Recherches en Structures & Technologies | LAB – UCLouvain

6ème journée de la recherche en LOCI – 2019, Louvain-la-Neuve, 25 janvier 2019

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– Faculty of Architecture, Architectural engineering and Urbanism [LOCI]
– http://sites.uclouvain.be/structech_loci/
Situation of S&T|LAB researches

- History of Sciences
- Construction History
- History of Engineering
- Design approaches
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- theoretical foundations
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- hyperstatic problems
- bending-related analyses
- masonry analyses
- (3D graphic statics)

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Culmann 1866-1886
Ritter 1889 – 1906
Ketchum 1907
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Boothby 2015

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Characterising approaches
Contemporary design approaches
Historical design approaches
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Characterising approaches
Contemporary design approaches
Historical design approaches

Structural objectivism
Structural expressionism
Structural Objectivism - (Expressing a proper structure)

Goal / philosophy:

Several levels: 1/ a will to **show** the structure; 2/ a will to **demonstrate** the structure / suggest the structural behaviour; 3/ a will to **demonstrate efficiency** of the structure

theoretical/artistic background:

linked *Realism (1850,...), Naturalism (=Realism), Neue Sachlichkeit (New Objectivity, 1925-...)* > a.o. Gropius, *Constructivist architecture (1920-1935)*
Structural Expressionism

Goal / philosophy:

present the world solely from a subjective perspective, distorting it radically for emotional effect in order to evoke moods or ideas. Expressionist artists sought to express the meaning of emotional experience rather than physical reality.

> Expressionist architecture (1900-1965...) : a.o. use of “concepts”

theoretical/artistic background:

*Expressionism* was a modernist movement, initially in poetry and painting, originating in Germany at the beginning of the 20th century.

linked to “*Formalism*” = characterising an emphasis on *form* over content or meaning

source : browsing *Wikipedia* pages,
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- Construction History
- History of Engineering
- Design approaches

Graphic Statics

- design purposes
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Characterising approaches

- Structural objectivism
- Structural expressionism

Contemporary design approaches

- J. Conzett
- B. Baker
- L. Ney
- R. Greisch
- J. Schwartz
- (A. Muttoni)
- (R. Furtado)
- ...

Historical design approaches

- Historical structures
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Graphic Statics
- design purposes
- hyperstatic problems
- bending-related analyses
- masonry analyses
- (3D graphic statics)

Contemporary extensions:
- design purposes
- hyperstatic problems
- bending-related analyses
- historical analyses (masonry)
- 3D graphic statics
- optimal solution > redistribution

- R. Maillart [1872-1940]
  - (M. Koechlin)
  - (S. Musmeci)
  - (A. Gaudi)

- use of graphic statics
  - theoretical foundations
  - design approach
  - decision tree
  - geometrical thinking
  - constructive approaches

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- ...

Characterising approaches
- Structural objectivism
- Structural expressionism

Contemporary design approaches

Historical design approaches
Robert Maillart's design approaches ...
Robert Maillart (1872 – 1940), Switzerland

~50 bridges / ~300 buildings

credits: ETH-Bibliothek Zurich, Image Archive
Theoretical foundations
Chronology of Maillart's bridges

- **three-hinged arch bridge**: 10
- **massive classical arch bridge**: 2
- **hinged massive classical arch bridge**: 4
- **stiffened arch bridge**: 13
- **arch with a strongly off-centre thrust line**: 2
- **continuous girder bridge**: 5
- **cantilever bridges**: 2
- **mushroom slabs**: 

**Locations**:
- Zurich
- Zuoz
- Tavanasa
- Salginatobel
- Felsegg
- Vessy
- Lachen
- Pampigny
- Aarburg
- Valschiølbach
- Schwandbach
- Toss Footbridge
- Innertkirchen
- Liesberg
- Grindelwald
- Magazzini generali Chiasso
- Schaffhausen
- Rhône

**Chronology**: 1890-1940
Structural design : inverting the process

- **Context**
  - external constrains

- **Use**
  - Internal constrains

- **Choice / definition of the structural behaviour**

  **Structural behaviours**
  - Status of parts
  - Status of materials

  **Typology** + **Forces**

  **Dimensioning**

  **Form**
  (corresponding – )
Maillart decision tree for structural typology

Structural issue

Structural response

Modes of the structural response

Mechanism 1
(and corresp. dimensioning)

Mechanism n
(and corresp. dimensioning)

