5th International Workshop
Design in Civil and Environmental Engineering
University of Rome La Sapienza. October 6-8, 2016

non conventional structural patterns for tall buildings :

From DiaGrid to HexaGrid and beyond…

DiST
Dipartimento di Strutture
per l'Ingegneria e l'Architettura

**Elena Mele, Massimiliano Fraldi,
Gian Maria Montuori, Gianpaolo Perrella**

Dept. Structures for Engineering and Architecture
University of Naples Federico II

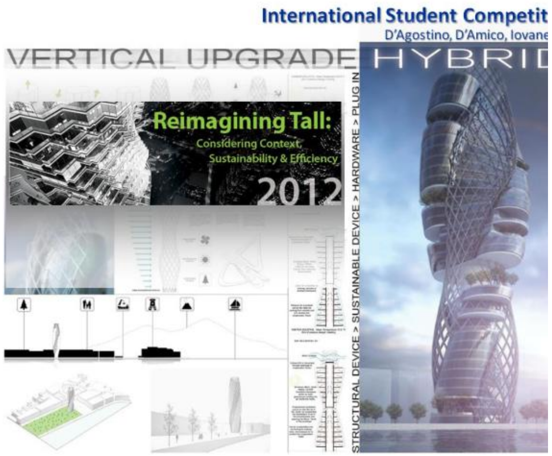
Layout

- introduction
- diagrid – as starting point
- generalization – structural patterns
- hexagrid
- voronoi

Tall Buildings @ Università degli Studi di Napoli Federico II

Structures for High-Rise and Long-Span Bldgs

(9 ECTS Course - Grad., Master)



international student design competition

student outdoor internship

Luis Bozzo, Barcelona	Luis Bozzo Estructuras y Proyectos, S.L.
Columbia University, New York WSP, New York	COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK WSP WSP Cantor Seinuk Structural Engineers
StarSeismic Inc., Budapest	STAR SEISMIC
SOM, San Francisco	SOM
Atelier One, London	atelier one STRUCTURAL ENGINEERS

Tall Buildings @ Università degli Studi di Napoli FEDERICO II

- case studies

  learning from precedents

- stiffness vs. strength design

  posing the right questions

- secondary bracing systems

  a hidden design problem

- non-regular triangular patterns

  exploring non-conventional

Diagrid

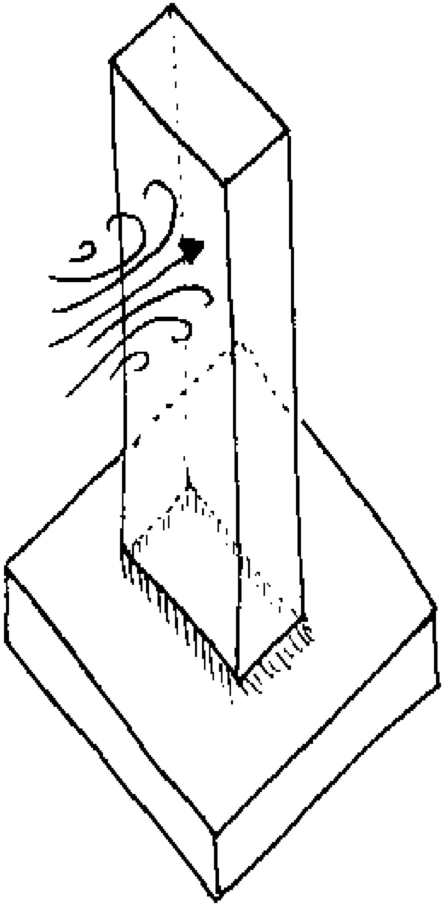
- **Hexagrid** - patterns, modeling, design
- from Hexagrid to **Voronoi** patterns

MICRO-MEGA

Nature inspired structures for tall buildings: patterns, modeling, analysis

THE IDEA : TB structure as a cantilever beam

The fundamental conceptual simplification : **TB → a cantilever beam**



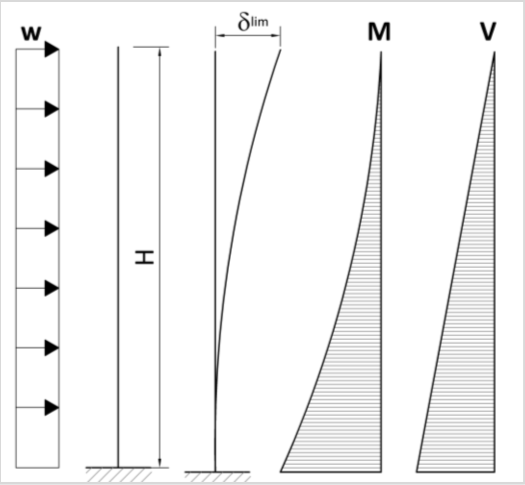
… By taking something as large and complex as a huge skyscraper, something formed by thousands of individual beams, columns, walls and slabs, and imagining it **as one simple entity**, the designer can design these giant structures rationally

In a certain sense, the tall building is the simplest of all structural problems

Bill Baker. **SOM Chicago**

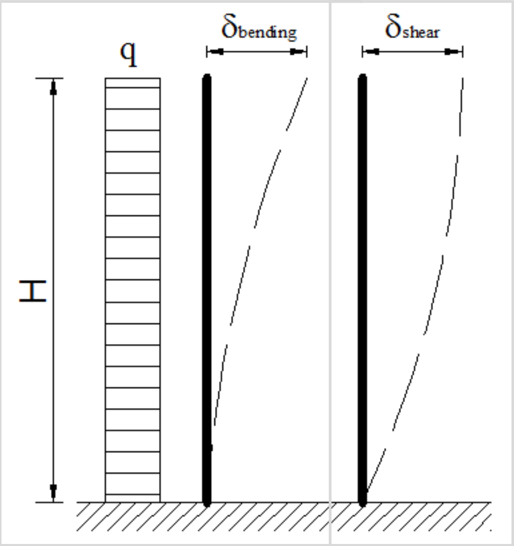
Engineering this Idea : Conceptual definition of structural systems

THE IDEA : TB structure as a cantilever beam



TB : a cantilever beam

globally statically determinant
approximate total forces known *a priori*
overturning moments and shears
flexural and shear deformations



$$\delta_{top} = \delta_{bending} + \delta_{shear} \leq \frac{H}{\alpha}$$

… the art and science of tall building design lies in selecting the appropriate system with adequate strength capacity and lateral stiffness

Stiffness requirements **Strength requirements**

Fazlur Khan and the TUBE concept

He revolutionized TB design from conventional MRF system to tubular system by imagining the true response of bldgs in 3D space

The history of modern skyscraper is the story of F. Khan

- **max (<u>potential</u>) bending efficiency**
  continuous vertical elements at the plan **perimeter**
- **shear resisting system** for carrying lateral loads to the vertical perimeter elements that, in turn, resist the overturning moments
- The **crucial point** of the tube system is that, in order for the **columns to work as elements of an integrated system** (a single giant cantilever beam) rather than an aggregation of individual elements or subsystems, and obtaining the ideal bending efficiency, it is necessary to interconnect them with an **effective (stiff) shear-resisting system**

the latest step in path towards optimization of TUBE structures

Framed Tube

Braced Tube

Diagrid

the latest step in path towards optimization of TUBE structures

Framed Tube

starting from the frame tube configuration

the structural efficiency has been highly increased thanks to the introduction of exterior mega-diagonals in the braced tube solution, which strongly reduce shear racking contribution to global deformation and shear lag effects

Braced Tube

diagrid as the evolution of braced tube

Braced Tube

the perimeter configuration still holds for preserving the maximum bending resistance and rigidity

the mega-diagonal members are diffusely spread over the façade

giving rise to closely spaced diagonals, a narrow diagonal grid

With the possibility of eliminating the vertical columns, thus the frame rectangular grid, which is the major source of shear racking and shear lag effects

Diagrid

… this is the moment of diagrid

… however the concept is not new : diagonal and triangulation is the oldest and most natural strategy for providing stability in the structural steelwork

Leadenhall Building

Hearst Tower

Swiss Re Building

Poly International Plaza

The Bow

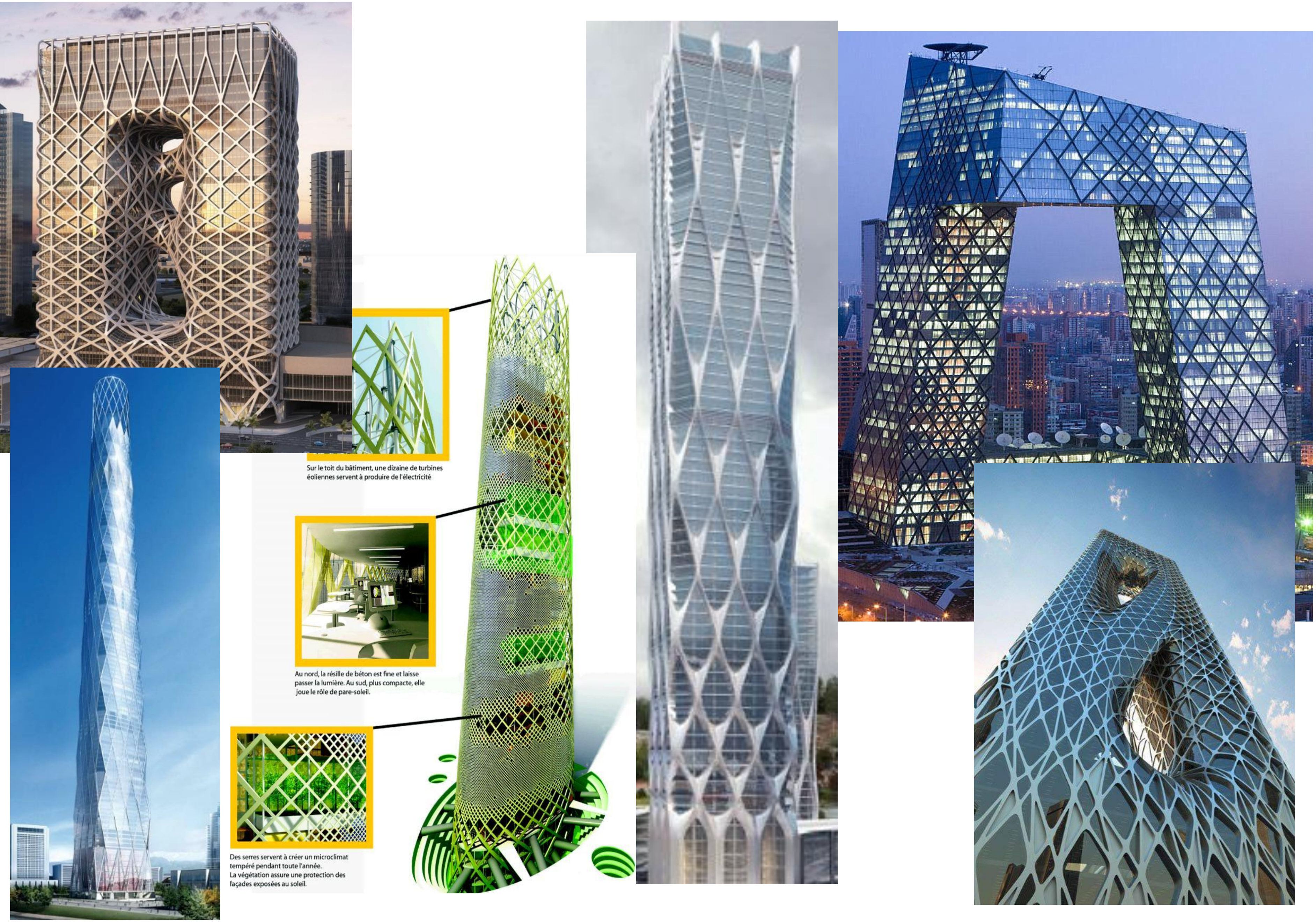
Guangzhou West Tower

Capital Gate

Guohua Financial Tower

what is strikingly new today in the latest years is a multiple and variegated use of triangle pattern, which brashly characterizes the aesthetics of important TBs, all diagrid, but each characterized, in an unique, different manner by triangulation

not only regular triangle tesselation



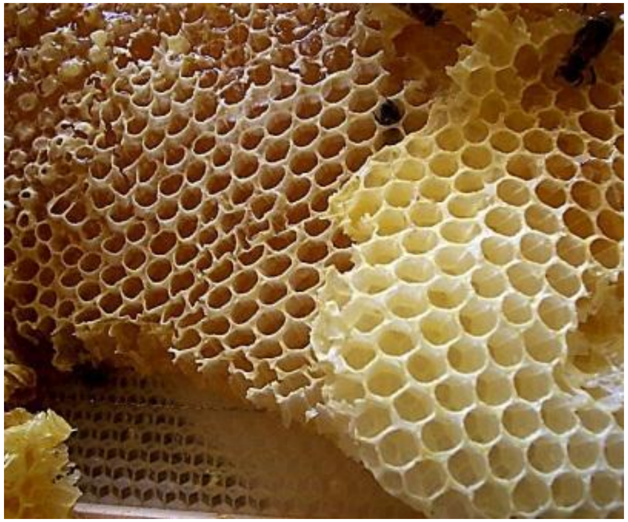
Sur le toit du bâtiment, une dizaine de turbines éoliennes servent à produire de l'électricité

Au nord, la résille de béton est fine et laisse passer la lumière. Au sud, plus compacte, elle joue le rôle de pare-soleil.

