Structural Design VI
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Structural Design VI: Computational Methods

Introduction

Computational Methods in Structural Design
Parametric Design
Parametric Graphic Statics
Digital Fabrication Of Structures
Form Finding
Construction and Panelisation of Shells and Tensile Structures

Fabrication-aware Structural Design

Advanced topics

Optimisation
Design to Production
Computational Methods in the Architectural Practice
Construction and Panelisation of Shells and Tensile Structures
Structural Design VI: Computational Methods

Introduction
- Computational Methods in Structural Design
- Parametric Design

Fabrication-aware Structural Design
- Parametric Graphic Statics
- Digital Fabrication Of Structures
- Form Finding
- Construction and Panelisation of Shells and Tensile Structures

Advanced topics
- Optimisation
- Design to Production
- Computational Methods in the Architectural Practice

Structural Design VI: Computational Methods
Introduction

Digital Fabrication Methods for

Steel Structures

Timber Structures

Concrete Structures

Masonry Structures

Design for Manufacturing

Lecture overview
Introduction

Digital Fabrication Methods for

Steel Structures

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Masonry Structures

Design for Manufacturing
Industrialised Architecture

Crystal Palace by Joseph Paxton (1851)
Programmable Loom

Jacquard loom by Joseph Marie Charles (1804)
First CNC-controlled Milling Machine

Servomechanism Laboratory of the Massachusetts Institute of Technology (MIT) (1950)
G-code (RS-274)

O1000
T1 M6
(Linear / Feed – Absolute)
G0 G90 G40 G21 G17 G94 G80
G54 X-75 Y-75 S500 M3 (Position 6)
G43 Z100 H1
Z5
G1 Z-20 F100
X-40 (Position 1)
Y40 M8 (Position 2)
X40 (Position 3)
Y-40 (Position 4)
X-75 (Position 5)
Y-75 (Position 6)
G0 Z100
M30
G-code (RS-274) / Technical drawings

Technical drawing
Potential Benefits of Digital Fabrication

- **mass-customisation**
- short production time
- high level of prefabrication
- high precision
- minimising errors and risk
- little adjustments on site
- enables new designs not possible otherwise

Prefabrication HIB roof, ETH Zürich, 2016, ERNE AG Holzbau
Walt Disney Concert Hall, Gehry Architects, 2003

Heydar Aliyev Center, Zaha Hadid Architects, 2012

Yas Viceroy Abu Dhabi Hotel, Asymptote Architecture, 2009

Centre Pompidou, Metz, Shigeru Ban Architects, 2010
Stress Trajectories

Principal stresses in an asymmetrically loaded beam
Introduction

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Design for Manufacturing
Steel: Bar and Node Systems

Interbau Exhibition Hall, Berlin (1957)
Steel: Bar and Node Systems

Heydar Aliyev Center, Zaha Hadid Architects (2012)
Steel: Bar and Node Systems

Milling and Trimming
Steel: Bar and Node Systems

Milling and Trimming
Steel: Bar and Node Systems

CNC Lathe Turning

HiLo Roof Prototype, Block Research Group, ETH Zurich (2017)
Steel: Bar and Node Systems

Franken Architekten, Take Off, Munich (2003)
Steel: Bar and Node Systems

Multi-Axes Milling

Matsuura Machinery multi-axes milling of a engine Block from solid work piece
Steel: Bar and Node Systems

Combined Laser Disposition and Milling

https://www.youtube.com/watch?v=L3CkzQQFZXs

10× faster than the powder bed method.

Additive manufacturing and milling in one machine, DMG Mori
Steel: Bar and Node Systems

Robotic 3D Metal Printing

https://www.youtube.com/watch?v=v2moJF8kqlg
Steel: Bar and Node Systems

3D-Sand-Printing for Metal Casting

Arup 3D-printing sand casts for complex steel structural elements (2017)

DBT ETH, Digital Metal (2017)
Steel: Bar and Node Systems

3D-Sand-Printing for Metal Casting

voxeljet AG

DBT ETH, Digital Metal (2017)
Steel: Frame Structures

Disney Concert Hall, Gehry Partners, 2003
Steel: Frame Structures
Steel: Frame Structures

Structural Steel Robotic Beam Assembly

https://www.youtube.com/watch?v=vCeXTKhuXyg
Steel: Frame Structures

Southern Cross Station, Grimshaw Architects (2007)
Steel: Frame Structures

CNC Bending

https://www.youtube.com/watch?v=4GfKnD61BGA
Bridge in Ditzingen, sbp, (2018-)
Steel: Shell and Surface Structures

CNC – laser/plasma/waterjet cutting

Laser and plasma CNC cutting (Trumpf)

Waterjet CNC cutting (Ballard Machine Works)
Steel: Shell and Surface Structures
Steel: Shell and Surface Structures

Incremental Sheet Forming (IBU)

http://trako.arch.rwth-aachen.de/cms/TRAKO/Forschung/Leichtbau/~isbf/Faltstrukturen-aus-Feinblech/lidx/1/
Steel: Shell and Surface Structures

