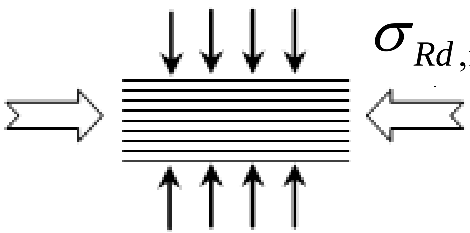
BOTTLE NECK – important **T**ransversal **T**ensile **F**orces



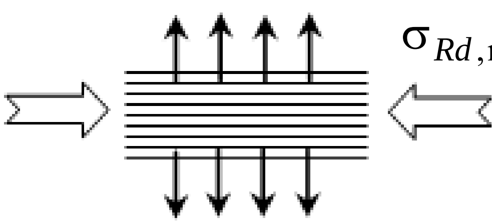
FAN – negligible TTF



PRISM – no TTF



$$\sigma_{Rd,\max} = f_{cd}$$



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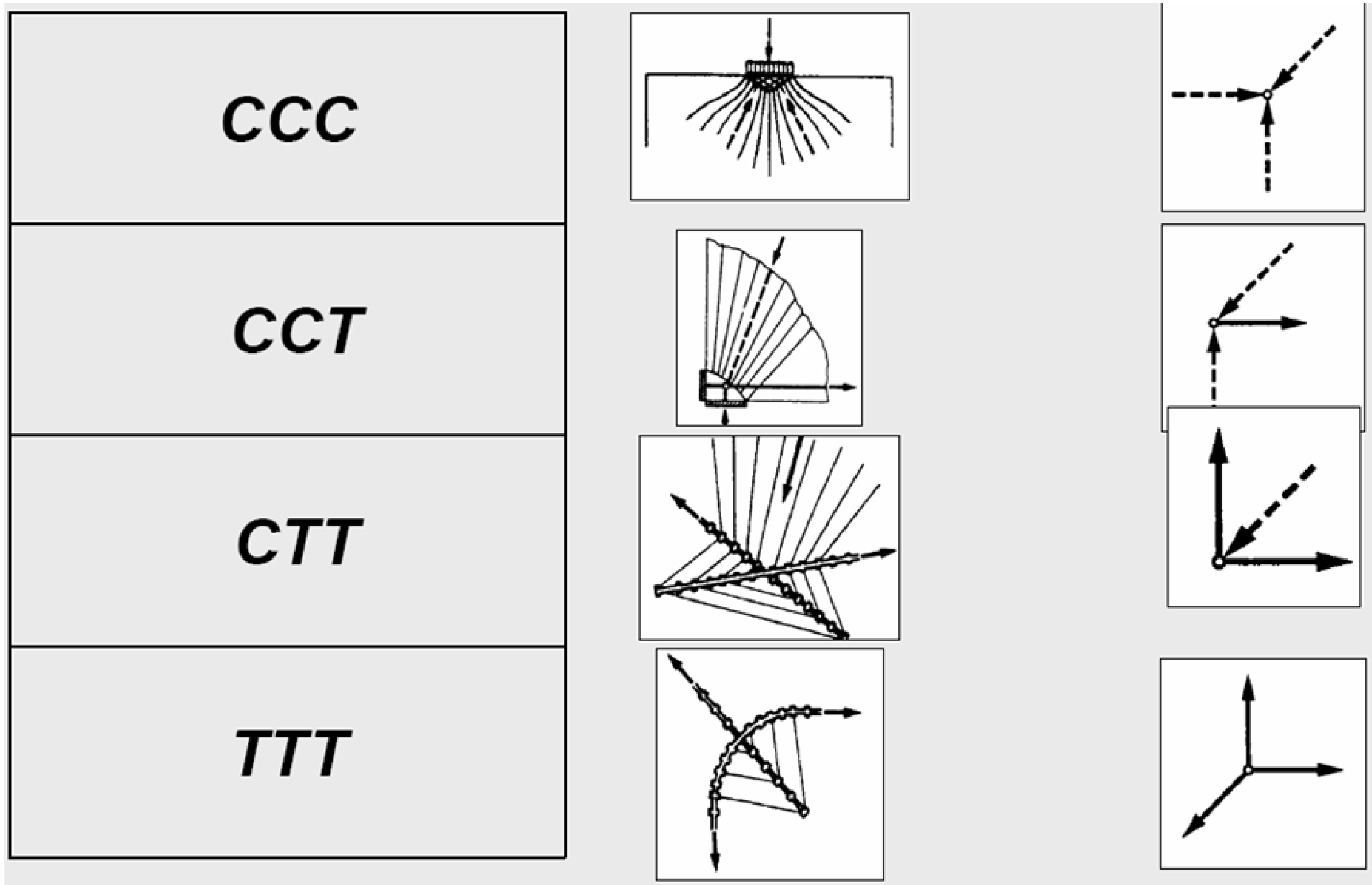
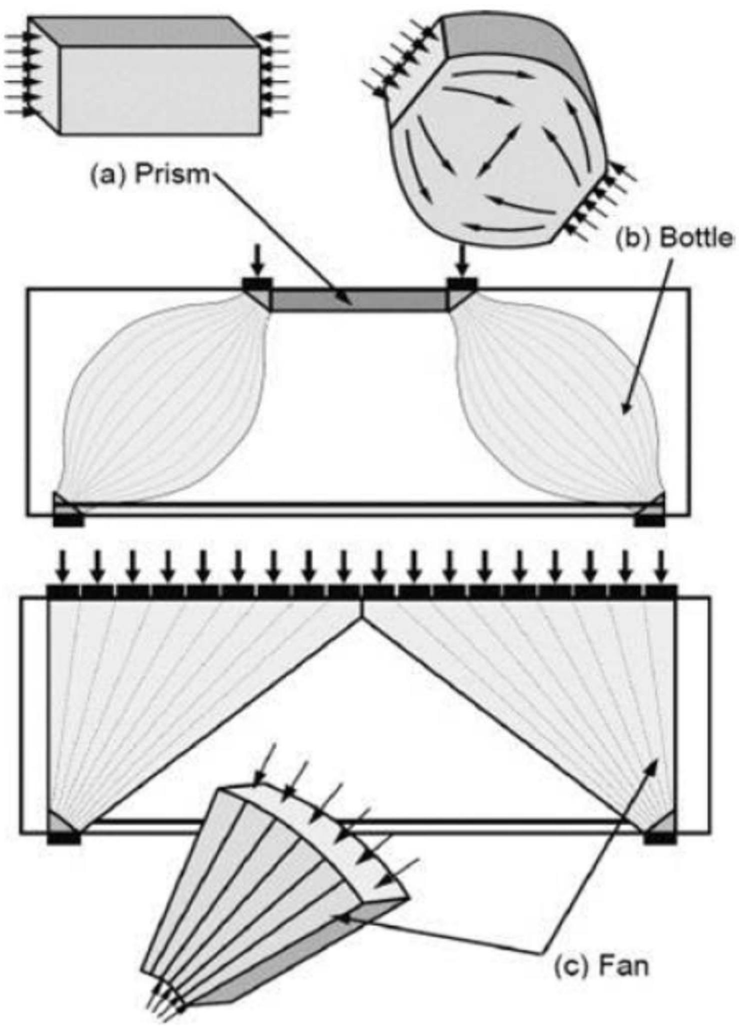
5. Design of B & D Regions / Calculul zonelor B și D



Node	Compression node without ties (C-C-C)	Compression node with ties in one direction (C-C-T)
	$v'f_{cd}$	$0.85\ v'f_{cd}$

where f_{cd} is the design concrete strength; $v' = 1 - f_{ck}/250$; f_{ck} is the concrete cylinder strength.

5. Design of B & D Regions / Calculul zonelor B și D



.7: Geometric shapes of struts (Schlaich and Schäfer 1991)

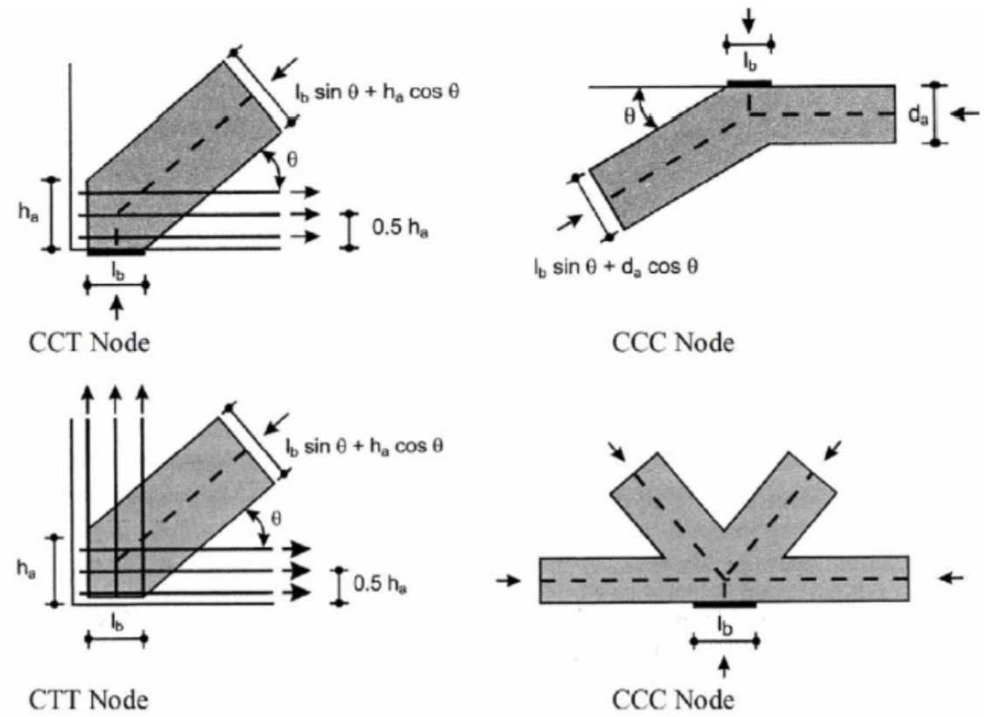


Figure 2.8: Types of strut-and-tie model nodes (Mitchell *et al.* 2004)

Design recommendations using EC 2 STM provisions

→ accurate shear strength predictions will achieve
→ consistent results for beams with a clear shear span to depth ratio of less than 2.
→ the maximum strains in the tensile reinforcement can be assumed to be strains at the point of yielding.