Des serres servent à créer un microclimat tempéré pendant toute l'année.
La végétation assure une protection des façades exposées au soleil.

generalization – bioinspired structural patterns

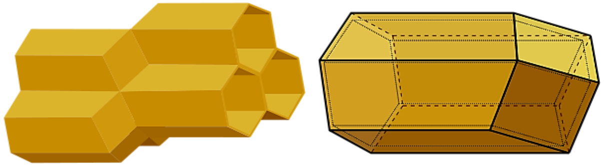
alternative geometrical patterns are worth of consideration for their structural efficiency and aesthetical qualities



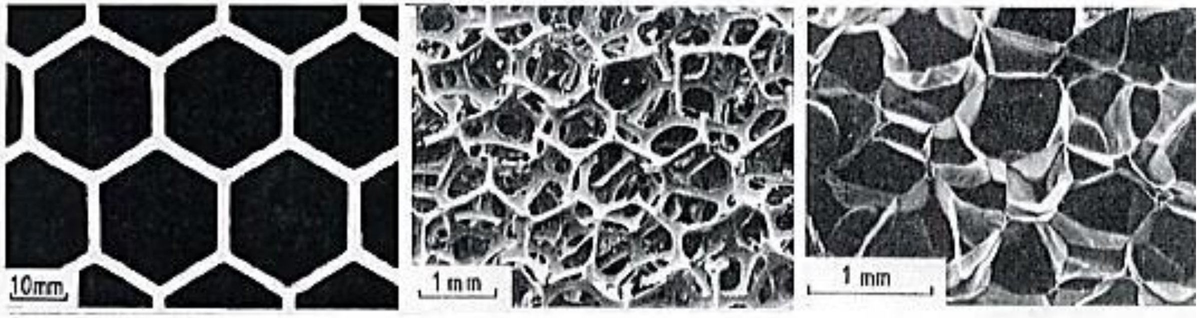
natural patterns, i.e. geometrical patterns observable in nature, can be a fruitful and almost endless source of inspirations for efficient man-made structures, at **all scale levels**

- from the very tiny - material design
- to the biggest – tall buildings

embracing all intermediate steps



cross-fertilization between science and engineering

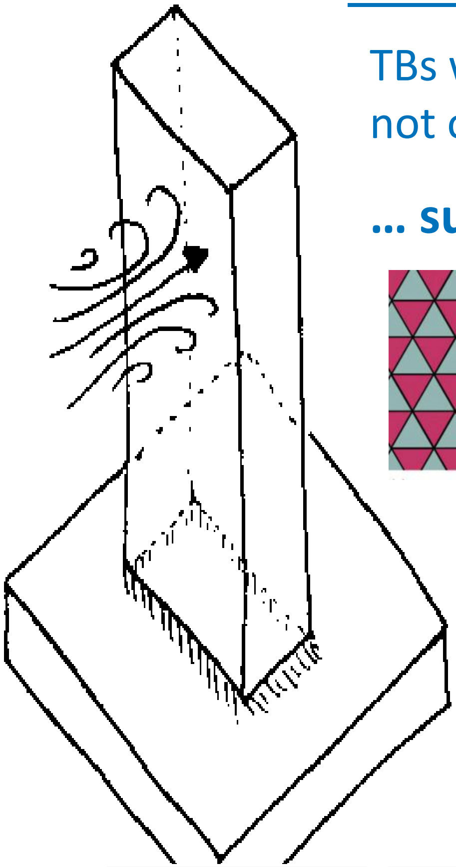


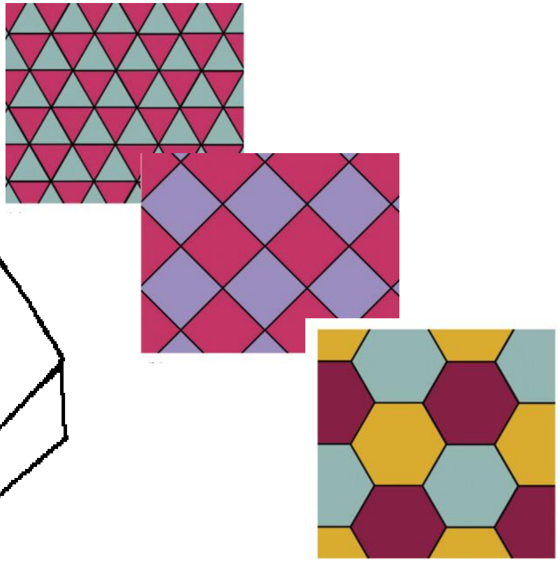
generalization – bioinspired structural patterns

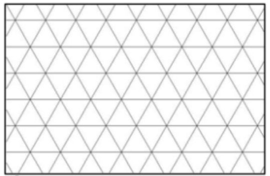
The Idea: The Structure as a Cantilever Beam

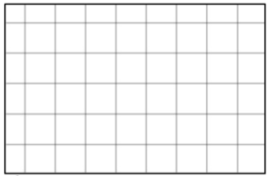
TBs with tube configuration can employ several different patterns:
not only triangle, not only the beam-column rectangular grid

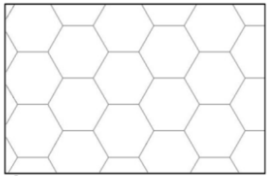
… suggestions come from the field of the geometry of tessellation

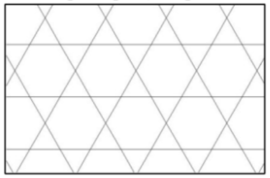


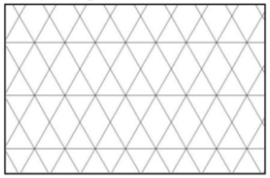


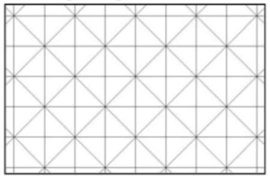

3^6 Triangular grid / Isogrid

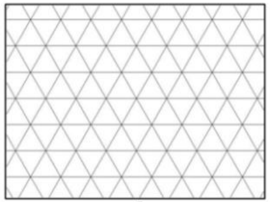

4^4 Square grid

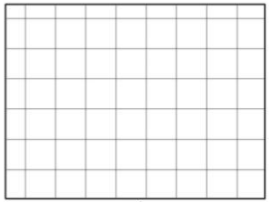

6^3 Hexagonal grid

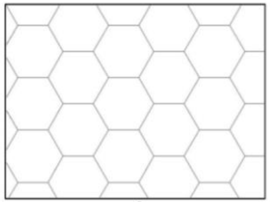

3.6.3.6. Trihexagonal / Kagome

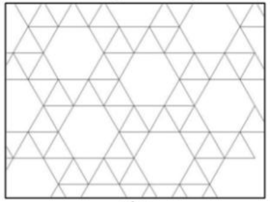

Diamond grid

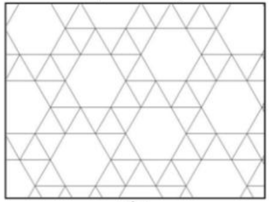

Mixed triangle grid

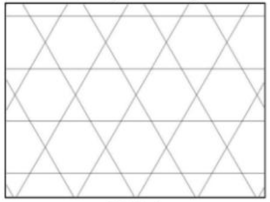

3^6
Triangular tiling

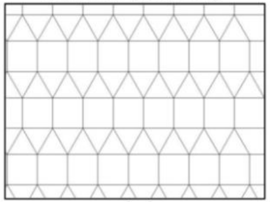

4^4
Square tiling

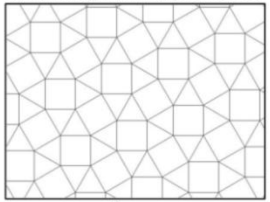

6^3
Hexagonal tiling

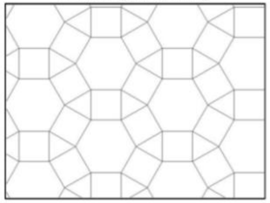

$3^4.6$
Snub hexagonal tiling

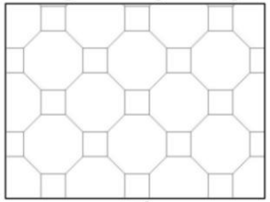

$3^4.6$
Snub hexagonal tiling reflection

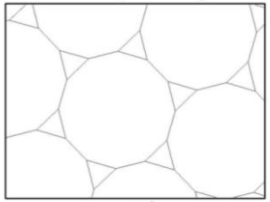

3.6.3.6
Trihexagonal tiling

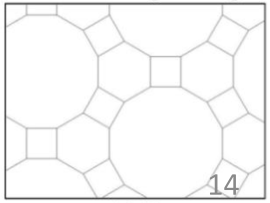

$3^3.4^2$
Elongated triangular tiling


$3^2.4.3.4$
Snub square tiling


3.4.6.4
Rhombitrihexagonal tiling

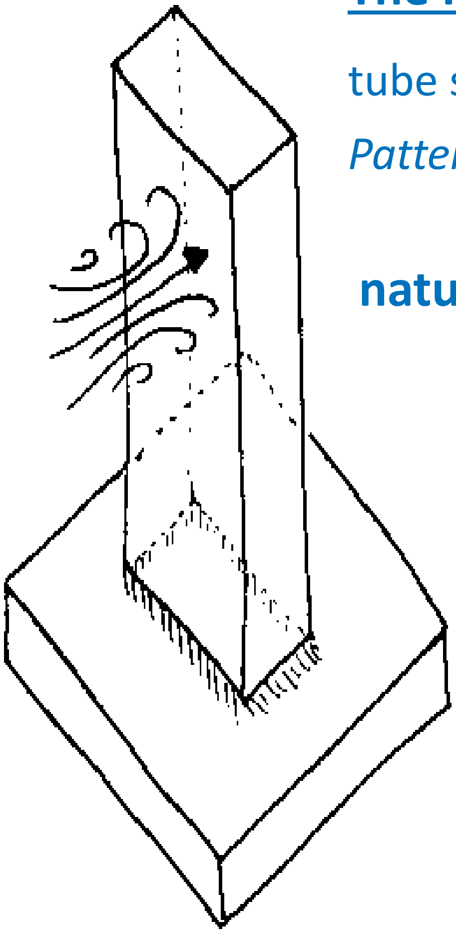

4.8^2
Truncated square tiling


3.12^2
Truncated hexagonal tiling


4.6.12
Truncated trihexagonal tiling

generalization – bioinspired structural patterns

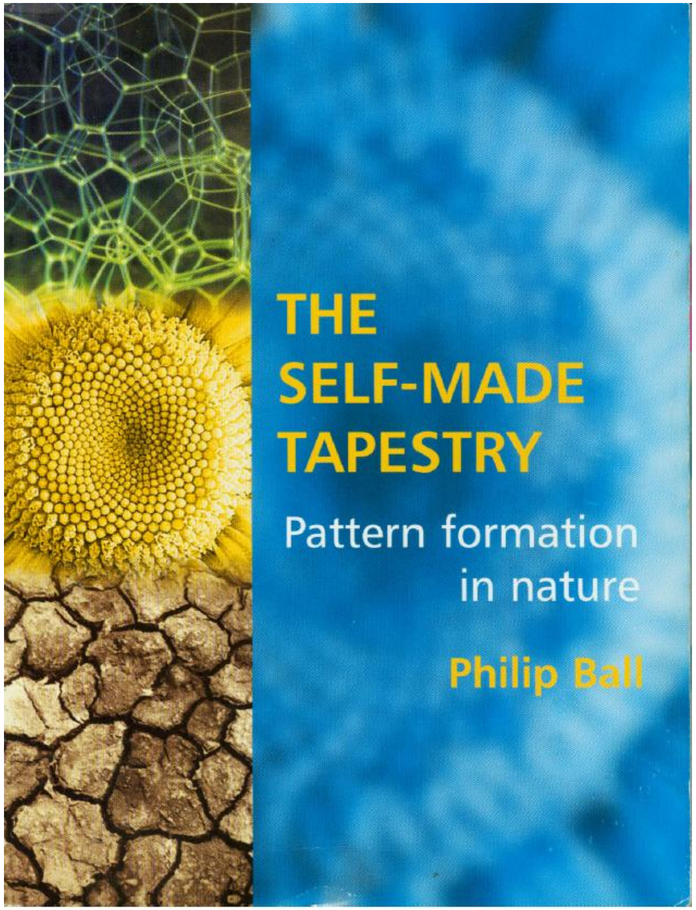
The Idea: The Structure as a Cantilever Beam