Assembling

Form
(corresponding –)

Analysis
Chronology of Maillart's bridges
Chronology of Maillart's bridges

- Masses of classical arch bridge: 2
- Hinged classical arch bridge: 4
- Stiffened arch bridge: 13
- Arch with a strongly off-centre thrust line: 2
- Continuous girder bridge: 5
- Cantilever bridge: 2
- Mushroom slabs: 

Maillart decision tree for structural typology

Loading \(\rightarrow\) Span \(\rightarrow\) Support condition \(\rightarrow\) Cantilever bridge

Support condition \(\rightarrow\) 3 hinged bridge

Span \(\rightarrow\) Support condition \(\rightarrow\) 2 hinged with off-centered thrust line

Support condition \(\rightarrow\) Rise \(\rightarrow\) Stiffened arch bridge

Span \(\rightarrow\) Girder bridge
Salginatobel three-hinged arch bridge: geometrical rules

Parabola and an Arc of a circle: R = 76.8 m  |  live load: 350 kg/m²
Maillart's early three-hinged arch bridges: geometrical rules

Arc of a circle:
R = 52 m
live load: 250 kg/m²

Line and an Arc of a circle:
R = 34 m
live load: 250 kg/m²

Two Arcs of a circle:
R = 70 and 58.5 m
live load: 250 kg/m²

Parabola and an Arc of a circle:
R = 76.8 m
live load: 350 kg/m²
Maillart's early three-hinged arch bridges: geometrical rules

Line and an Arc of a circle:
R = 150 m 
live load > 500 kg/m²

Two Arcs of a circle:
R = 100 and 150 m 
live load: 500 kg/m²

Straight lines
live load: 500 kg/m²
The Salginatobel Bridge of 1929 and Felsegg Bridge of 1933
Constructive approaches
Constructive approaches
Contemporary extensions
Extending graphic statics: managing bending problems

DESIGN OF IMPROVED FRAME STRUCTURES THROUGH OPERATIONS ON GRAPHIC STATICS RECIPROCAL POLYGONS

Goal / objective:

Support design processes related to frame structure using graphic statics environment

historical / theoretical background:

Culmann 1866-1886
Ritter 1889 – 1906
Ketchum 1907
Wolfe 1921
Maillart 1932
Pirard 1950
Boothby 2015
Extending graphic statics : managing bending problems

Main contributions :

Culmann laid the foundation stone of the historical management of bending using graphic statics [Culmann, 1866, p.124]

The funicular polygon used to solve the beam problem was referred to as a graphical "integration machine" [Stüssi, 1951, p. 2]

Otto Mohr [Mohr, 1868] found that the deflection curve of an elastic beam in bending could be represented by a funicular polygon

Application on a rigid portal Frame of two fixed columns and a girder :Wolfe, 1921.

Robert Maillart: Hs 1085
1938-2 Überführung der Weissensteinstrasse in Bern,
ETH Archiv Collection
EXTENDING GRAPHIC STATICS: HISTORICAL ANALYSES

STRUCTURAL ASSESSMENT OF MASONRY ARCHES USING ADMISSIBLE GEOMETRICAL DOMAINS

Goal / objective:

Assessing the safety of historical structures through numerical indicator / safety factor, beyond guaranteeing a possible equilibrium

historical / theoretical background:

Méry 1840
Moseley 1843,
Rankine (1858)
Alfred Durand-Claye (1867)
J. Heyman 1995
Extending graphic statics: historical analyses

Main contributions:

Equilibrium through shape:

Thrust line theory [Moseley 1833, Méry 1840]

+ Static theorem of plasticity: equilibrium if at least 1 thrust line in structure [Heyman 1995]

+ Graphic statics
Contributions:

+ Static theorem of plasticity: equilibrium if at least 1 thrust line in structure [Heyman 1995]
+ Graphic statics
+ admissible (geometrical) domains

$$\frac{H_{\text{max}}}{H_{\text{min}}} = \text{stability/safety index}$$

Area of domain = robustness index
Extending graphic statics: static redundancy

Limit state analysis using graphic statics: application to pin-jointed frameworks & structures in bending

Goal / objective:

Overcome the difficulty of treating elastic compatibility with graphic statics

Develop graphical analysis at limit state, not only design

Support the design process by giving insights on the structural safety in real time

Historical / theoretical background:

Culmann 1866-1886: redundant beams

Maxwell 1864: stiffness of frames

(Ritter 1889 – 1906)?