→ Adequate anchorage should also be provided for the tensile steel reinforcement at the supports to prevent premature reinforcement slip failure.
→ If design is to be made purely on EC2 STM provisions, it should be done for beams that have a clear shear span to depth ratio a_v/d of less than 1, which are considered as deep beams. This is to avoid any unsafe predictions in the shear strength.

→ For $1 \leq a_v/d \leq 2$, the effective concrete strengths of the direct strut from Modified Compression Field Theory should be used. Anything above the av/d range of 2 ought to be designed with the Eurocode 2 Sectional model.

6. STM EXAMPLES

6. STM examples / Exemple de modele de bare

CHOOSING THE MODEL

INTUITIVELY

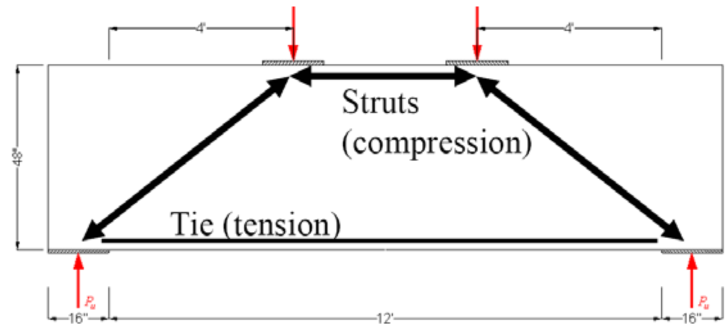
LOAD-PATH METHOD

ELASTIC ANALISYS

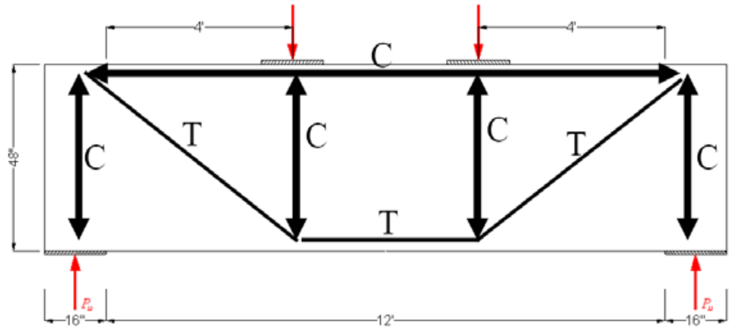
(Prof. Clipii T.)

CHOOSING THE MODEL

1. NO MECHANISM
2. LESS NUMBER OF TIES
3. SHORTER TIES



YES !



NO !

4. ONE ELEMENT – TWO LOADS – TWO MODEL

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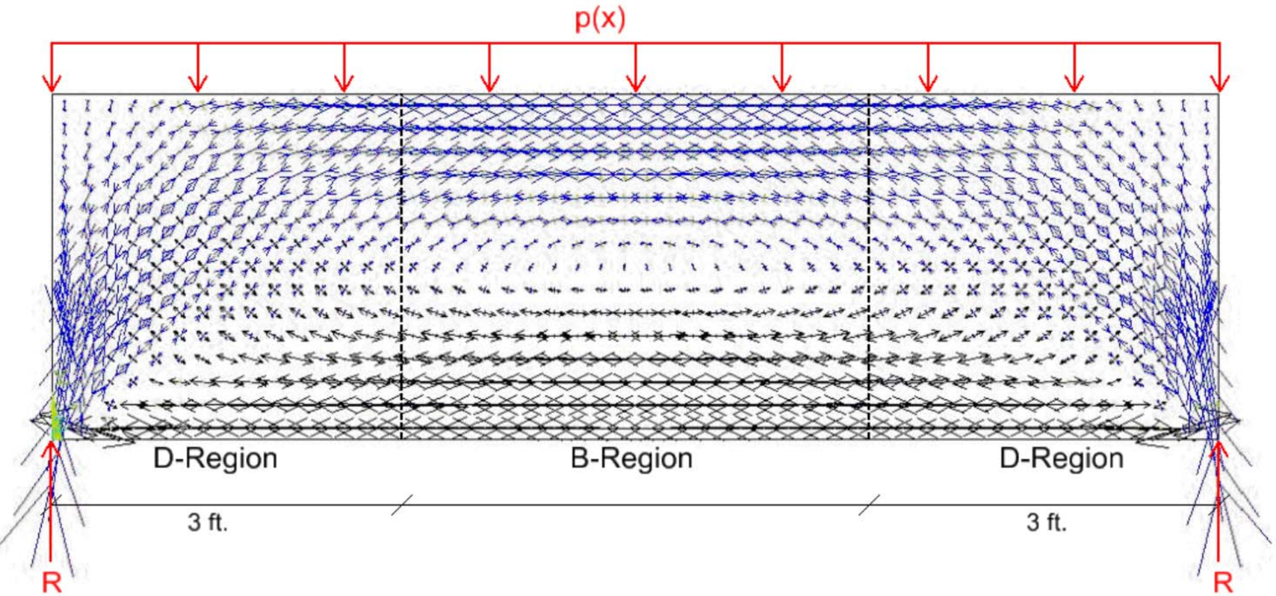
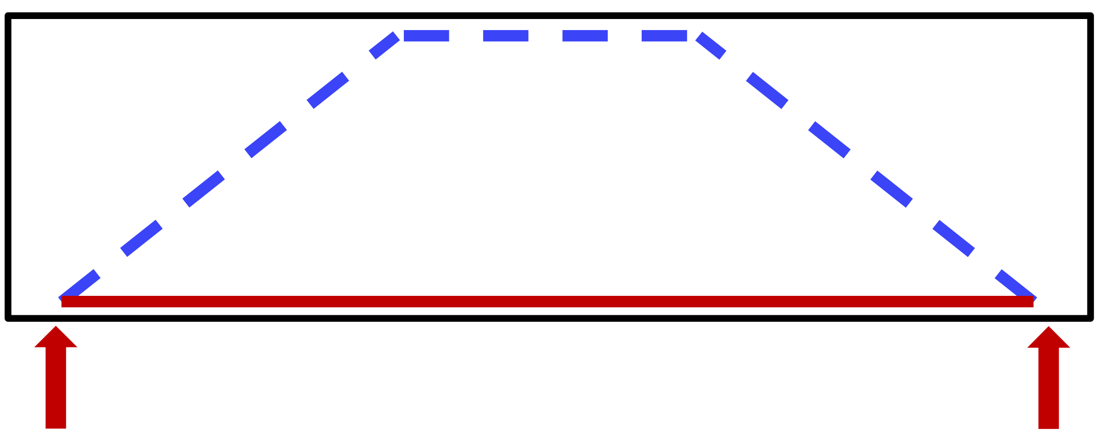
6. STM examples / Exemple de modele de bare