tube structural pattern: not only triangle

Patterns offer structure to the realm of ideas

natural vocabulary of patterns

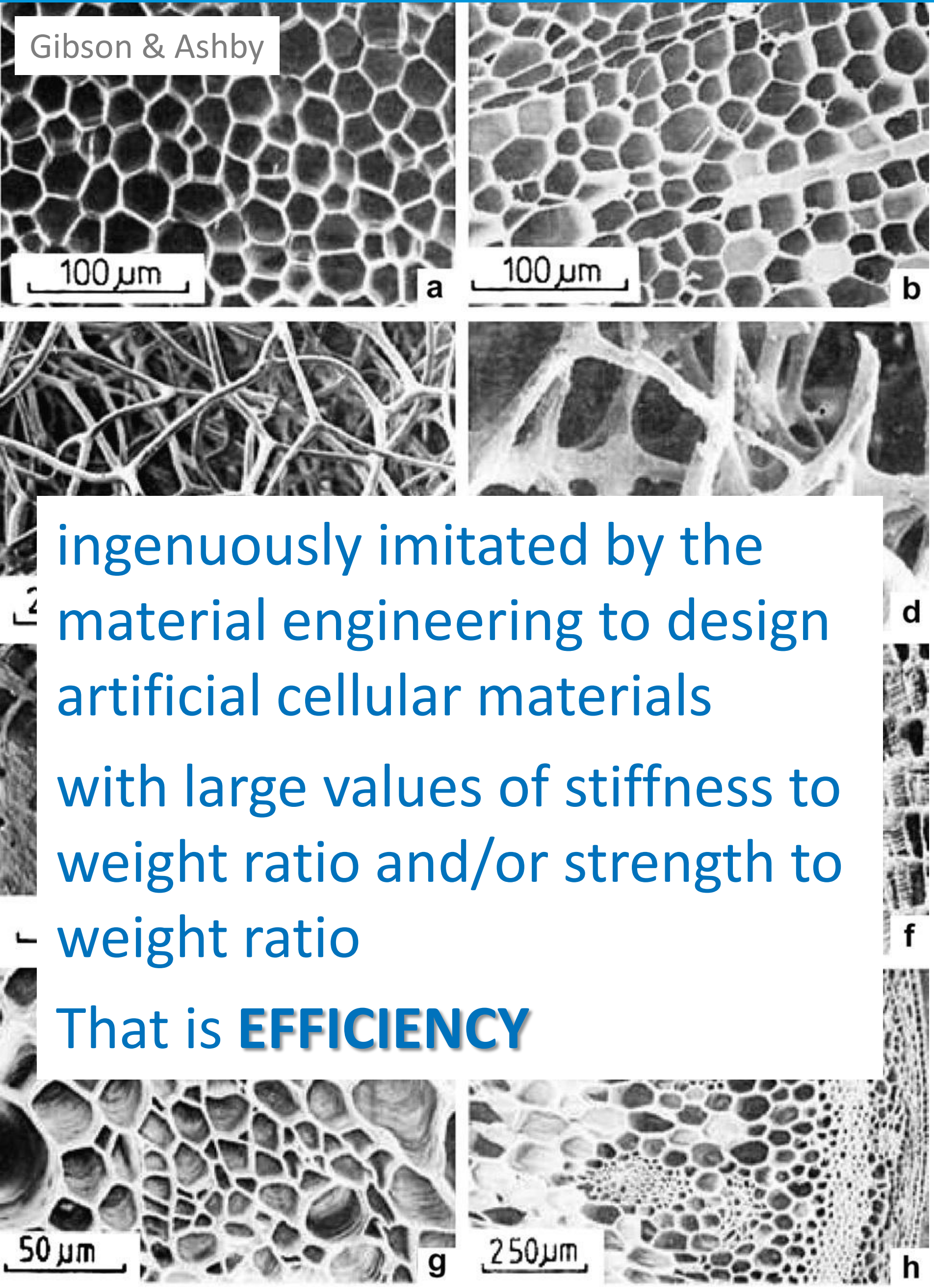


THE
SELF-MADE
TAPESTRY

Pattern formation
in nature

Philip Ball

generalization – bioinspired structural patterns



Gibson & Ashby

ingenuously imitated by the material engineering to design artificial cellular materials

with large values of stiffness to weight ratio and/or strength to weight ratio

That is **EFFICIENCY**

examples of cellular materials

a – cork　b – balsa　c – sponge
d – cancellous bone　e – coral
f – cuttlefish bone　g – iris leaf
h – stalk of plant

… when modern man builds large load-bearing structure, he uses dense solids; steel, concrete, glass.
When nature does the same, she generally uses cellular materials; wood, bone, coral.
There must be good reason for it

M.F.Ashby

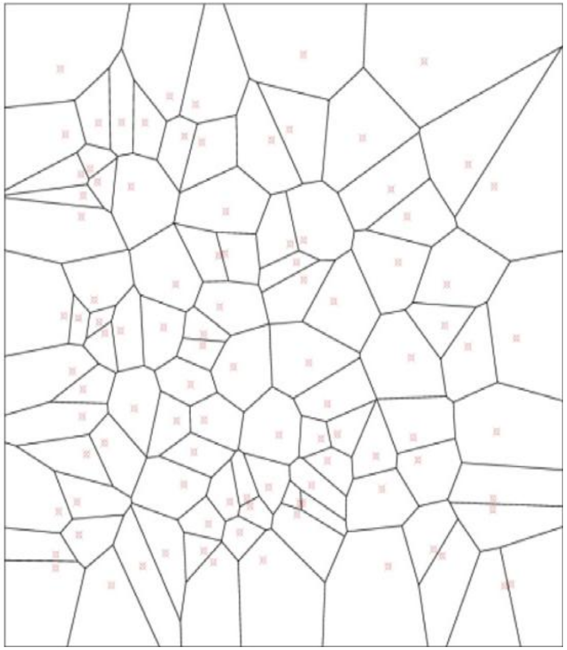
… the art of structure is how and where putting holes, building with holes, with things with no weight

R. Le Ricolais

generalization – bioinspired structural patterns

Most of these natural patters can be and actually are modelled by means of Voronoi diagrams

… voronoi patterns in nature



the partitioning of a plane into convex polygons, starting from a number n of points, or seeds, such that each polygon contains exactly one generating point and every point in a given polygon is closer to its generating point than to any other

generalization – bioinspired structural patterns

… today,
the fascination for organic forms and natural patterns can be often observed in the field of TBs, with

proposals, projects, visions

(all, more or less explicitly, utilizing hexagonal patterns)

coming from the world of architecture

On the contrary engineers, the structural engineers, are less prone to explore the potentials of these non conventional patterns as structural grid

generalization – bioinspired structural patterns

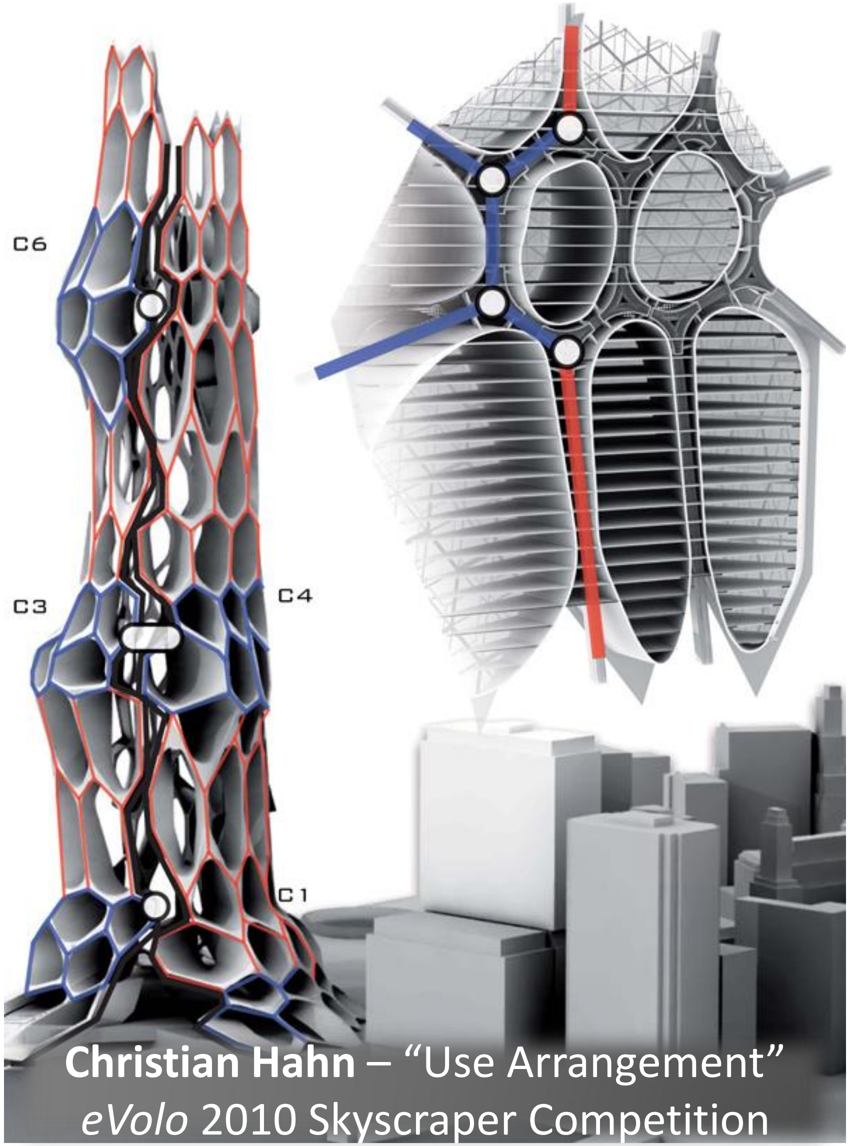
… hexagonal patterns in buildings

NanoTowers, Dubai
Jansen et al. + Arup

SinoSteel Tower
Tianjin China
MAD+ECADI

generalization – bioinspired structural patterns

… voronoi patterns in buildings



Christian Hahn – “Use Arrangement”
eVolo 2010 Skyscraper Competition

SOM

LAVA
Bionic Tower

generalization – bioinspired structural patterns

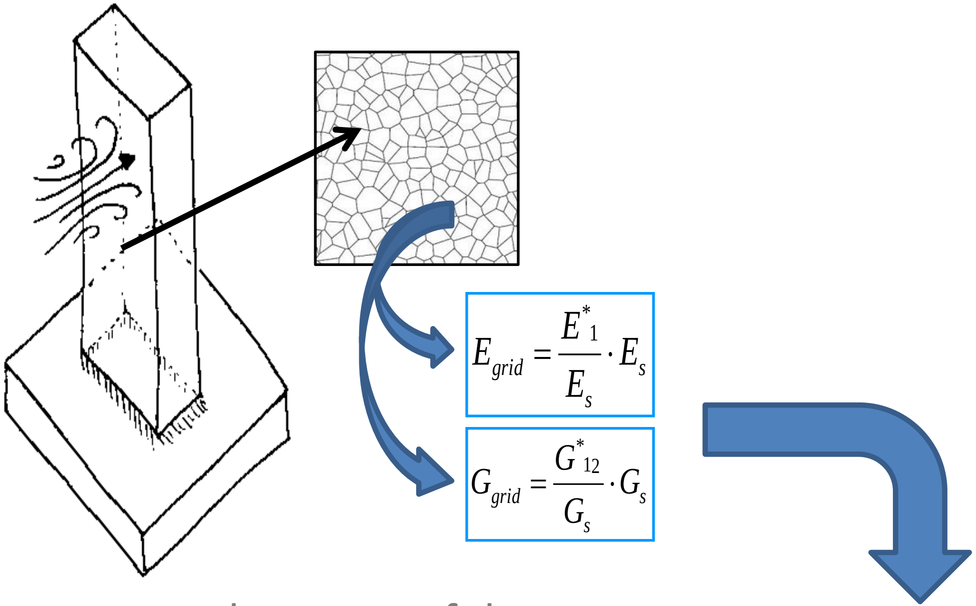
design, modeling and analysis of non-conventional structural patterns: nor as familiar as in the case of the orthogonal pattern (beam-column frame) neither as straightforward as in the case of the triangular pattern (diagrid)

Challenging task for the research in structural engineering:
define a **homogenization approach for dealing with any structural pattern**

idealize the pattern as a continuous depleted medium characterized by penalized mechanical properties ⟺ **material engineering cellular materials**

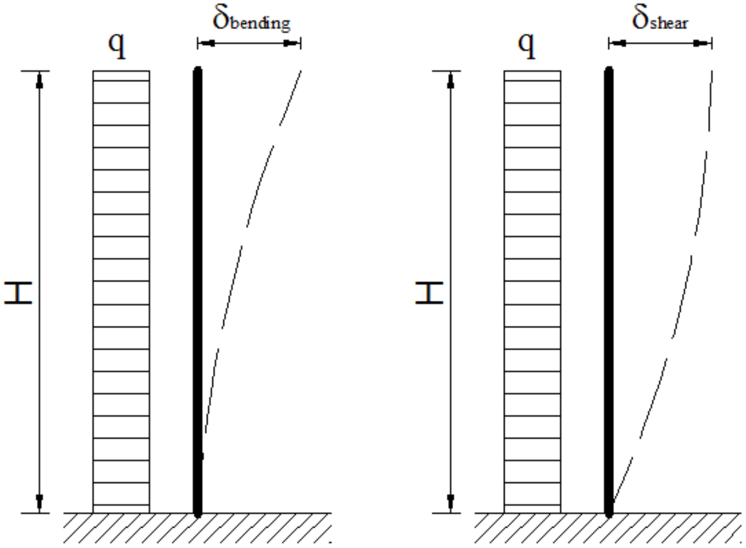
generalization – bioinspired structural patterns

A tall building with TUBE configuration, with ANY structural pattern, can be designed still adopting the the very simplified cantilever beam model (with box cross section), still according to a simple global stiffness design criterion, provided that :



$$E_{grid} = \frac{E^*_1}{E_s} \cdot E_s$$

$$G_{grid} = \frac{G^*_{12}}{G_s} \cdot G_s$$



the structural pattern of the tube has been preliminarily characterized from the mechanical point of view, and equivalent, effective, homogenized mechanical properties have been defined

$$\boxed{\delta_{tot} = \delta_{bending} + \delta_{shear} = \frac{q \cdot H^4}{8 \cdot (EI)_{grid}} + \frac{q \cdot H^2}{2 \cdot (GA)_{grid}} \cdot \chi < \frac{H}{500}}$$

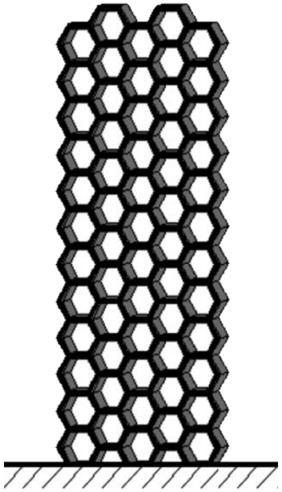
In the simple formula expressing the top drift, given by the flexural and racking contributions, the effective properties of the grid are considered

generalization – bioinspired structural patterns

mechanical characterization of ANY structural pattern: defining E_{grid} and G_{grid}

material enginering cellular materials

Representative Volume Element (RVE), i.e. the smallest homogeneous material volume which macroscopic constitutive relationships must be referred to



regular patterns

eg. Hexagrid, diagrid, orthogonal frames ….