Lander and Cotton 1900ca: graphical method of deflections to statically indeterminate frames

Wolfe 1921: continuous beams

+ many others
Extending graphic statics: static redundancy

Main contributions: BEAMS

Culmann 1866

Wolfe 1921
Extending graphic statics: static redundancy

Main contributions: FRAMES

Maxwell 1864

Lander & Cotton 1900 ca

Theorem of reciprocity

\[
\frac{Wd'}{L \sin^2 \alpha} \cdot a(l - b) \cdot \{l + 2(b - a)\}.
\]
Extending graphic statics: static redundancy

New approach: LIMIT STATE ANALYSIS

Fivet 2013

Rondeaux 2017:
- frameworks
- beams
DESIGN OF IMPROVED FRAME STRUCTURES THROUGH OPERATIONS ON
GRAPHIC STATICS RECIPROCAL POLYGONS

Goal / objective:

Maximising robustness properties of structures during a design process with graphic statics

Historical / theoretical background:
Maxwell [1864, 1890]
Michell [1904]
Muttoni, Schwartz & Thürlimann [1997]
Baker et al. [2012]
Fivet [2013]
Extending graphic statics: optimal solutions + robustness

Main contributions: LOAD PATHS

Maxwell 1890

“In any system of points in equilibrium in a plane under the action of repulsions and attractions, the sum of the products of each attraction multiplied by the distance of the points between which it acts is equal to the sum of the products of the repulsions multiplied each by the distance of the points between which it acts” (considering rigid-plastic material behaviour + fully stressed design)

\[
\sum_i L_{t,i} F_{t,i} - \sum_i L_{c,i} F_{c,i} = \sum_i L_{t,i} A_i \frac{F_{t,i}}{A_i} - \sum_i L_{c,i} A_i \frac{F_{c,i}}{A_i} = \sum_i V_{t,i} \sigma_t - \sum_i V_{c,i} \sigma_c = \sigma(V_t - V_c) = \sum F_i \cdot d_i
\]

constant value

System of forces

Form diagram

Force diagram
Extending graphic statics: optimal solutions + robustness

Main contributions: LOAD PATHS

Michell 1904, Baker et al. 2012

\[ \sum_{i} L_{t,i} F_{t,i} + \sum_{i} L_{c,i} F_{c,i} = \sum_{i} L_{t,i} A_{i} \frac{F_{t,i}}{A_{i}} + \sum_{i} L_{c,i} A_{i} \frac{F_{c,i}}{A_{i}} = \sum_{i} V_{t,i} \sigma_{t} + \sum_{i} V_{c,i} \sigma_{c} = \sigma (V_{t} + V_{c}) = \boxed{\sigma V} \]

to be minimized

\[ \sum_{i} L_{t,i} F_{t,i} - \sum_{i} L_{c,i} F_{c,i} = \sum_{i} L_{t,i} A_{i} \frac{F_{t,i}}{A_{i}} - \sum_{i} L_{c,i} A_{i} \frac{F_{c,i}}{A_{i}} = \sum_{i} V_{t,i} \sigma_{t} - \sum_{i} V_{c,i} \sigma_{c} = \sigma (V_{t} - V_{c}) = \boxed{\sum F_{i} \cdot d_{i}} \]

constant value

System of forces

Form diagram

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Extending graphic statics: optimal solutions + robustness

Main contributions: ADMISSIBLE GEOMETRICAL DOMAINS

Fivet 2013

Form diagram

Force diagram
Extending graphic statics: optimal solutions + robustness

New approach: LOAD PATHS + DOMAINS FOR ROBUSTNESS ASSESSMENT

In an ideal material:

- Domain of alternative positions → possible force redistributions in case of damage
- Position leading to minimal load path → preferential flow for forces
Extending graphic statics: optimal solutions + robustness

New approach: LOAD PATHS + DOMAINS FOR ROBUSTNESS ASSESSMENT

In reinforced concrete structures: (predefined tie positions)

Interactivity using Rhino and Grasshopper

Form diagram  Force diagram  Variables (Grasshopper)
Extending graphic statics: 3D Graphic Statics

Design of improved frame structures through operations on graphic statics reciprocal diagrams

Goal / objective:

Managing complex 3D design and analysis problems using graphic statics

Historical / theoretical background:

Maxwell [1864]
Cullman [1866]
Rankine [1868]
Cremona [1872]
Föppl [1892]
Saviotti [1888]
Mayor [1903-1909]
Pirard [1950]
Foulon [1969]

Mayor, B. Application de la statique graphique aux systèmes de l’espace. Bulletin technique de la Suisse romande (29(1903) - 35(1909)).
Extending graphic statics : 3D Graphic Statics

Categorization of the existing approaches:

- Projective approach
- Composite approach
- Full 3D approach

Various Perspectives on the extension of graphic statics to the third dimension
Extending graphic statics: 3D Graphic Statics

Full 3D approaches:
- Both diagrams are defined and handled in a 3D space

Polyhedral-based approach
Vector-based approach

Goals:
- Visual convenience of the diagrams
- Understanding the force flow of the structure
- Tool for structural design and analysis
- Structures mixing compression & tension
- Complex 3D structures (irregular geometries)
- Structures mixing materials

Mackinlay J., Automating the design of graphical presentations of relational information. Transactions on Graphics, 1986; 5(2); 110-141.
Extending graphic statics : 3D Graphic Statics

Full 3D approaches:

Polyhedral-based approach

Akbarzadeh M. Three-dimensional Graphical Statics using Polyhedral Reciprocal Diagrams, ETH Zurich, Department of Architecture Zurich, 2016 (October).
Extending graphic statics: 3D Graphic Statics

Full 3D approaches:

Vector-based approach

3D vector-based form and force diagrams of a « tree-structure »
Extending graphic statics: 3D Graphic Statics

Vector-based Graphic statics:

**Lines in F corresponds to lines in F***
- Full 3D approach (both diagrams are defined and handled in a 3D space)
- Vectors > extension of 2D > visual convenience
- Main issue > reciprocity
- step by step graphical construction
- No limitations in terms of typologies of structures (pin-jointed force networks)

3D vector based form and force diagrams of a suspended bridge
Extending graphic statics : 3D Graphic Statics

Vector-based Graphic statics:

**Main steps of the research**
- Resolution of global equilibrium
- Resolution of local equilibrium
- Assembly of 3D vector-based force diagrams
- Transformations of the diagrams
- Development of computational tools (in progress)
- Applications (in progress)

Vector-Based 3D Graphic Statics, : a framework for the design of spatial structures based on the relation between form and forces
P. D’Acunto, J-Ph. Jasienski, P. Ohlbrock, C.Fivet, D. Zastavni & J. Schwartz
International Journal of Solids & Structures, 2018 - (pending review)
Extending graphic statics: 3D Graphic Statics

Vector-based Graphic statics:

Transformation of the form and force diagram

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Extending graphic statics: 3D Graphic Statics

Vector-based Graphic statics:

Applications

- Design & construction of a 3D node

*Optimized geometry found through subdivision of the force diagram*

*3D printed sand mold*

*Aluminium casting*

Application of the subdivision of the force diagram to design the geometry of a structural node - Jasienski [2017]
Extending graphic statics: 3D Graphic Statics

Vector-based Graphic statics:

Applications

- Design of a spoked-wheel stadium

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Team and history

Structures & Technologies LAB in the faculty LOCI at UCLouvain is:

- a research team young of 9 years
- include currently 10 members active in research on topics about structures or design.
- collaborate with various external people that brings to 13 the number of people associated to its researches.

Jean-Philippe Jasinski, Arch.Eng.

Jean-Philippe Jasinski graduated as an engineer from UCL, having undertaken a six-month exchange programme at the Universidad de los Andes in Bogotá, Colombia. He currently works part-time at the UCL Faculty of Engineering and Architectural Studies as a researcher and teaching assistant. Besides, he has been working in various firms in Brussels and abroad (Charles Fossé, Kemrock, 2008) and has specialized in the field of energy in buildings and sustainable development. From 2004 to 2009 he was a PhD student in the Materials Processing Laboratory (LabMat) of the University of Louvain. Since 2010, he has been working part-time at the UCL Faculty of Architecture (LOCI). He is the coordinator of the project for the design of new concrete blocks for the second phase of the Louvain-la-Neuve campus. He is also a member of the Design and Engineering Research Group (DERG) and has been working on the design of new concrete blocks for the second phase of the Louvain-la-Neuve campus. He has been a teaching assistant at the Faculty of Architecture of LOCI since 2005. He is currently working on the design of new concrete blocks for the second phase of the Louvain-la-Neuve campus.