Simply supported beam subjected to a uniformly distributed load

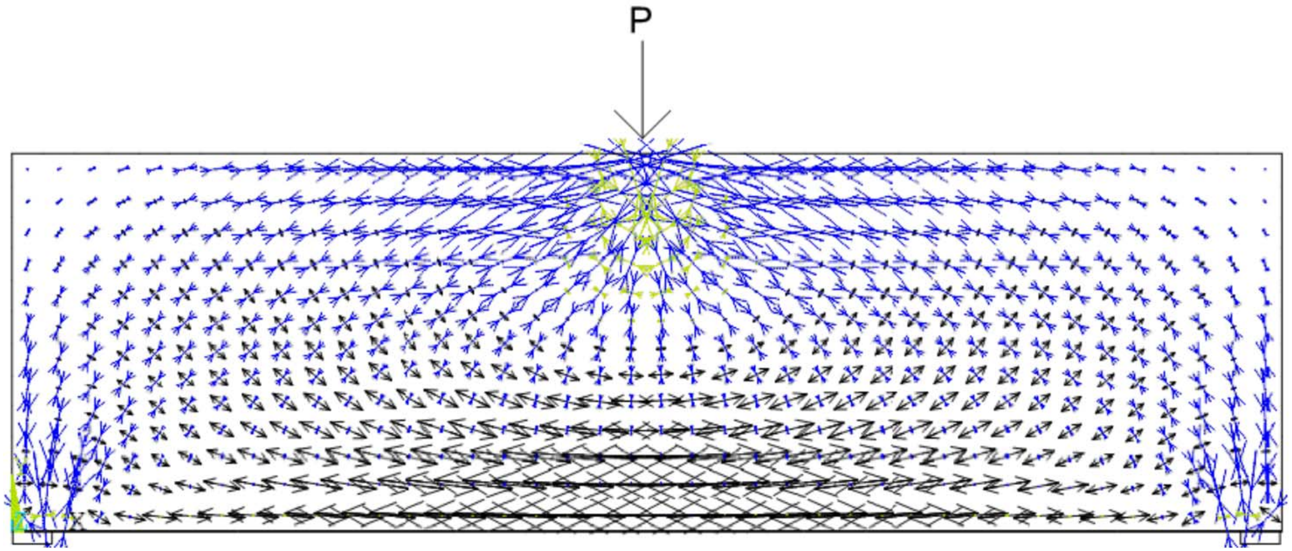


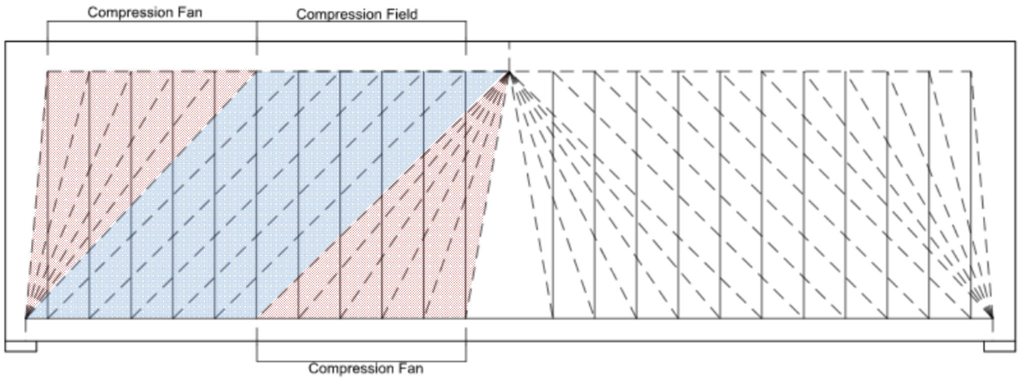


blue arrows = compressive stresses
black arrows = tensile stresses

6. STM examples / Exemple de modele de bare

Simply supported beam subjected to a concentrated load at its center



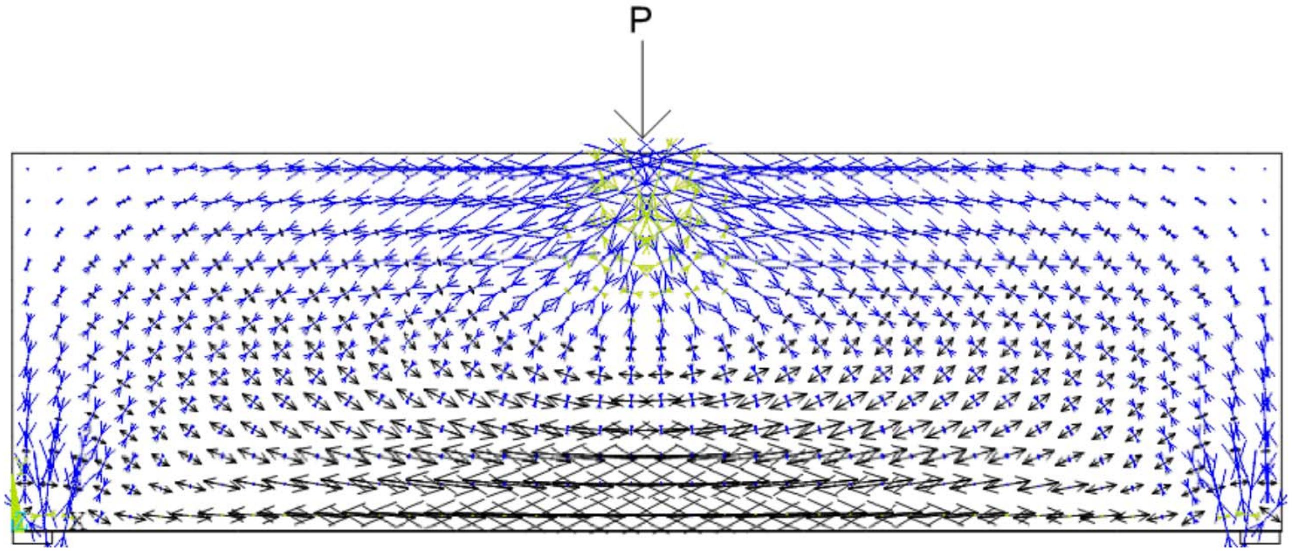


Indeterminate Truss → Solving by several iteration

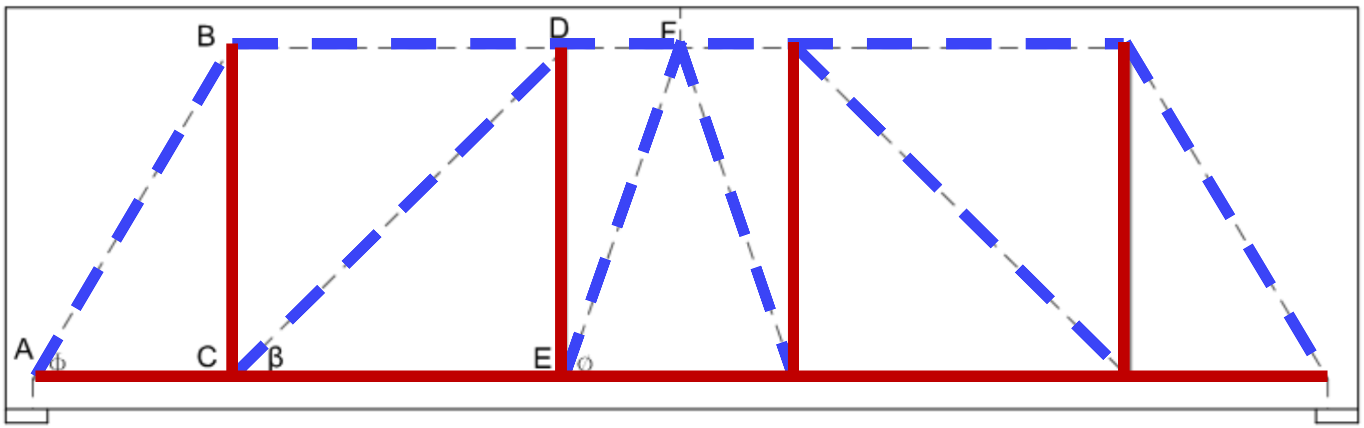
blue arrows = compressive stresses
black arrows = tensile stresses

6. STM examples / Exemple de modele de bare

Simply supported beam subjected to a concentrated load at its center



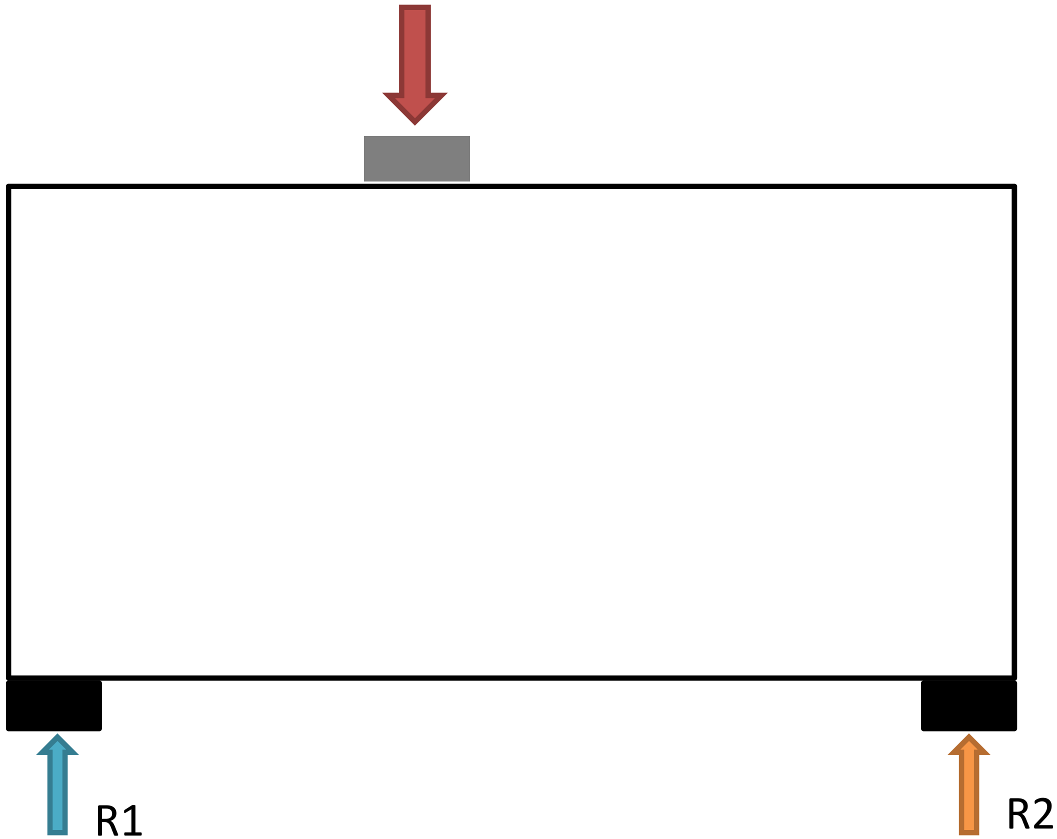
Determinate Truss → the member forces to be easily solved