RVE is the structural model of the basic geometric unit of the grid (unit cell)

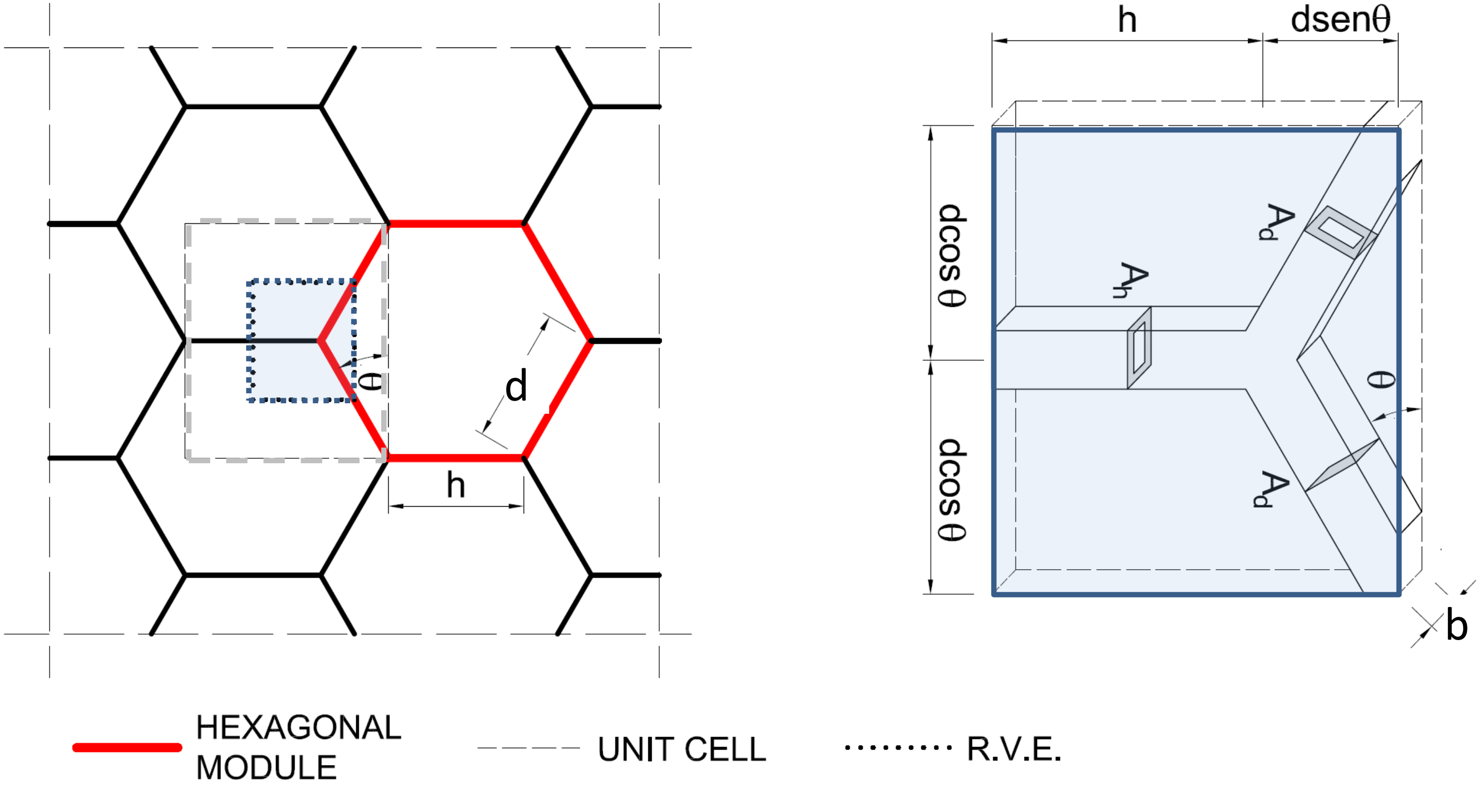
RVE can be established by looking at deformation modes and resisting mechanisms of the basic geometric unit (unit cell)

non regular, non periodic patterns

eg. Voronoi grid

RVE should be established on a statistical base, after having identified the governing geometric parameters of the grid

HEXAGRID structural assemblage of horizontal and diagonal members → hexagonal frames



Can be recognized:

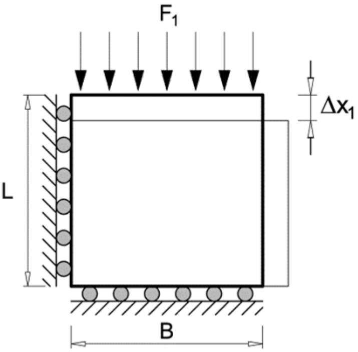
a hexagonal module (like the triangle module in diagrid)

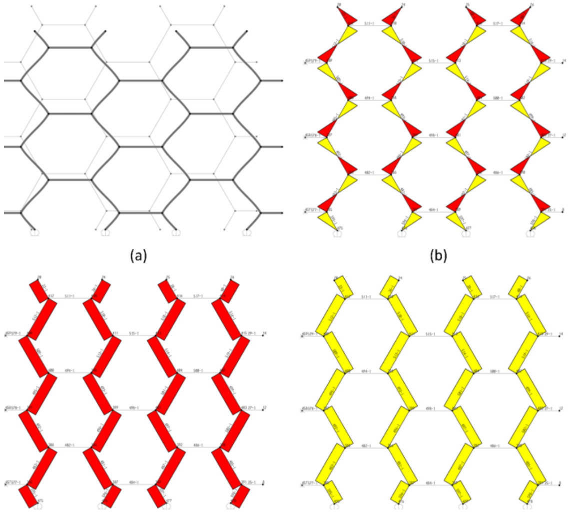
an unit cell, which is the basic geometric unit, that replicated, can completely tessellate the plane, without voids and overlaps

and a RVE, which is the structural model of the unit cell

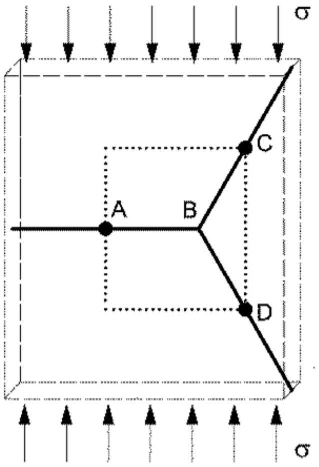
axial test

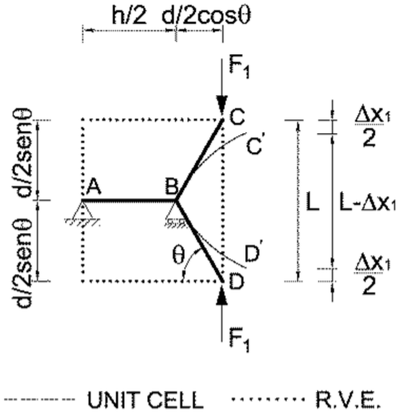
$$E^*_1 = \frac{\sigma}{\varepsilon} = \frac{\dfrac{F_1}{B\cdot b}}{\dfrac{\Delta x_1}{L}}$$




(a)

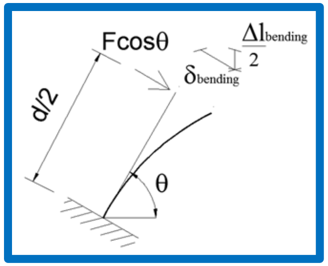
(b)

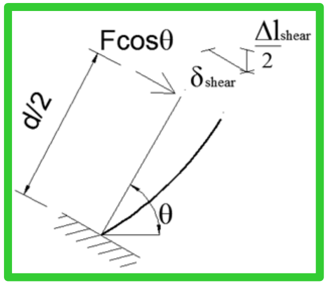


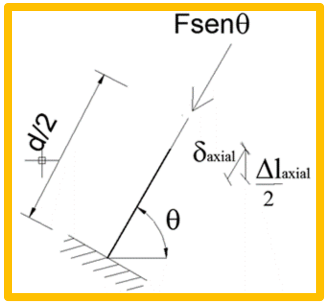


$$\sigma = \frac{F}{A} = \frac{F}{(h + d\cos\theta)\cdot b}$$

$$\varepsilon = \frac{\Delta l}{l} = \frac{\Delta l_{bending} + \Delta l_{shear} + \Delta l_{axial}}{dsen\theta}$$







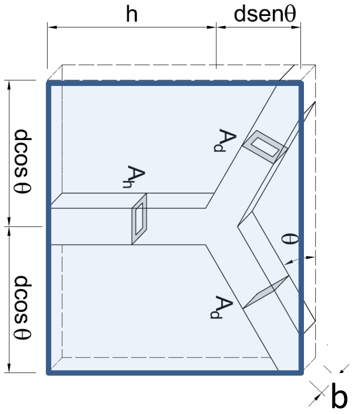
$$\boxed{E^*_1 = \frac{\sigma}{\varepsilon}}$$

mechanical characterization of HEXAGRID structural pattern

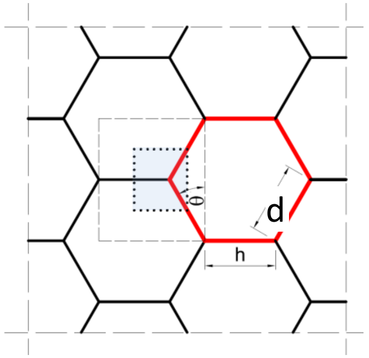
$$\boxed{E^*_1 = \frac{\sigma}{\varepsilon}}$$

effective axial stiffness

$$\frac{E^*_1}{E_s} = \frac{12 I_d \, sen\theta A_d}{(h + d\cos\theta) b \left[\cos^2\theta \left(d^2 A_d + 24 I_d \chi (1+\nu)\right) + 12 sen^2\theta I_d\right]}$$



(local) geometrical properties of the member cross sections

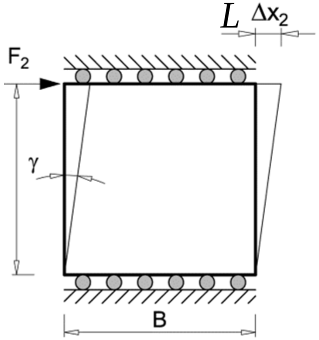


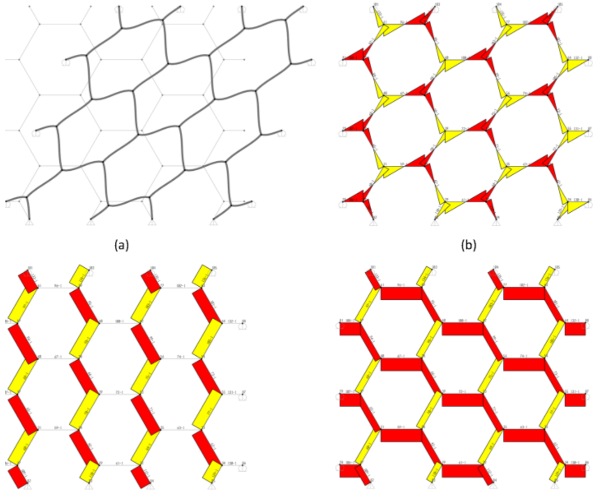
(global) geometrical properties of the grid

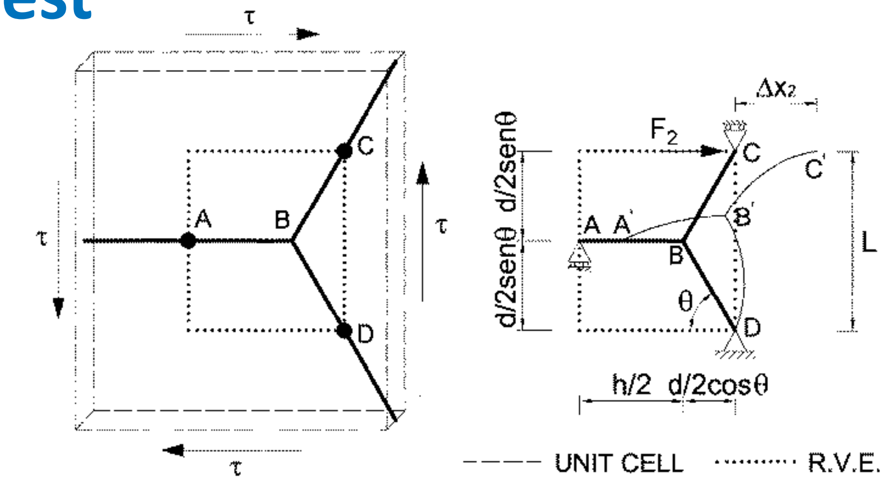
mechanical characterization of HEXAGRID structural pattern

shear test

$$G^*_{12} = \frac{\tau}{\gamma} = \frac{\dfrac{F_2}{B\cdot b}}{\dfrac{\Delta x_2}{L}}$$







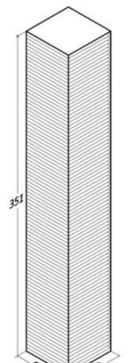
effective shear modulus

$$\frac{G^*_{12}}{G_s} = \frac{24\cdot\boxed{A_d}\cdot\boxed{A_h}\cdot\boxed{I_d}\cdot\boxed{I_h}(1+\nu)\boxed{(h}+\boxed{d}\cos\boxed{\theta)}sen\boxed{\theta}}{\left[\begin{array}{l}12\cdot\boxed{A_h}\cdot\boxed{I_d}\cdot\boxed{I_h}\cdot b\cdot\cos\boxed{\theta(}2\cdot\boxed{d}\cdot\boxed{h}+\boxed{(d^2}+\boxed{h^2})\cos\boxed{\theta)}\\+b\cdot sen^2\boxed{\theta(}(12\cdot\boxed{A_h}\cdot\boxed{I_d}\cdot\boxed{I_h}\cdot\chi_d(\boxed{d^2}+2\cdot\boxed{h^2}(1+\nu)))\\+(\boxed{A_d}\cdot\boxed{d}\cdot\boxed{h}\cdot(\boxed{A_h}\cdot\boxed{h}\cdot(2\cdot\boxed{h}\cdot\boxed{I_d}+\boxed{d}\cdot\boxed{I_h})+48\cdot\boxed{I_d}\cdot\boxed{I_h}\cdot\chi_h(1+\nu))))\end{array}\right]}$$

(local) geometrical properties of the member cross sections

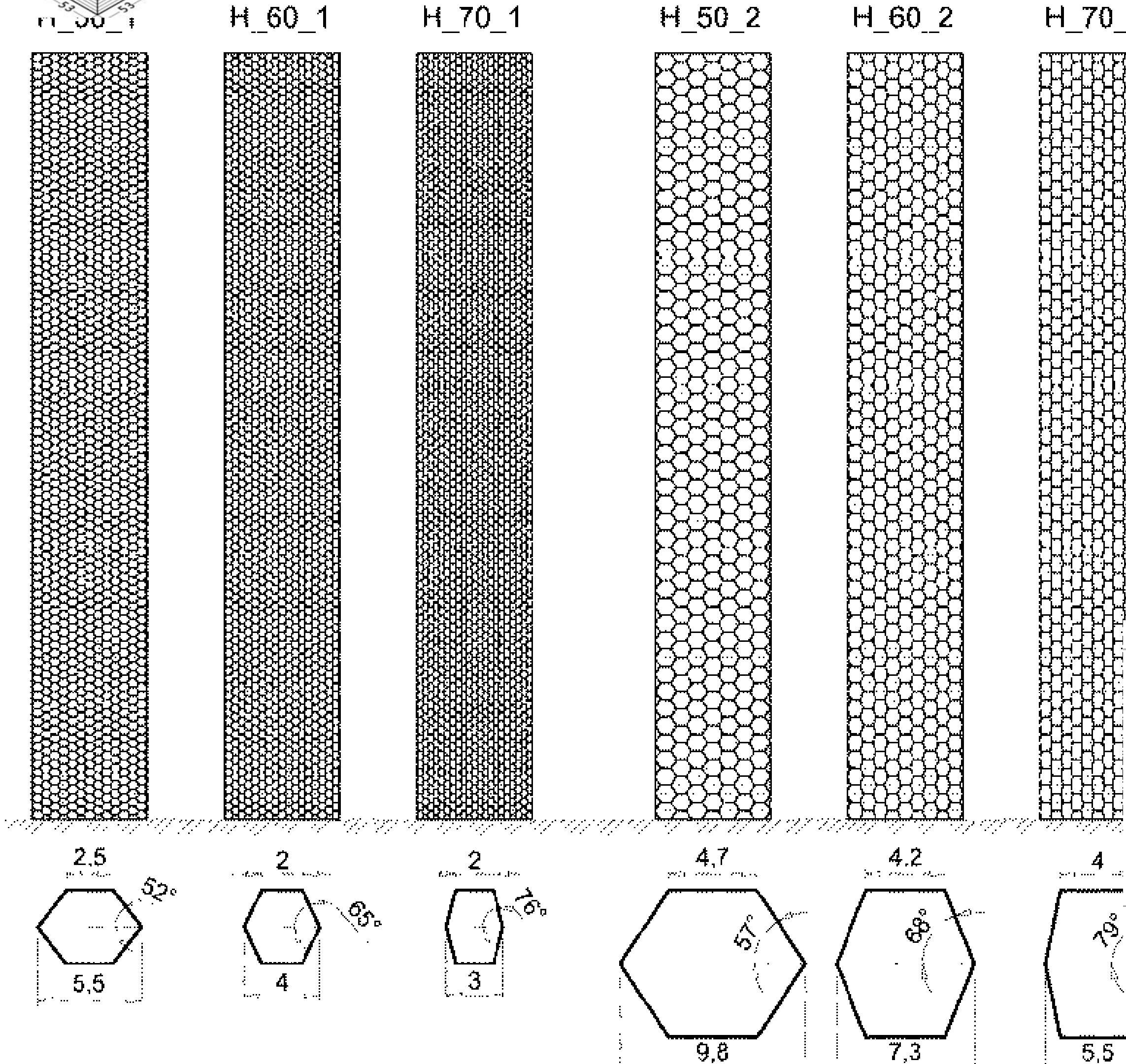
(global) geometrical properties of the grid

preliminary member sizing – hexagrid tall building



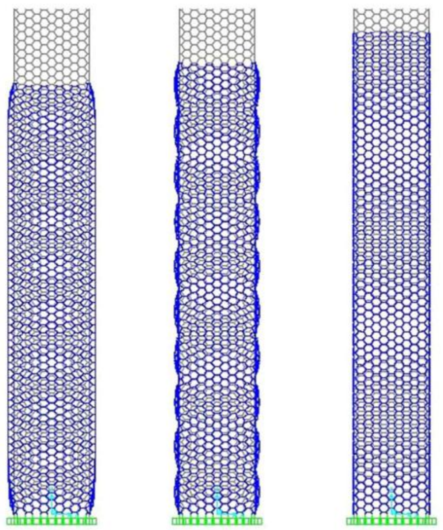
building model

$$\delta_{tot} = \delta_{bending} + \delta_{shear} = \frac{q \cdot H^4}{8 \cdot (EI)_{grid}} + \frac{q \cdot H^2}{2 \cdot (GA)_{grid}} \cdot \chi < \frac{H}{500}$$

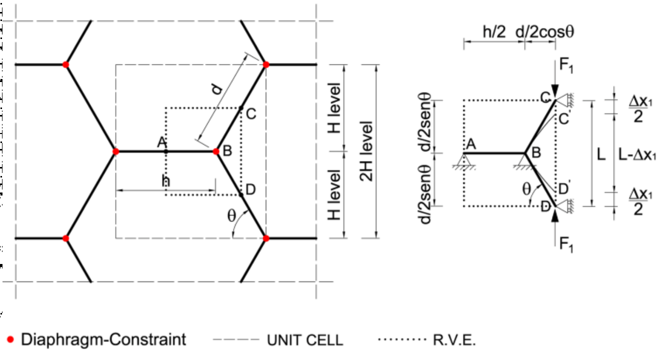


stiffening effect of floor rigid diaphragm on vertical def. mode

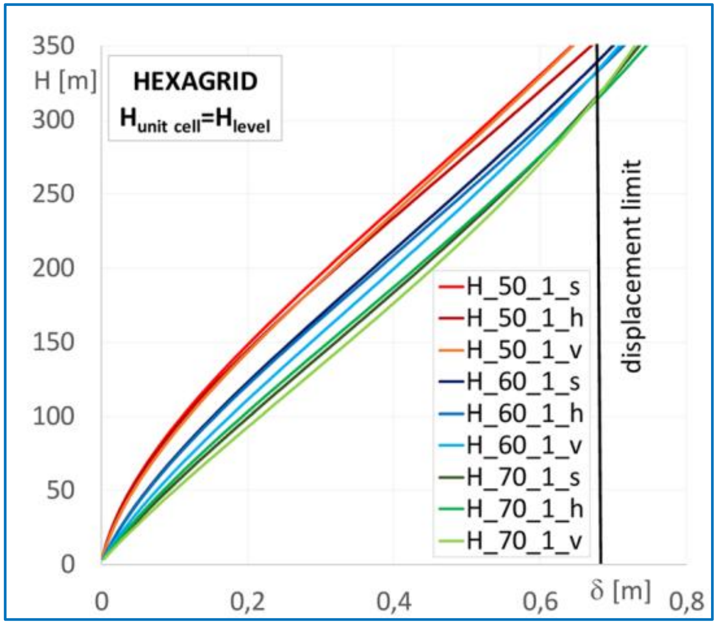
no RD **10 RD** **90 RD**



changing the RVE

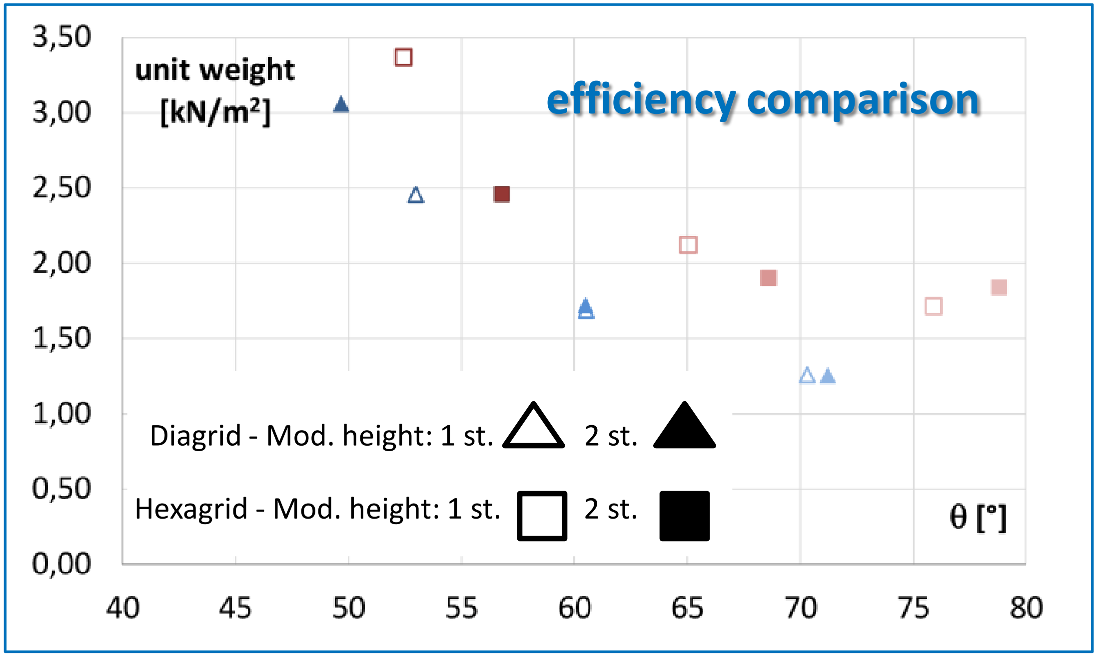


preliminary member sizing – hexagrid tall building



FE analysis of the hexagrid solutions obtained with the design procedure → confirm the expected structural performance (top drift close to H/500)

- hexagrids, being bending-dominated structures, are inherently less stiff, thus less weight efficient, than diagrids, that are stretch-dominated structures
- the rigid diaphragm effect provides a considerable increase of the stiffness of the hexagrid, making it comparable to the diagrid

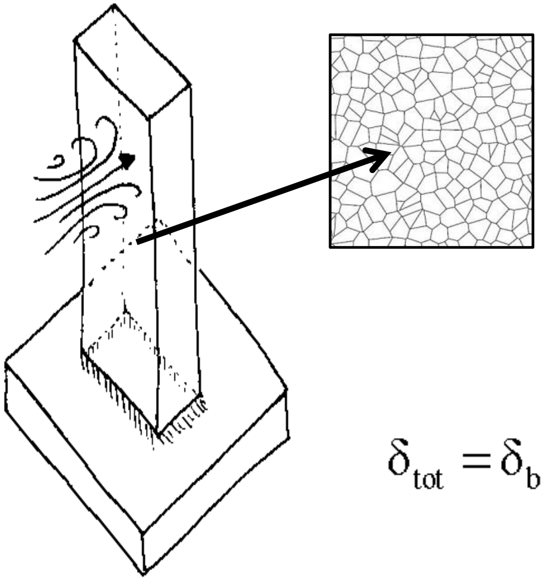


design procedure suitable for quick evaluations during the preliminary design stage