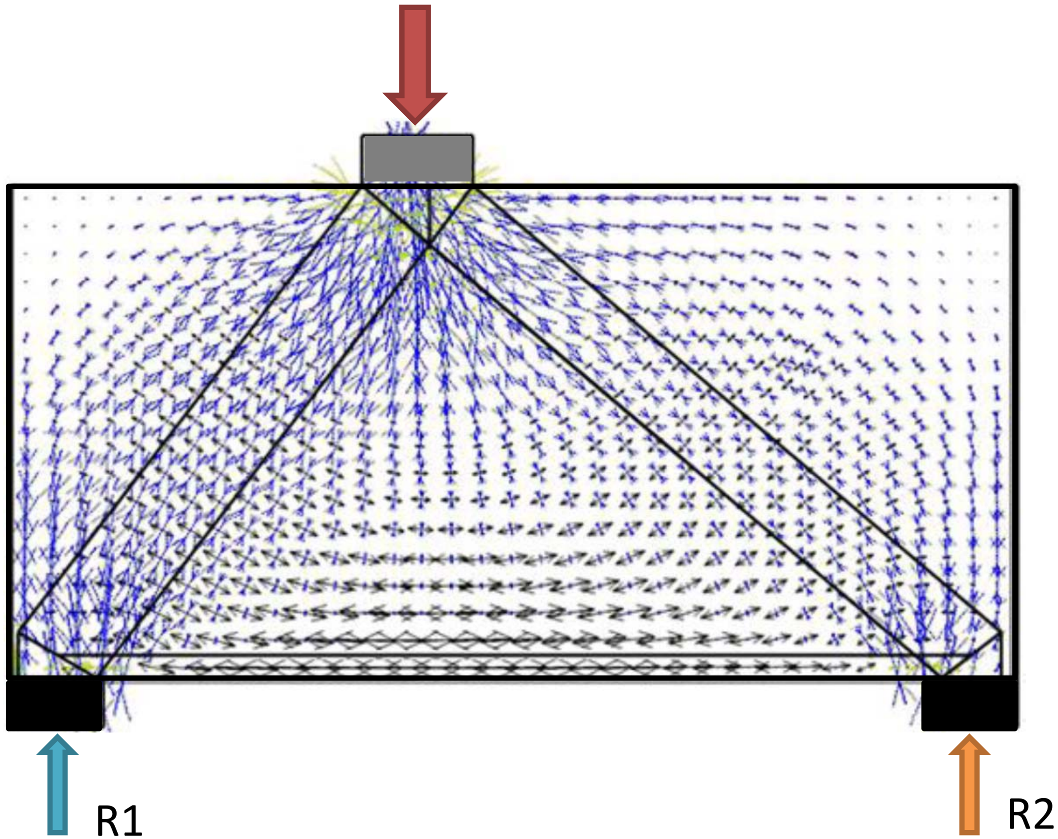
blue arrows = compressive stresses
black arrows = tensile stresses

6. STM examples / Exemple de modele de bare

Deep Beam with concentrated load

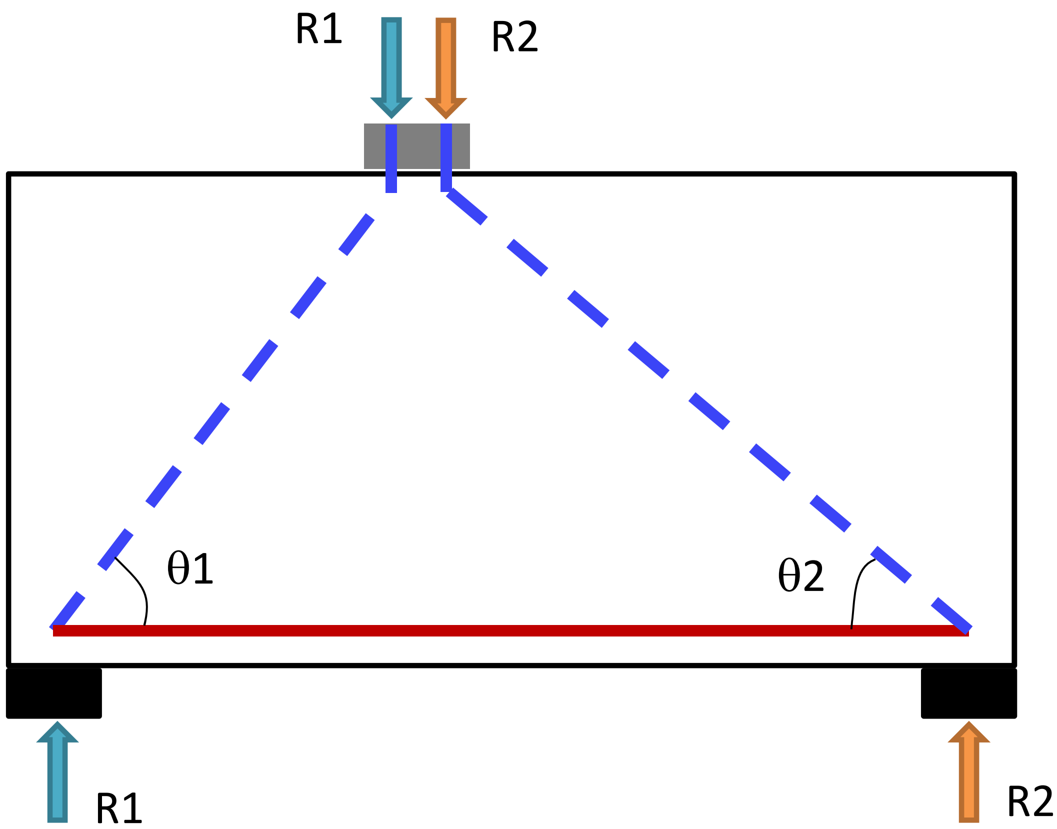


Deep Beam with concentrated load



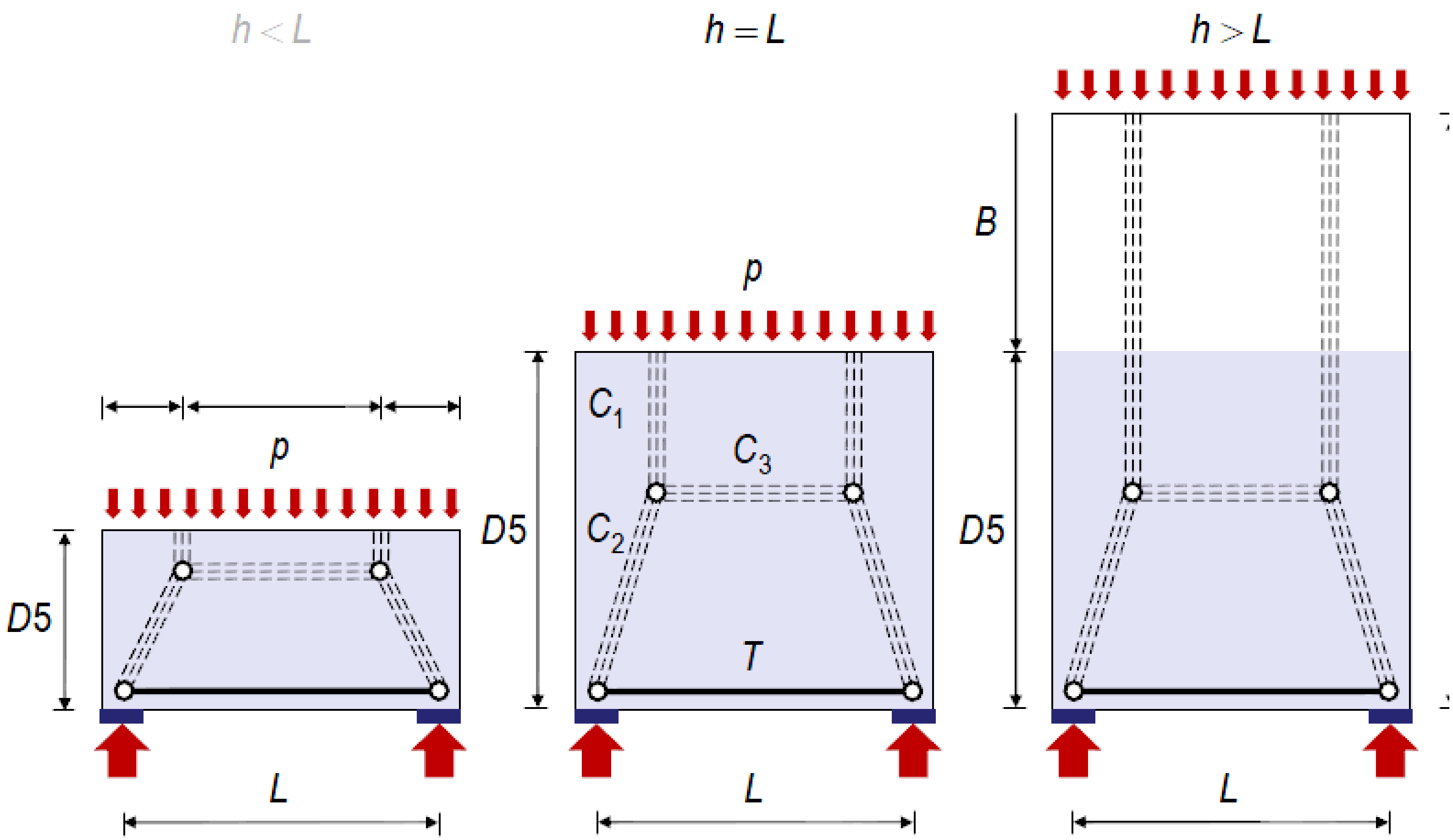
6. STM examples / Exemple de modele de bare