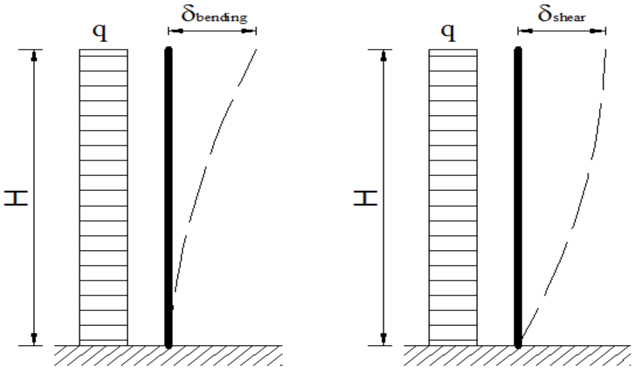
can provide a deep understanding of the effects of varying geometrical and mechanical parameters on the overall structural behavior

voronoi

In the case of Voronoi grid, the idea is basically the same, with only an additional step and a slightly greater complexity



… still the cantilever beam model with box cross section ….



$$\delta_{tot} = \delta_{bending} + \delta_{shear} = \frac{q\,H^4}{8 \cdot E^*_{1,H}\,\eta_{E1,A}\,I} + \frac{q\,H^2}{2\,G^*_{12,H}\,\eta_{G12,A}\,A}\chi = \frac{H}{500}$$

hexagrid

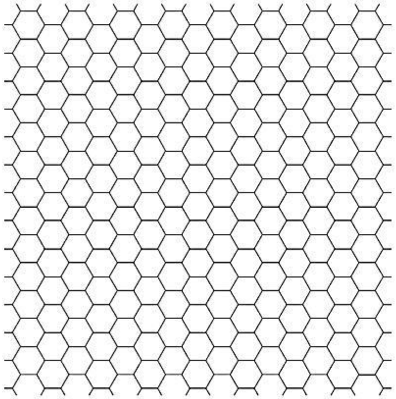
correction factors

→ use the effective properties of the regular hexagrid, multiplied by **correction factors**, able to account for the irregularity of the Voronoi pattern

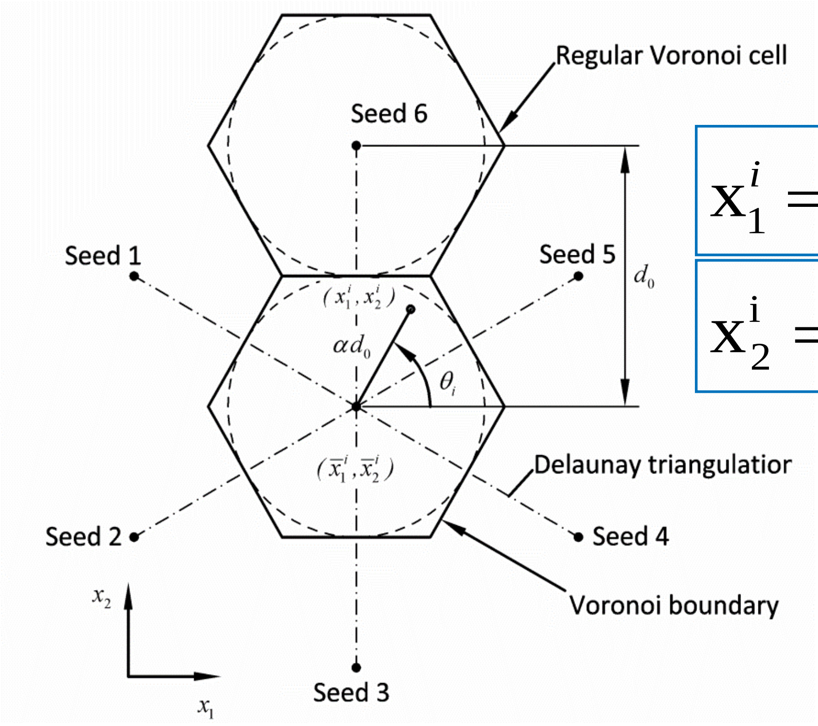
In order to establish these correction factors, the first step is to construct a Voronoi grid starting from a regular hexagrid

construction of Voronoi diagram

1. apply Voronoi tassellation to a regular array of points



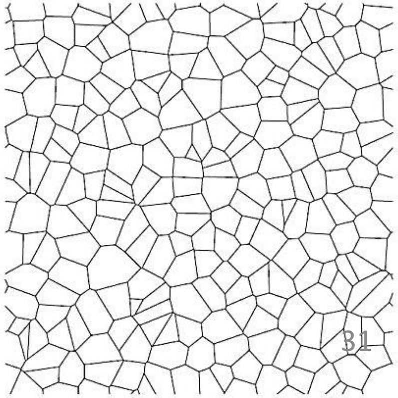
2. alter the coordinates of the seeds



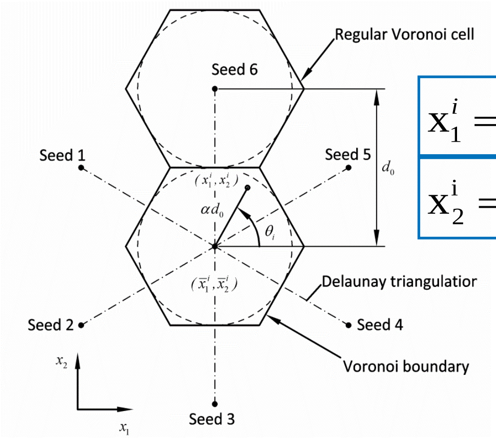
$$x_1^i = \bar{x}_1^i + \alpha\left(d_0 \operatorname{Cos} \vartheta_i\right) \cdot \varphi_i$$

$$x_2^i = \bar{x}_2^i + \alpha\left(d_0 \operatorname{Cos} \vartheta_i\right) \cdot \varphi_i$$

3. generate the irregular Voronoi pattern



construction of Voronoi diagram



$$x_1^i = \bar{x}_1^i + \alpha\left(d_0 \, \mathrm{Cos}\,\vartheta_i\right)\cdot\varphi_i$$

$$x_2^i = \bar{x}_2^i + \alpha\left(d_0 \, \mathrm{Cos}\,\vartheta_i\right)\cdot\varphi_i$$

ϑ : random angle between x_1 the line connecting the perturbed and non perturbed position of the seed s

uniform distribution PDF

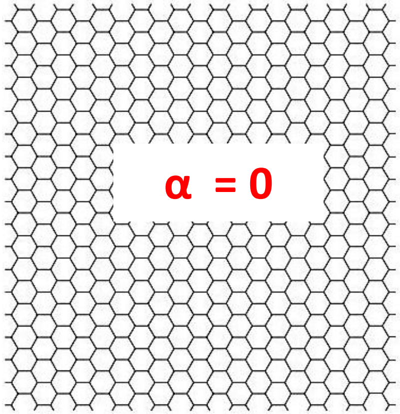
$$P_\vartheta(\vartheta_i) = \begin{cases} 1/2\pi & 0 \le \vartheta_i \le 1 \\ 0 & \vartheta_i < -1, \vartheta_i > 1 \end{cases}$$

φ : random scale factor

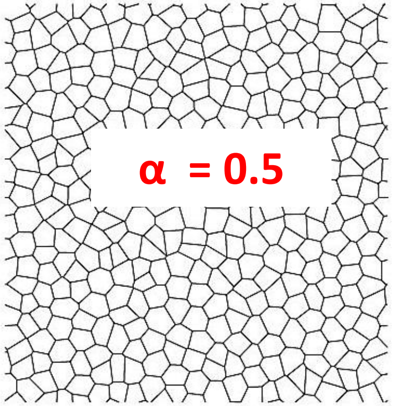
uniform distribution PDF

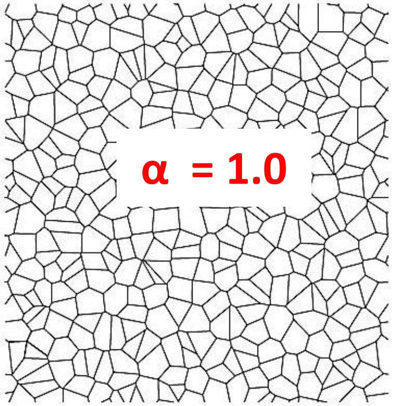
$$P_\varphi(\varphi_i) = \begin{cases} 1/2 & -1 \le \varphi_i \le 1 \\ 0 & \varphi_i < -1, \varphi_i > 1 \end{cases}$$

α [0,1] defines the irregularity degree of the Voronoi grid



Regular geometry





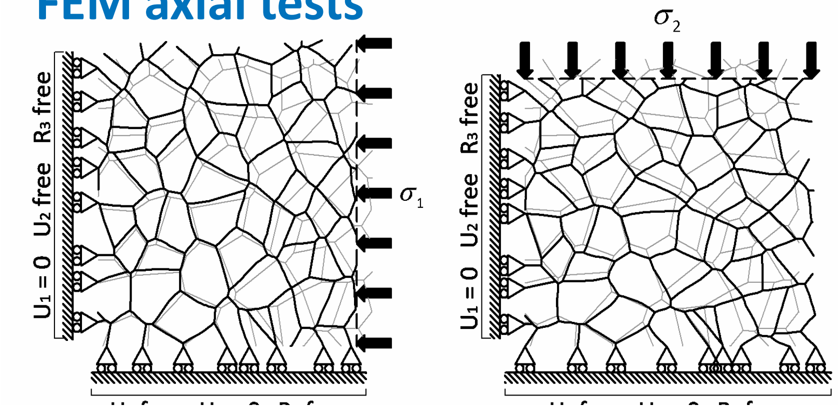
Maximum Irregularity

α is the major parameter that characterizes the irregular grid geometry →the correction factors

for each values of α (i.e. for each level of irregularity), infinite geometric configurations (Voronoi diagrams) can be generated varying the two random parameters

mechanical characterization of Voronoi pattern

FEM axial tests

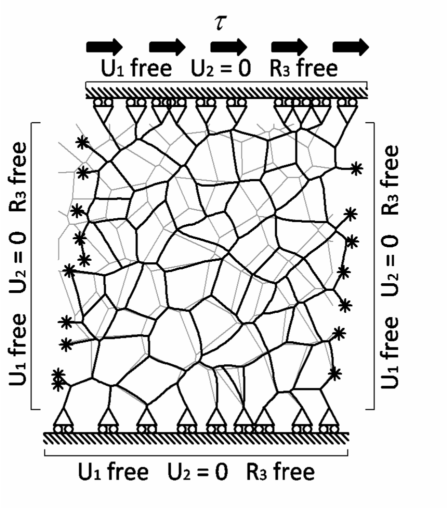


$$E^*_1 = \frac{\sigma}{\varepsilon} = \frac{\dfrac{F_1}{B \cdot b}}{\dfrac{\Delta x_1}{L}}$$

Voronoi (FEM results)

$$\eta_{E1,\,i} = \frac{E^*_{1,V,\,i}}{E^*_{1,H}}$$

hexagrid



FEM shear test

$$G^*_{12} = \frac{\tau}{\gamma} = \frac{\dfrac{F_2}{B \cdot b}}{\dfrac{\Delta x_2}{L}}$$