Deep Beam with concentrated load



6. STM examples / Exemple de modele de bare

Deep Beam with distributed load



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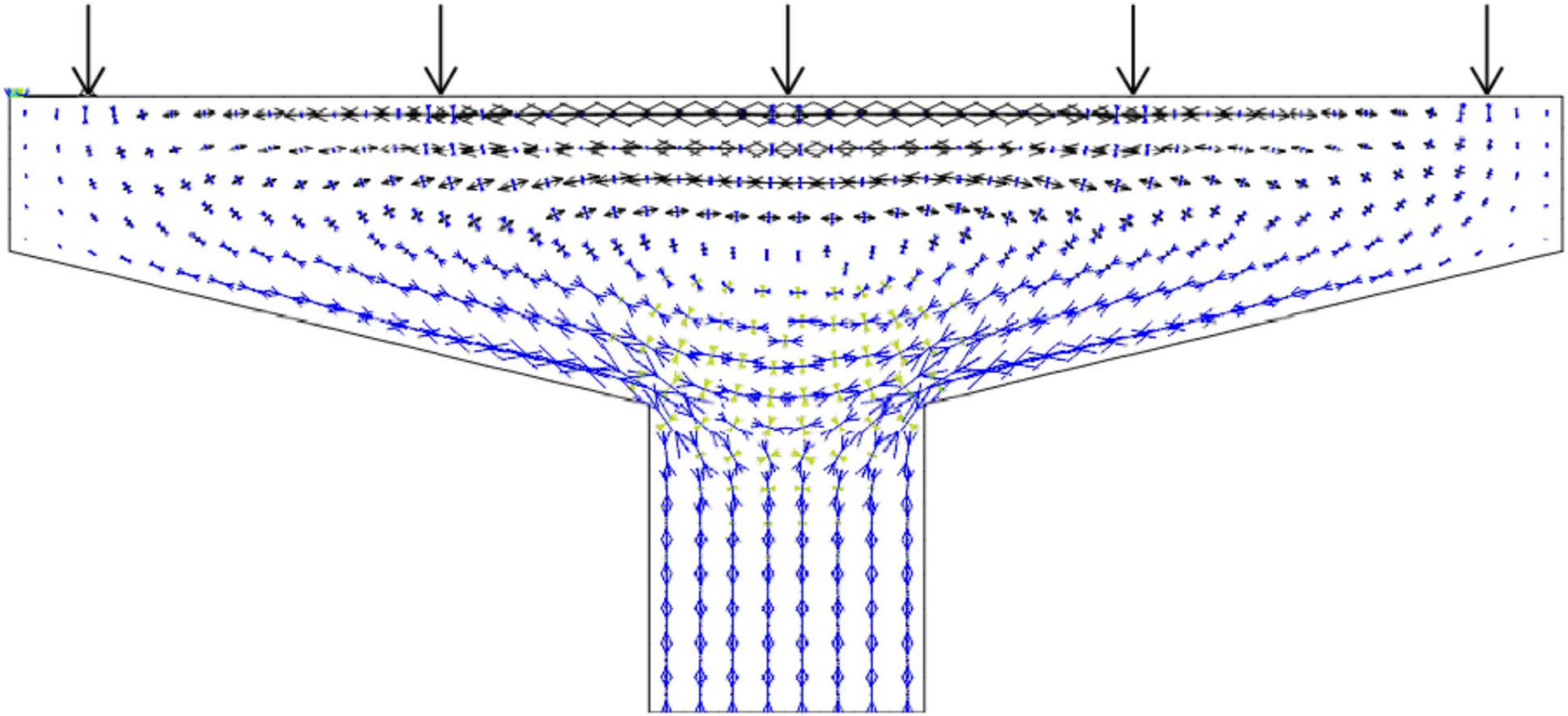
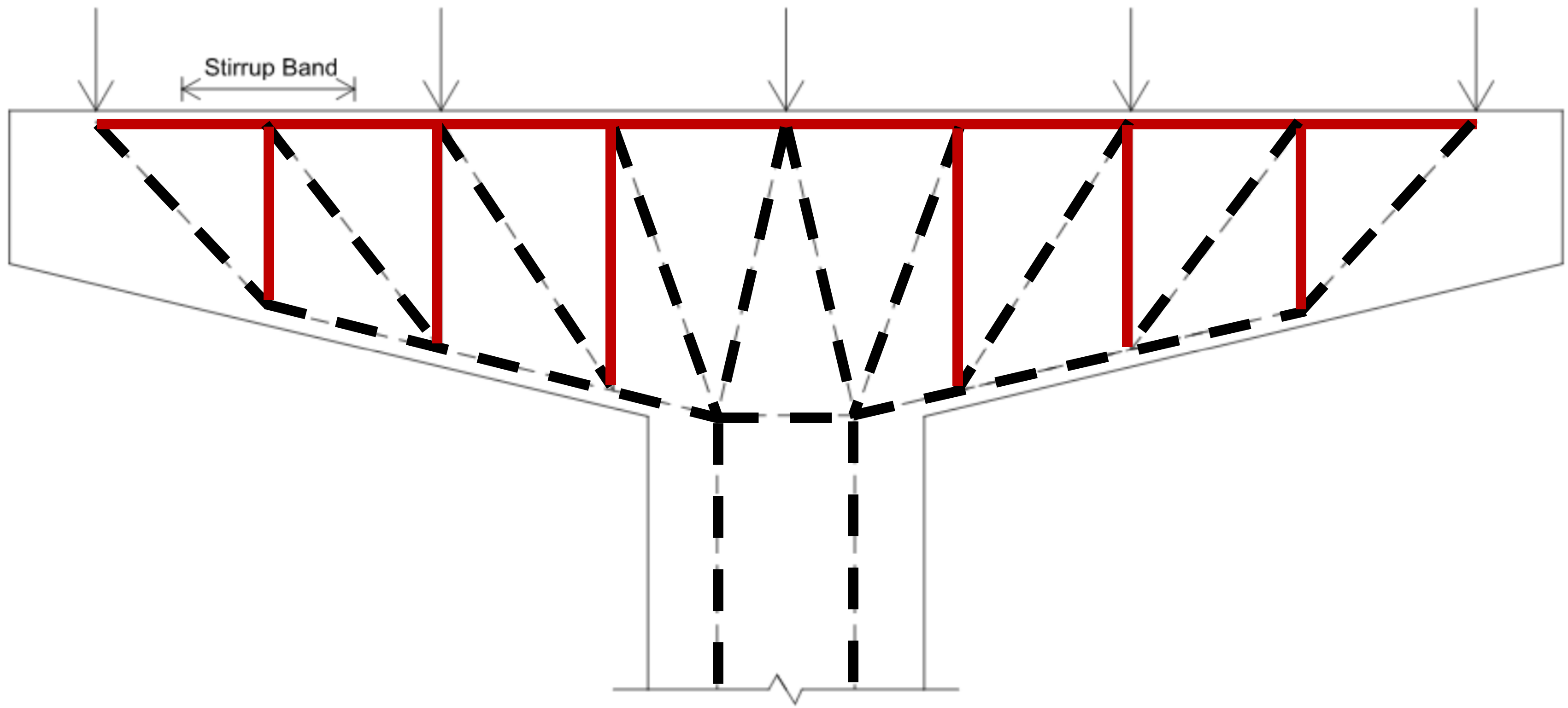
6. STM examples / Exemple de modele de bare

Bridge Pier Cap Design



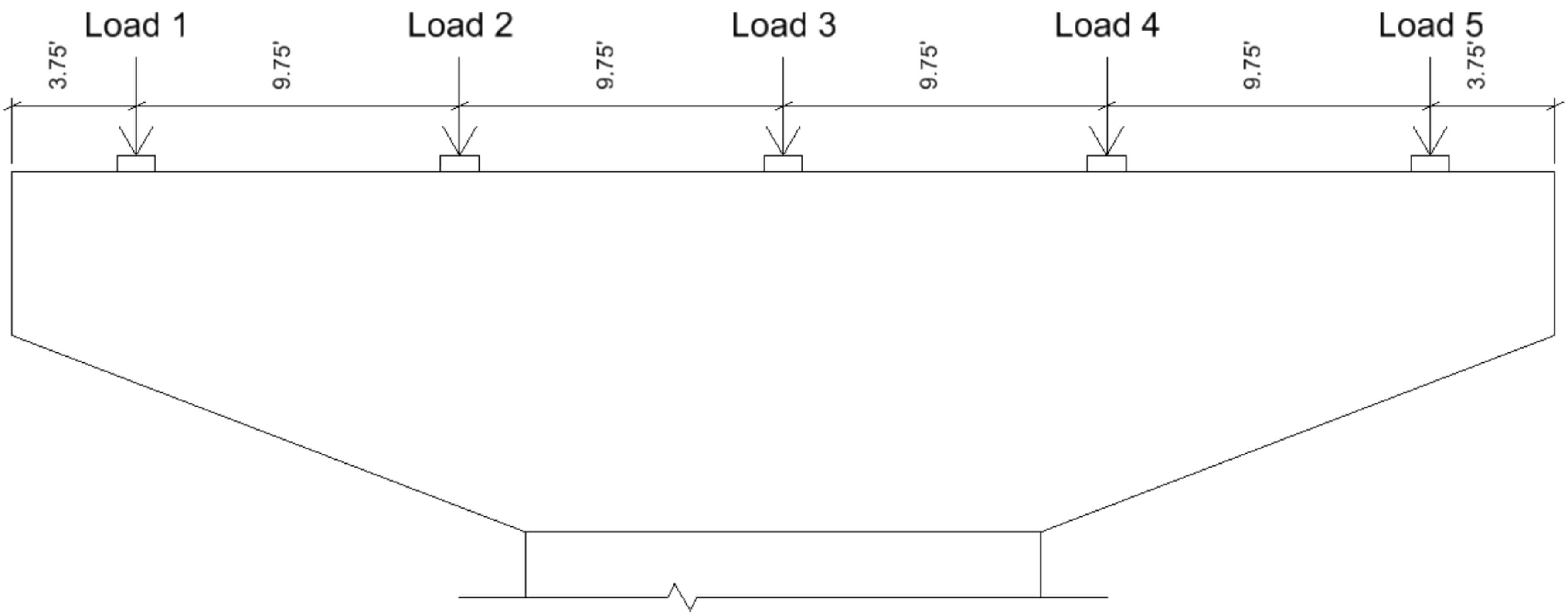
6. STM examples / Exemple de modele de bare

Bridge Pier Cap Design



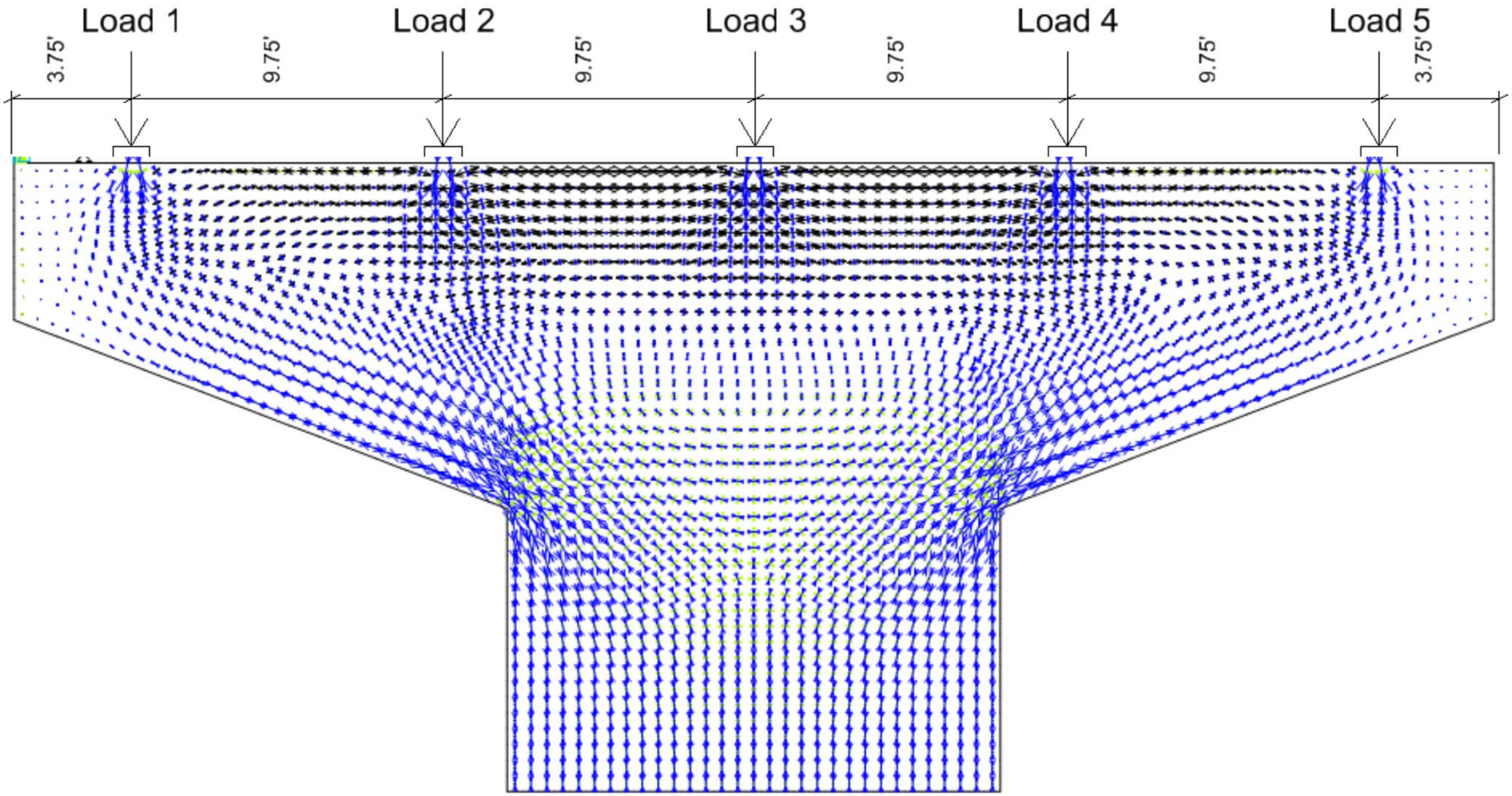
6. STM examples / Exemple de modele de bare