Voronoi (FEM results)

$$\eta_{G12,\,i} = \frac{G^*_{12,V,\,i}}{G^*_{12,H}}$$

hexagrid

Given the random nature of the parameters θ and ϕ, the mechanical characterization of the pattern and the derivation of the correction factors should be obtained through statistical analysis of the FE results obtained on an appropriate number of specimens, generated for the same α, varying θ and ϕ

mechanical characterization of Voronoi pattern

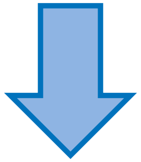
statistical approach

sensitivity analysis

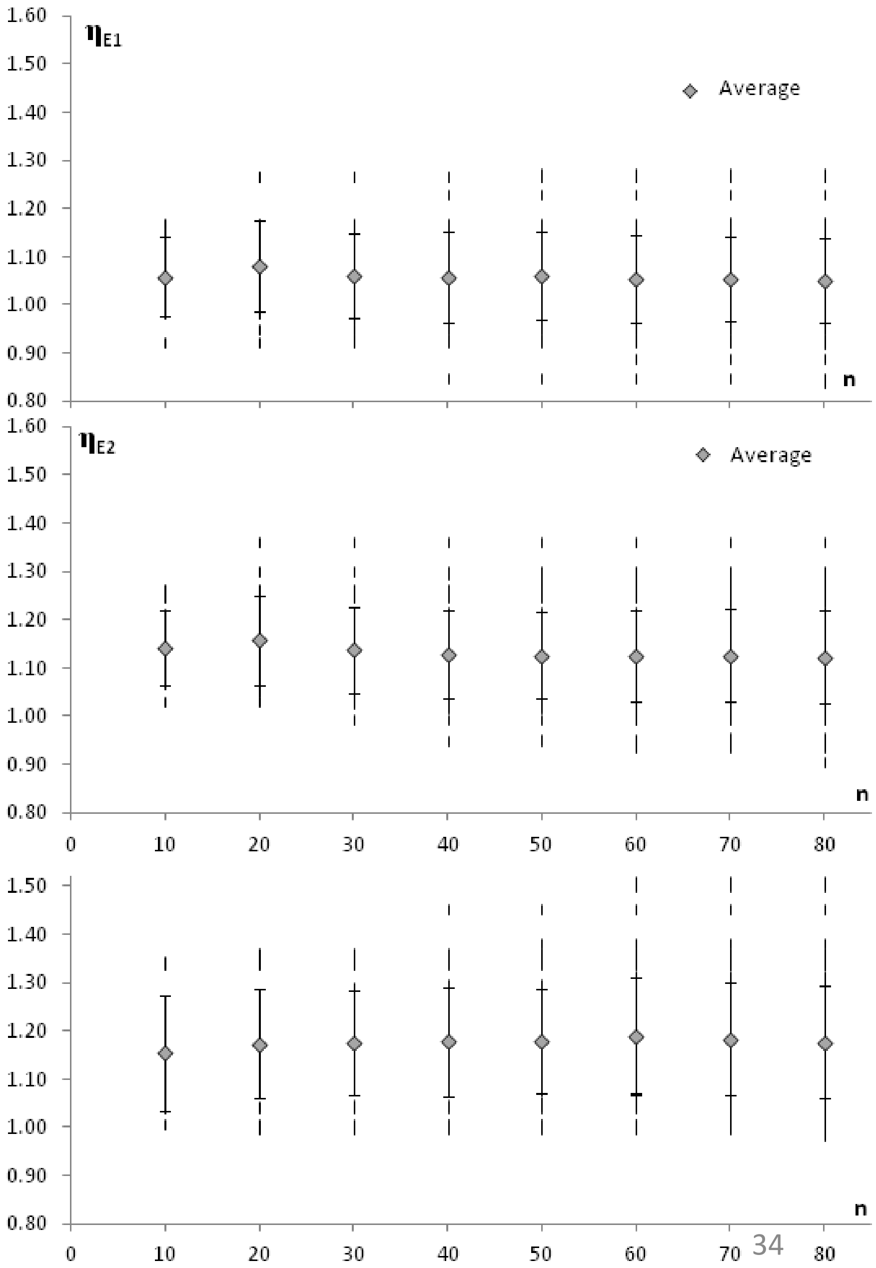
→ average and standard deviation of

$$\eta_{E1,\,i} = \frac{E^*_{1,V,\,i}}{E^*_{1,H}};\ \ \eta_{E2,\,i} = \frac{E^*_{2,V,\,i}}{E^*_{2,H}};\ \ \eta_{G12,\,i} = \frac{G^*_{12,V,\,i}}{G^*_{12,H}}$$

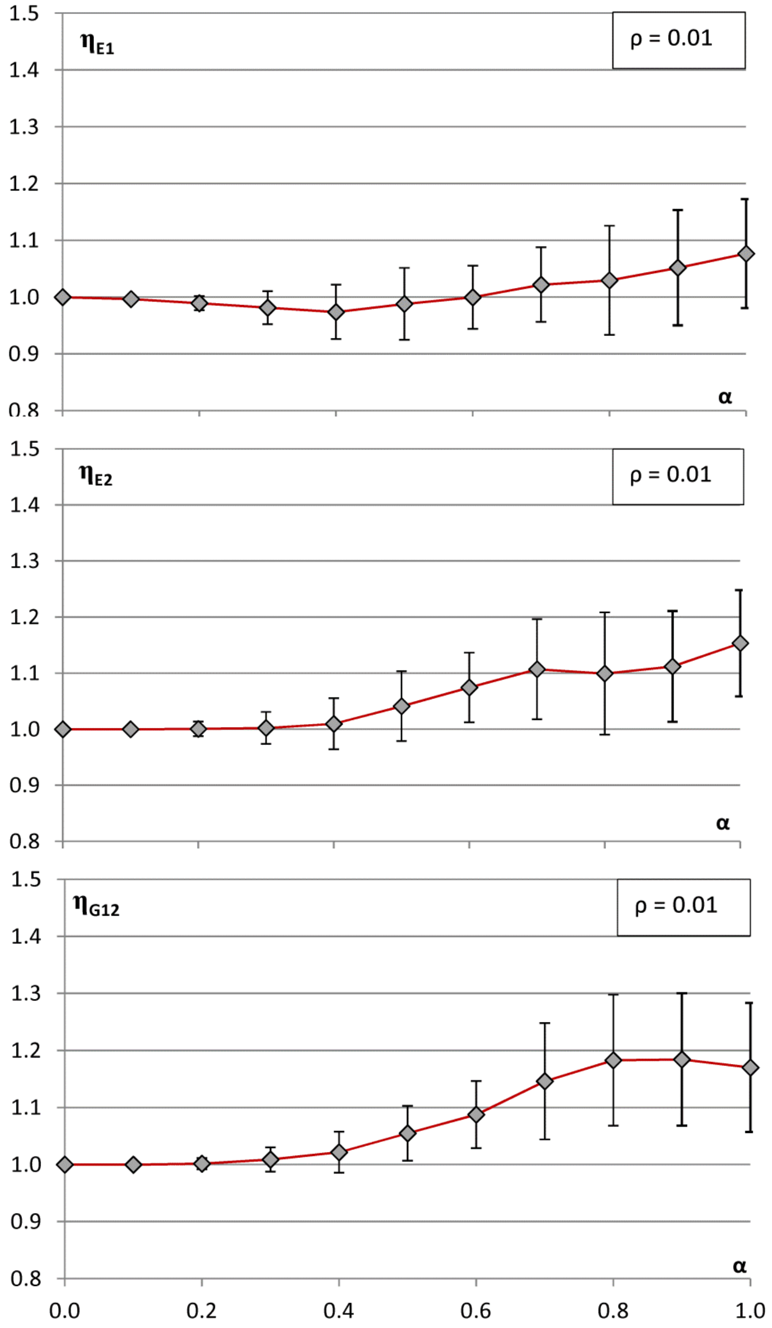
varying the no. of specimens



20 specimens for each irregularity levels (each values of α)



mechanical characterization of Voronoi pattern



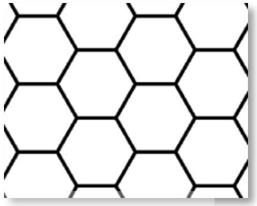
Therefore, for each degree of irregularity, in the range 0.0 – 1.0, 20 specimens have been generated and tested

In this way the average values of the correction factors have been obtained as a function of α

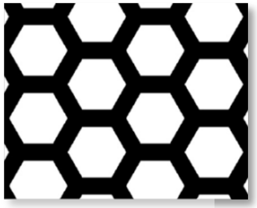
mechanical characterization of Voronoi pattern

Another important design parameter for the grid is the relative density ρ, defined as the solid volumetric fraction

$$\rho = \frac{\rho^{*}}{\rho_{vol}} = \frac{\sum_{i=1}^{n} l_i \cdot A_{.i}}{L_1 \cdot L_2 \cdot b}$$

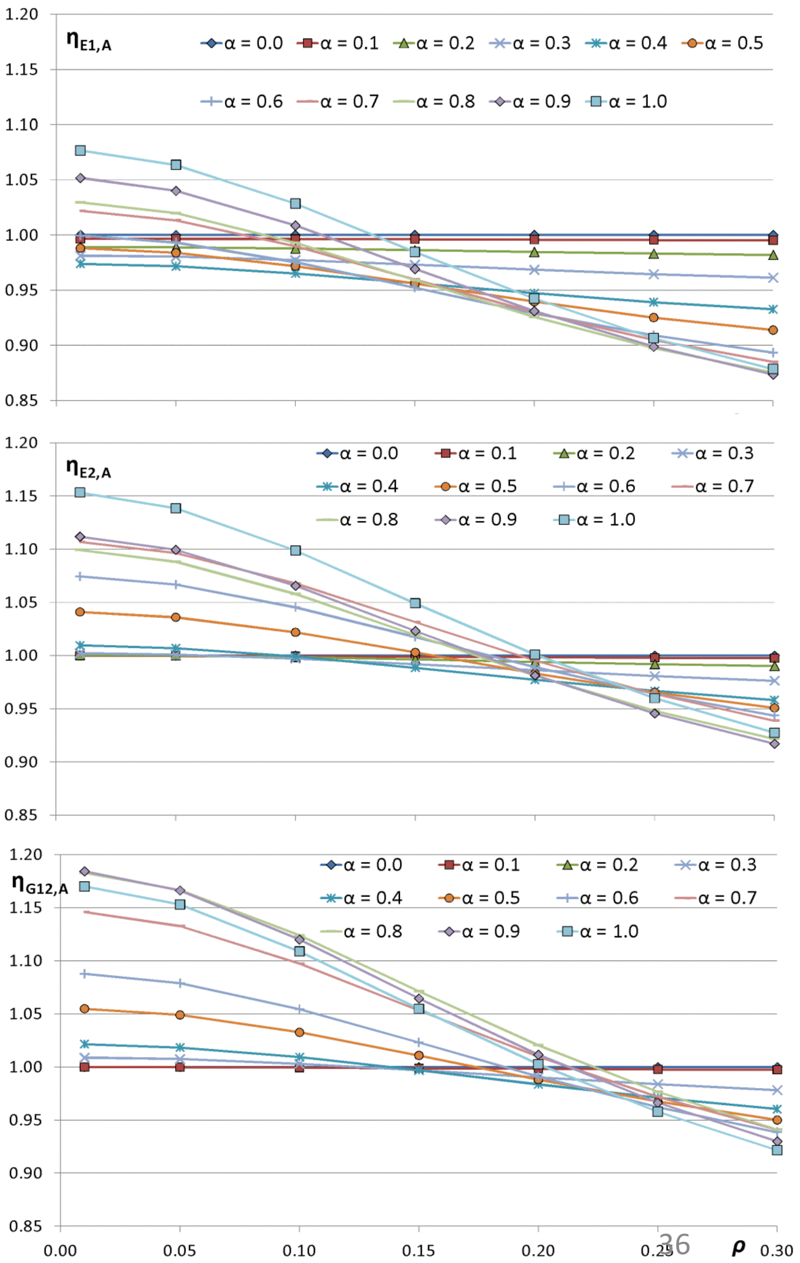


ρ = 0.05



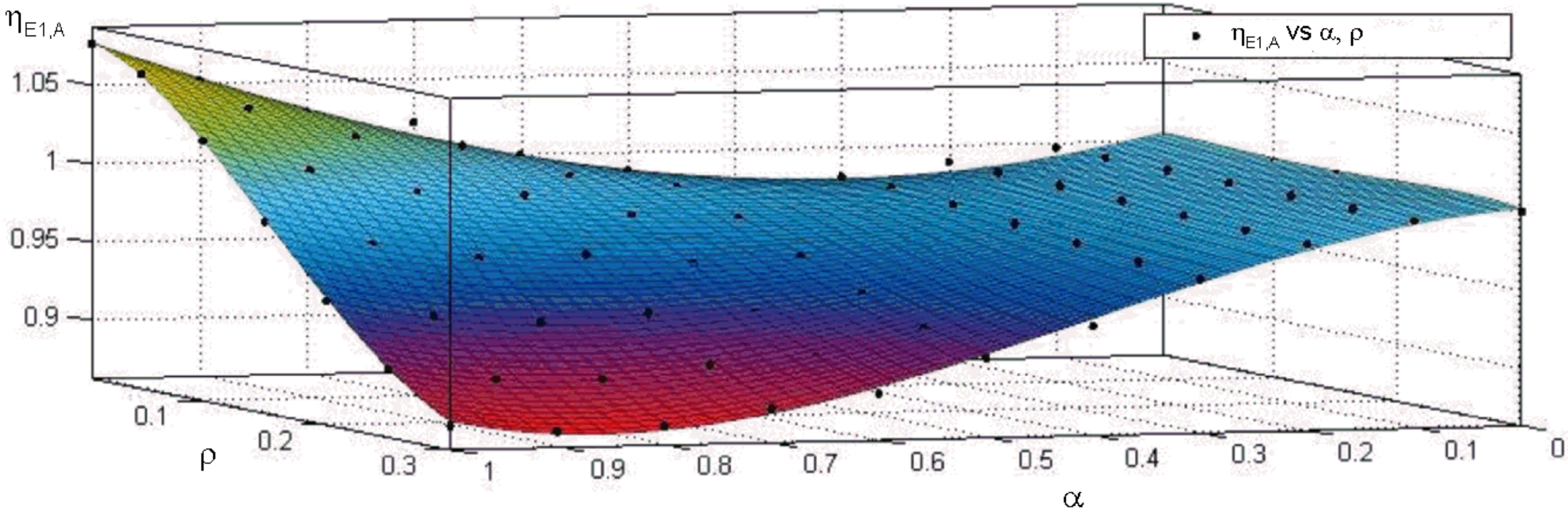
ρ = 0.30

varying ρ between 0.01 and 0.30, for each value of α, the average correction factors are expressed as a function of ρ



mechanical characterization of Voronoi pattern

A surface fitting of the results has provided polynomial expressions for the average correction factors as a function of α and ρ



$$\eta_{i,A} = f(\rho,\alpha) = k_{00} + k_{00}\cdot\alpha + k_{01}\cdot\rho + k_{20}\cdot\alpha^2 + k_{11}\cdot\alpha\cdot\rho + k_{02}\cdot\rho^2 + k_{30}\cdot\alpha^3 + k_{21}\cdot\alpha^2\cdot\rho +$$