Bridge Pier Cap Design

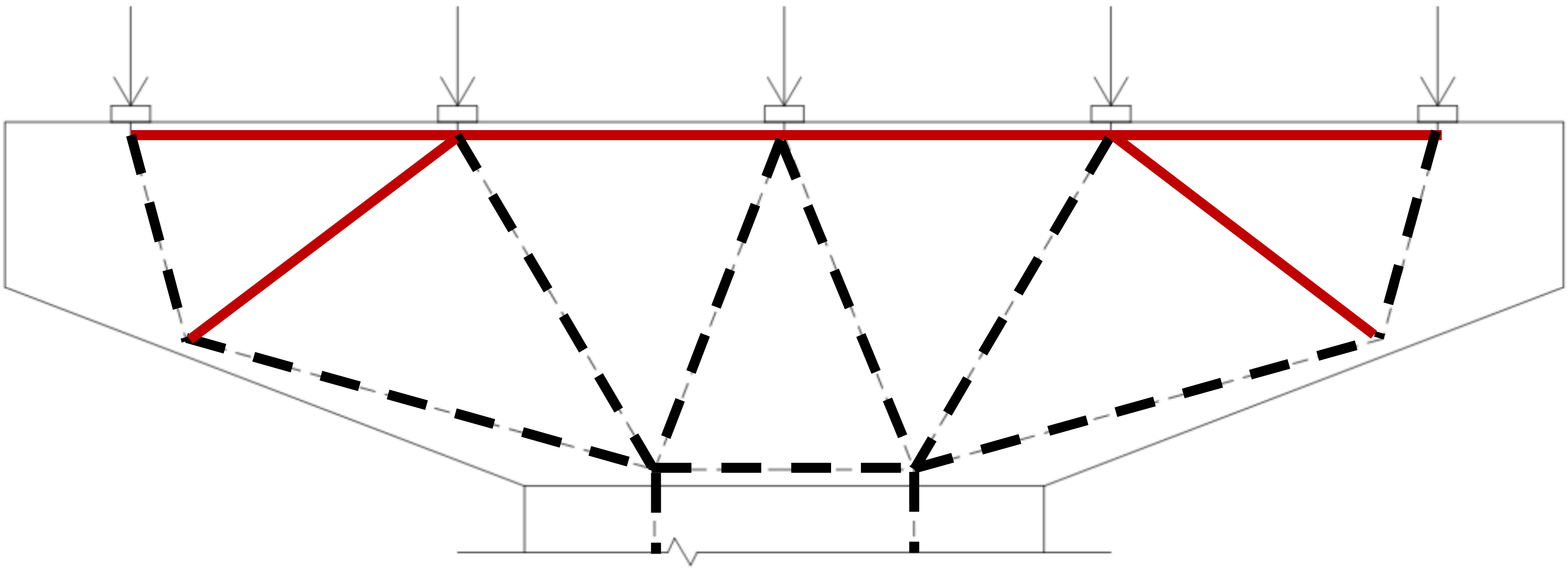


6. STM examples / Exemple de modele de bare

Bridge Pier Cap Design



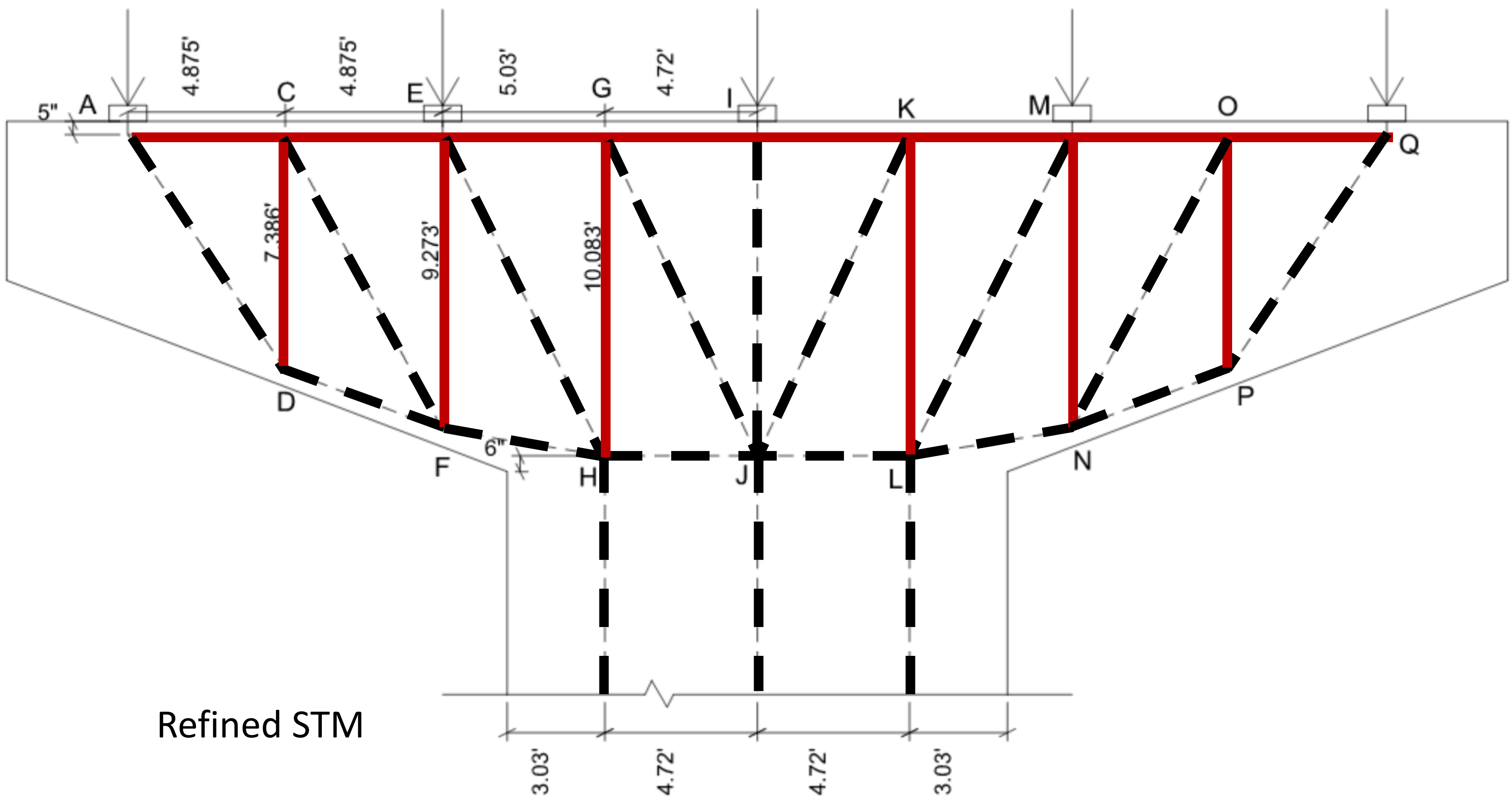
Bridge Pier Cap Design



Simple STM

6. STM examples / Exemple de modele de bare

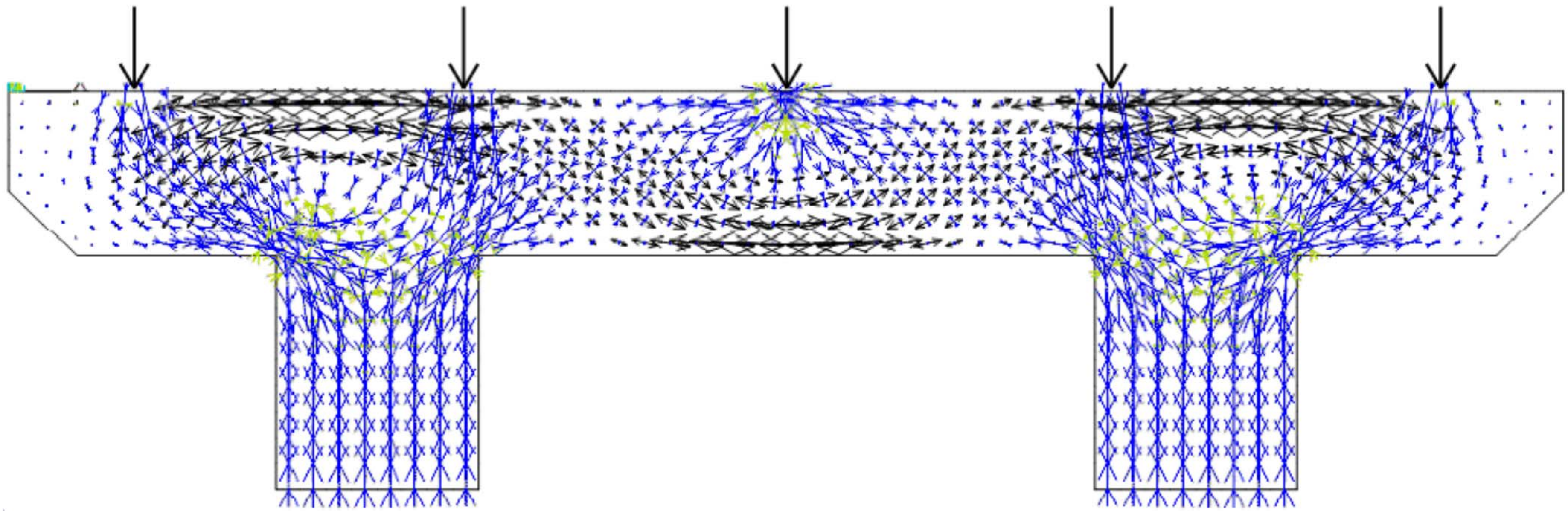
Bridge Pier Cap Design



Refined STM

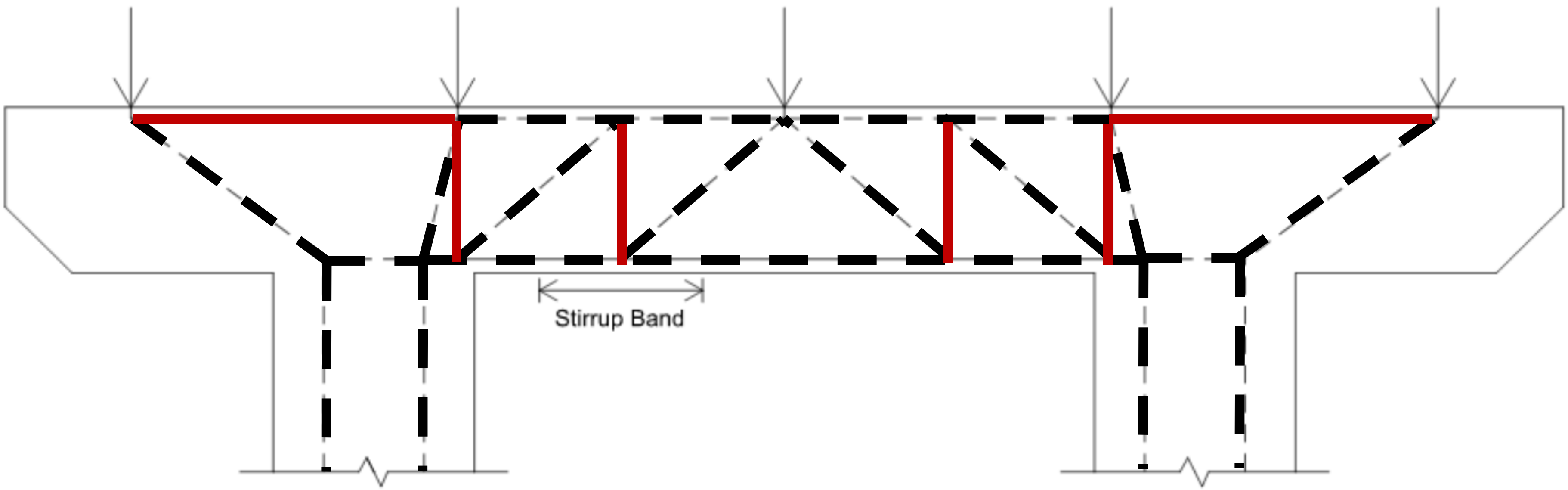
6. STM examples / Exemple de modele de bare

Bridge Pier Cap Design



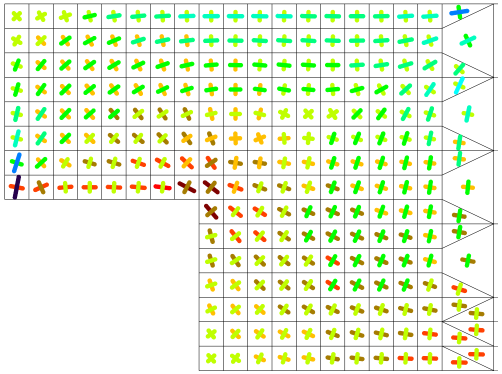
6. STM examples / Exemple de modele de bare

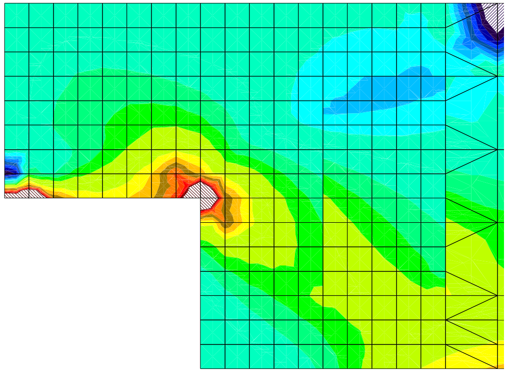
Bridge Pier Cap Design

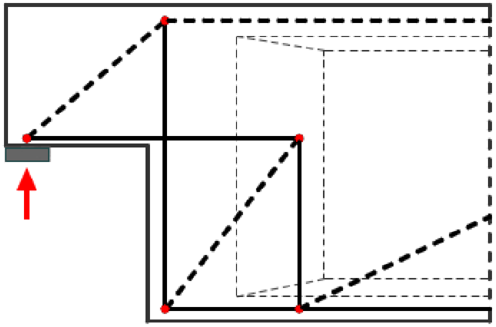


6. STM examples / Exemple de modele de bare

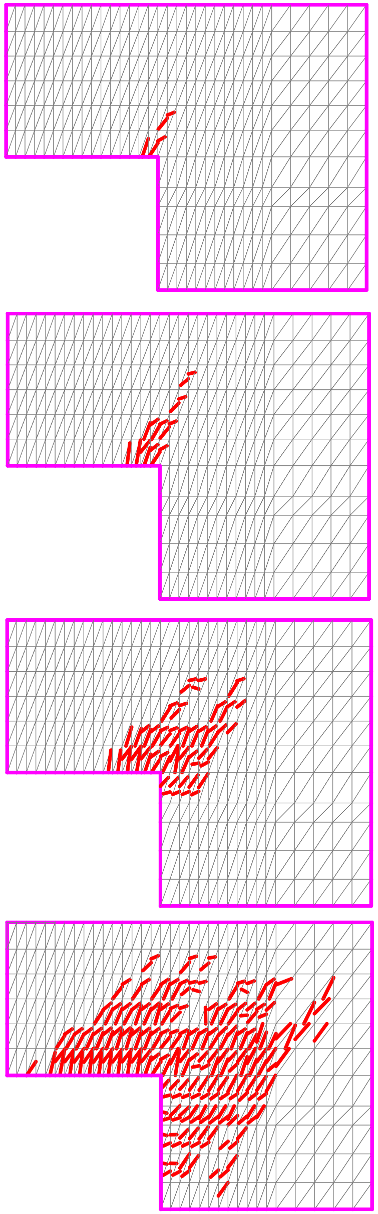
Dapped-ends



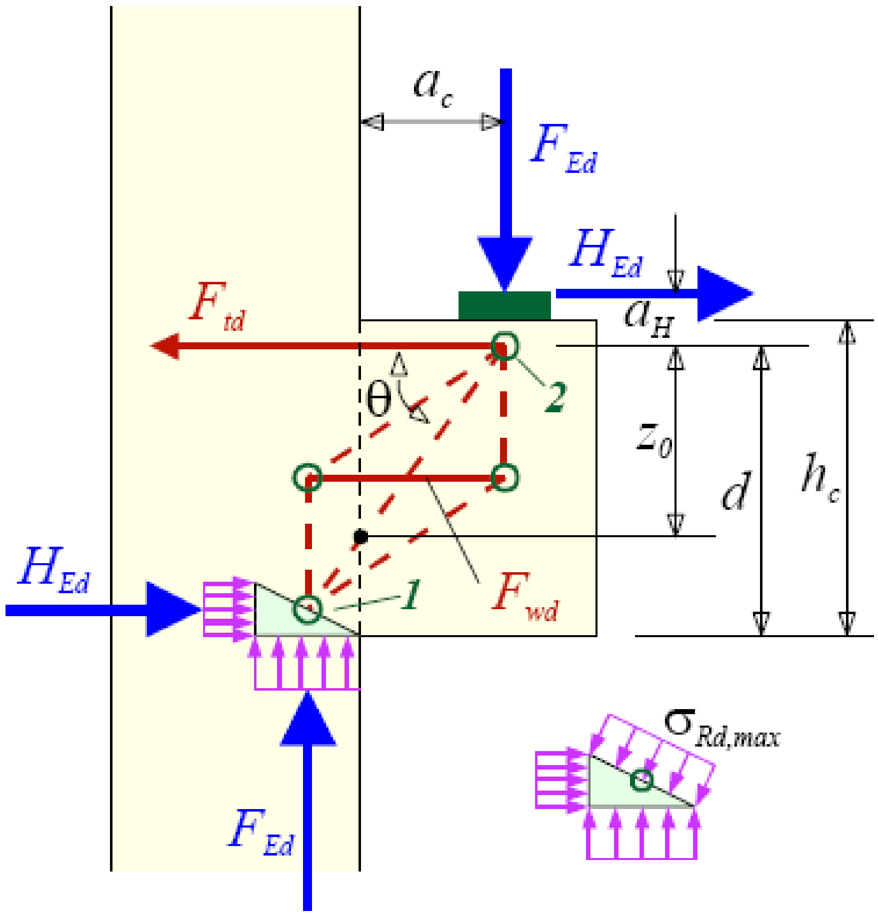




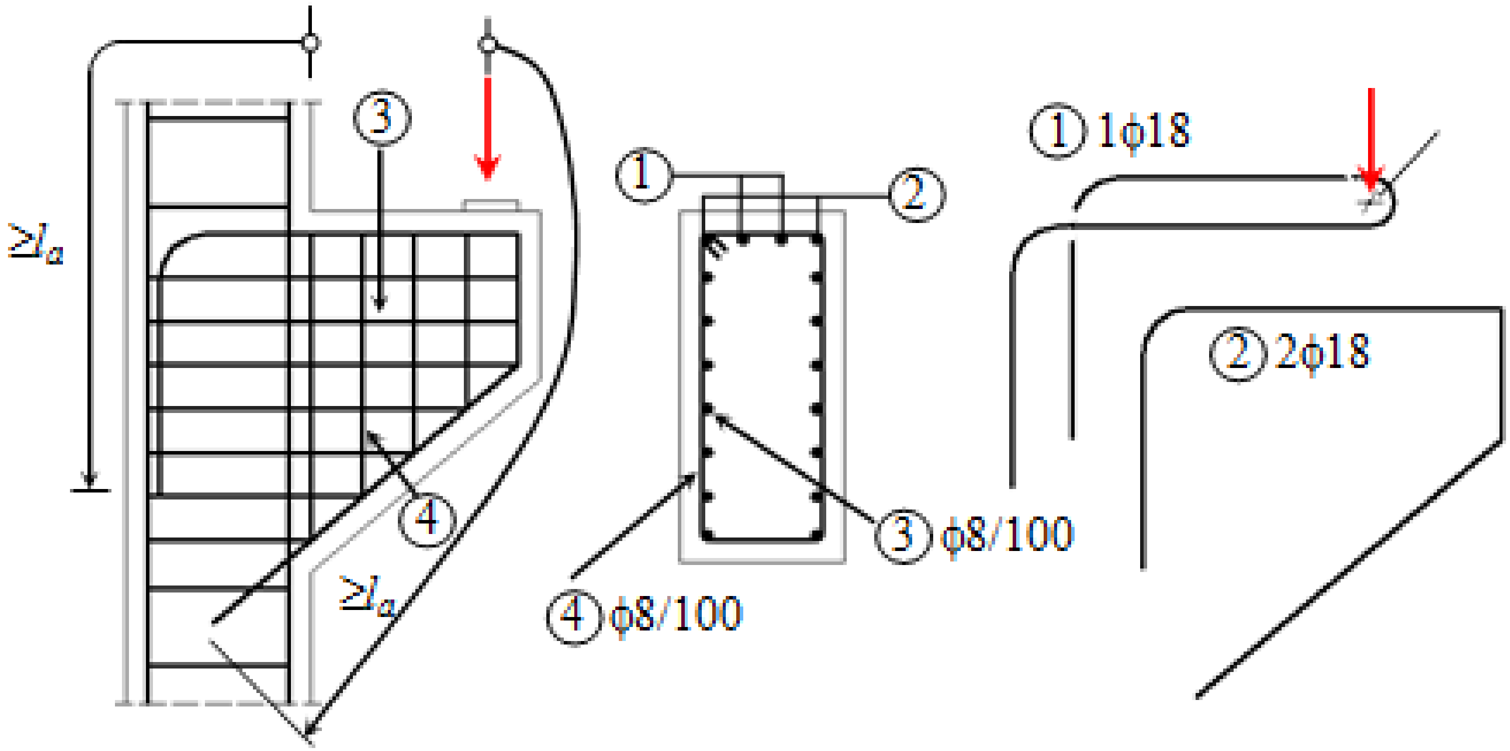
(a) Schlaich model [19] (b) Martin model [20]



Corbels (in conformity to EC2)

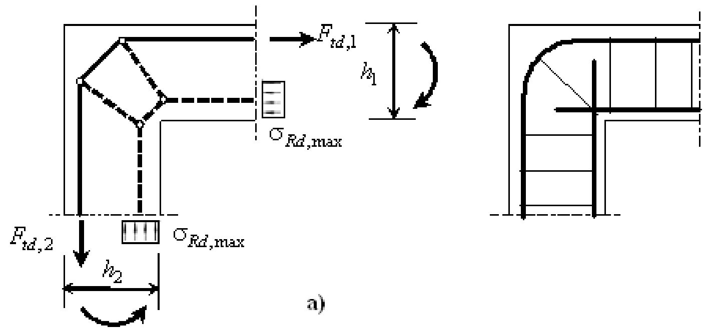


Corbels (in conformity to EC2)

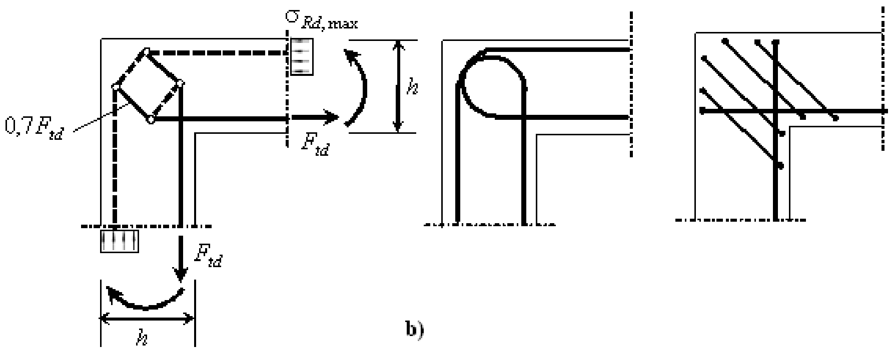


6. STM examples / Exemple de modele de bare

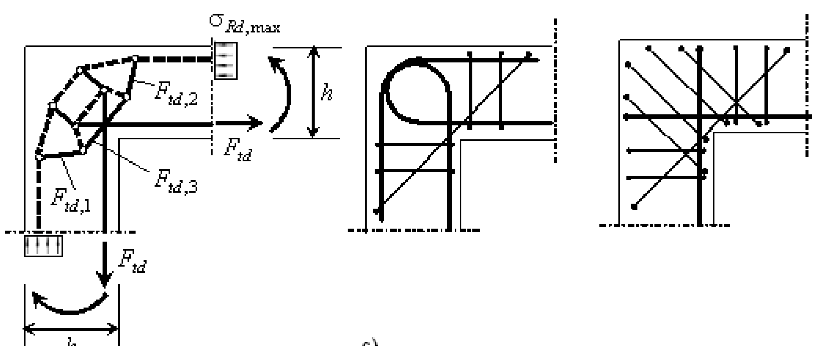
Beam-to-column joints (in conformity to EC2)



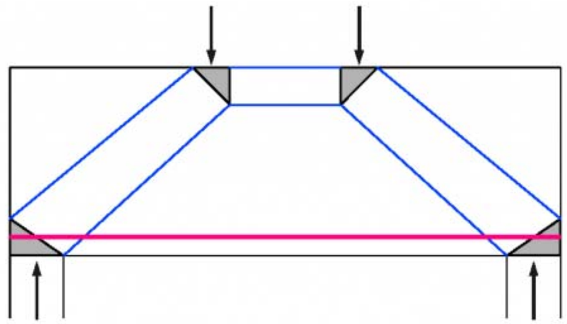
a)



b)



c)



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THANK YOU FOR YOUR ATTENTION!