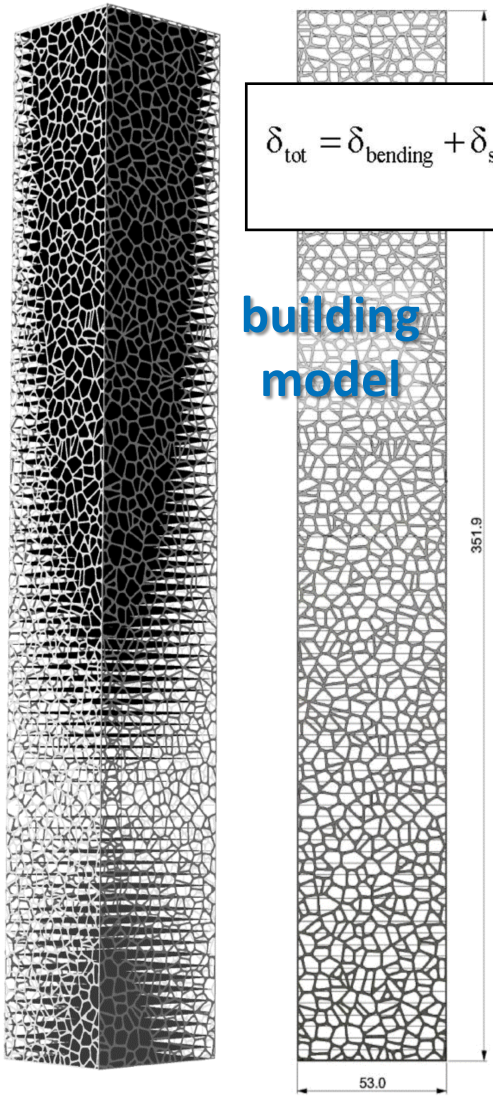
$$+k_{12}\cdot\alpha\cdot\rho^2 + k_{03}\cdot\rho^3 + k_{31}\cdot\alpha^3\cdot\rho + k_{22}\cdot\alpha^2\cdot\rho^2 + k_{13}\cdot\alpha\cdot\rho^3 + k_{04}\cdot\rho^4$$

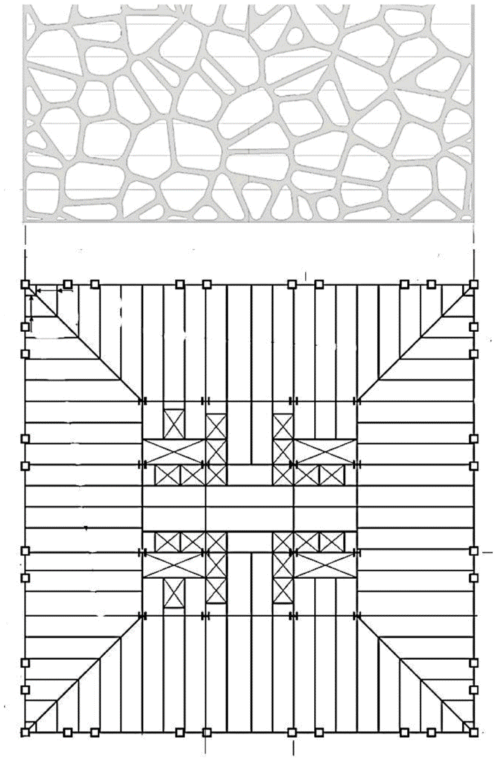
correction factors for calculating the mechanical properties of the Voronoi pattern, characterized by α and ρ, starting from the regular hexagrid with the same ρ

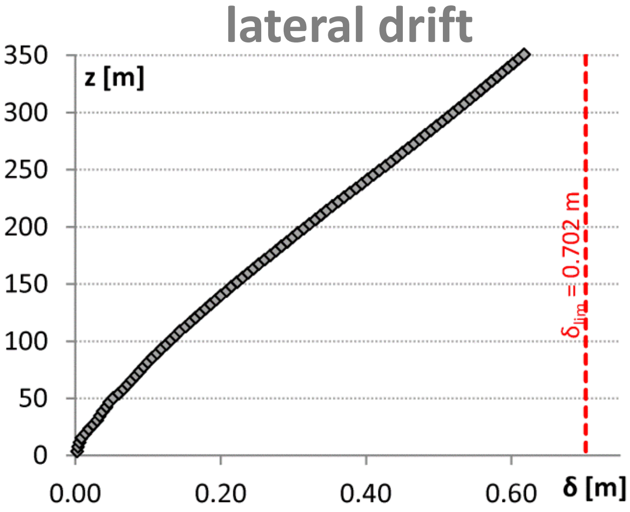
preliminary member sizing – voronoi tall building

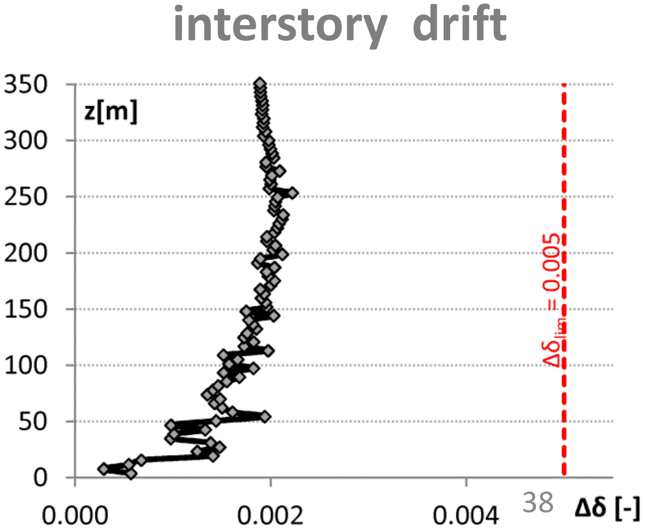
stiffness design criterion applied for sizing members of a TB model with Voronoi structural pattern; design solution checked by means of FEA

$$\delta_{tot} = \delta_{bending} + \delta_{shear} = \frac{qH^4}{8\,\boxed{E^*_{1,H}}\,\boxed{\eta_{E1,A}}\,I} + \frac{qH^2}{2\,\boxed{G^*_{12,H}}\,\boxed{\eta_{G12,A}}\,A}\chi = \frac{H}{500}$$









conclusive remarks

- **the design procedure allows for defining the cross sections of a very large number of structural members, assembled according to an apparently random grid, by means of simple relationships**

- within the framework of the proposed approach, it is possible to deal with geometrical patterns characterized by **density and/or irregularity degree variable along the building height**

- So, density optimization, irregularity optimization, or **member size optimization**, best tuning the strength and stiffness along the elevation, can be obtained with small effort and retaining the conceptual consistency of the procedure.

voronoi

irregularity variations

α = 1.0

α = 0.9

α = 0.8

α = 0.7

α = 0.6

α = 0.5

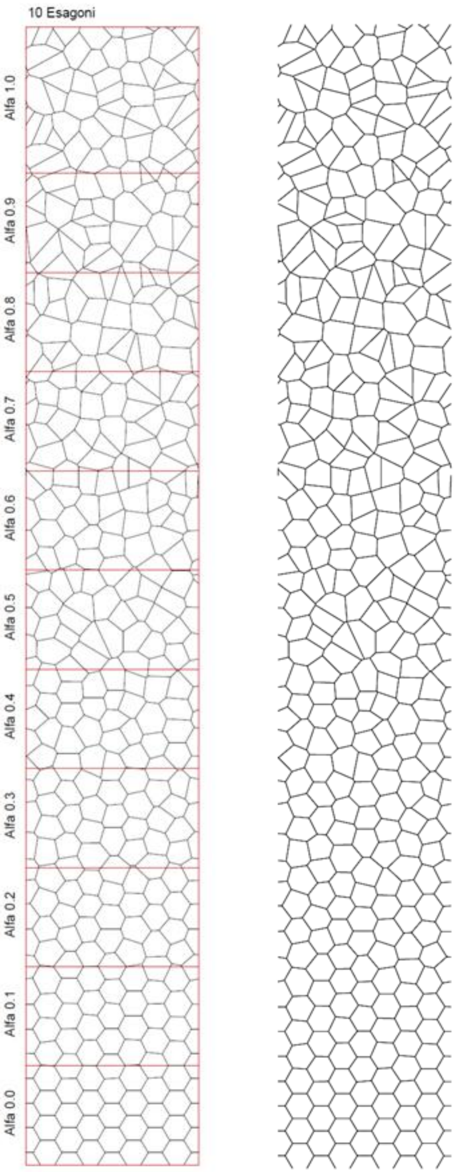
α = 0.4

α = 0.3

α = 0.2

α = 0.1

α = 0.0



density variation along buildings height

6 hex

6 hex

8 hex

10 hex

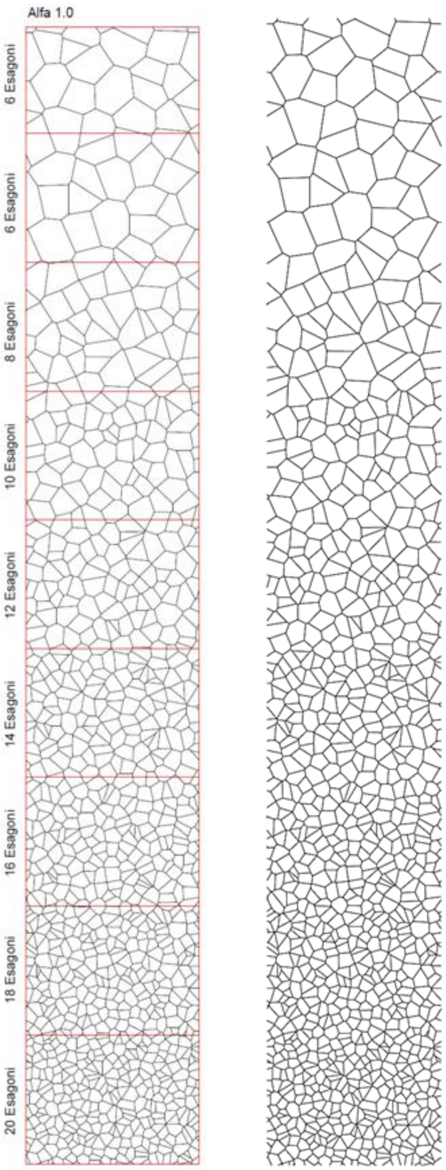
12 hex

14 hex

16 hex

18 hex

20 hex



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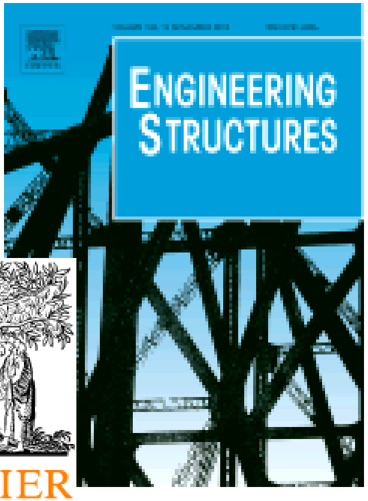
E. Mele, M. Toreno, G. Brandonisio, A. De Luca, A. **2012**
Diagrid structures for tall buildings: Case studies and design considerations
The Structural Design of Tall and Special Buildings. 23, 124–145, **2014** (online July 2012)

G. Montuori , **E. Mele**, G. Brandonisio, A. De Luca. **2013**
Design criteria for diagrid tall buildings: Stiffness versus strength
The Structural Design of Tall and Special Buildings. 23, 1294–1314, **2014** (online Nov. 2013)

G. Montuori , M. Fadda, G. Perrella, **E. Mele**. **2015**
Hexagrid – hexagonal tube structures for tall buildings: patterns, modeling and design
The Structural Design of Tall and Special Buildings. 24, 912-940, **2015** (online April 2015)

G. Montuori, G. Perrella, V. Della Vista, M. Fraldi, **E. Mele**. **2016**
Hexagrid-Voronoi transition in structural patterns for tall buildings. (rev.)



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Geometrical patterns for diagrid buildings: exploring alternative design strategies
Engineering Structures 71 (2014) 112–127

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Engineering Structures 75, 477–488

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3rd International Conference on Structures and Architecture ICSA2016
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Proc. Structural Engineers World Congress SEWC 2011
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De Luca, A., **Mele, E.**, Giordano, A., Grande, E. 2005
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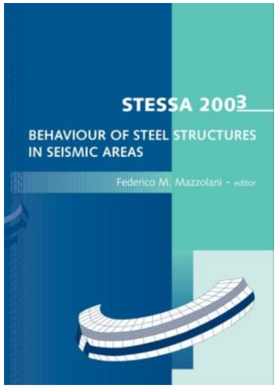
COST C12 Conference "Improving buildings' structural quality" 20-22 Jan. 2005, Innsbruck, Austria

De Luca A., Di Fiore F., **Mele, E.**, Romano A. 2003
The collapse of the WTC twin towers: analysis of the design approach
4th Int. Conf. STESSA 2003. Behaviour of Steel Structures in Seismic Areas. 9-12 June 2003, Naples, Italy



any comments, observations, questions …

… several research needs and design topics worth of study and analysis

glad to discuss them with anyone interested in