Arum, Zaha Hadid, Venice Biennale (2012)
Steel: Shell and Surface Structures

Robotic folding

https://www.youtube.com/watch?v=8jgpgyxM54U
Introduction

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Design for Manufacturing
Traditional timber framework

Traditional timber joint connections
Timber: Frame Structures

CNC timber trimming machines

Hundegger AG, joinery machine P8 (1981)
Timber: Frame Structures

CNC timber trimming machines

Roof truss with prefabricated parts
Timber: Frame Structures

CNC timber trimming machines

Hundegger AG, joinery machine K2 Robot (2014)
Timber: Frame Structures

Centre Pompidou-Metz, Shigeru Ban Architects (2010)
Timber: Frame Structures

Multi-axes CNC timber framing

Centre Pompidou-Metz, Shigeru Ban Architects (2010)

Blumer + Lehmann, Multi-axes CNC timber framing
Timber: Shell and Surface Structures

Elefantenhaus Zoo Zurich, Markus Schietsch Architekten (2014)
Timber: Shell and Surface Structures

2.5D CNC milling
Timber: Shell and Surface Structures

2.5D CNC milling

Axyz machine in workshop
Timber: Shell and Surface Structures
Timber: Shell and Surface Structures
Timber: Shell and Surface Structures

5-Axes CNC milling and sawing

https://www.youtube.com/watch?v=co8yamUb6nl

Vidy Theater, IBOIS,ibois, EPFL (2017)
Timber: Trusses

Roof trusses
Timber: Trusses

Automated truss assembly 2D

https://www.youtube.com/watch?v=sQh2s2e0C7k
Timber: Trusses

ITA Arch Tec Lab, ETH Zürich (2017)
Timber: Trusses

Automated truss assembly 2.5D

https://www.youtube.com/watch?v=VKn-ZO-nXJA
Timber: Trusses

Automated truss assembly 2.5D

Mastering the “Sequential Roof”, Aleksandra Anna Apolinarska et al.
Timber: Trusses

Automated truss assembly 3D

Gramazio Kohler Research, ETH Zurich, ERNE AG Holzbau (2017-)

Timber: Shell

ICD/ITKE Research Pavilion 2015-16, University of Stuttgart (2016)
Timber: Shell

Robotic sewing of thin plywood
Introduction

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Design for Manufacturing
Concrete: Shell and Surface Structures

TWA terminal-interior, Saarinen (1962)
Concrete: Shell and Surface Structures

Robotic milling

TailorCrete demonstrator, Superpool, Danish Technological Institute (2014)  Robotic EPS foam milling
Concrete: Shell and Surface Structures

Robotic hot-wire and hot-blade cutting

Odico, Robotic hot-wire and hot-blade cutting
Concrete: Shell and Surface Structures
Concrete: Shell and Surface Structures

2.5D milling
Concrete: Shell and Surface Structures

2.5D milling

Disposed formwork, designtoproduction
Concrete: Shell and Surface Structures

Adaptable moulds

TailorCrete, Gramazio Kohler Research, ETH Zurich (2009-2013)
Concrete: Shell and Surface Structures

Adaptable moulds

TailorCrete, Gramazio Kohler Research, ETH Zurich (2009-2013)
Concrete: Shell and Surface Structures

Flexible formwork

HiLo Roof Prototype, Block Research Group, ETH Zurich (2017)
Concrete: Shell and Surface Structures

3D-printing with concrete (extrusion)
Concrete: Shell and Surface Structures

3D-printing with concrete (extrusion)  
https://www.youtube.com/watch?v=K0pL0tqhQt8
Concrete: Shell and Surface Structures

3D-printing with concrete (extrusion)

- Structural bond/reinforcement
- Surface accuracy, geometric constraints
Concrete: Linear Elements
Smart Dynamic Casting (SDC)
Concrete: Linear Elements

Smart Dynamic Casting (SDC)

https://www.youtube.com/watch?v=B12LOj4oxcw

Gramazio Kohler Research, ETH Zurich (2012-)
Concrete: Reinforcement
Concrete: Reinforcement

CNC rebar bending

https://www.youtube.com/watch?v=IppJWziK024
Concrete: Wall Elements

Mesh Mould Metal
Concrete: Wall Elements

Mesh Mould Metal

https://www.youtube.com/watch?v=TCJOQkOE69s
Introduction

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Design for Manufacturing
Masonry: Brick Structures

Robotic brick laying

ESPRIT 3 6450 ROCCO, Karlsruhe University, (1992–6) 
SAM, Construction Robotics (2017)
Masonry: Brick Structures

Robotic brick laying

Winery Gantenbein / Gramazio & Kohler + Bearth & Deplazes (2006)  
Gramazio & Kohler (2006)
Masonry: Stone Structures

Armadillo Vault, Block Research Group (2016)

Collier Memorial, Höweler + Yoon Architecture LLP (2015)
Masonry: Stone Structures

Robotic milling
Masonry: Stone Structures

Abrasive wire-cutting, Multi-Axes milling and cutting

Escobedo Group
Masonry: Stone Structures

3D-Sand-Printing (artificial sandstone)

voxeljet AG

Funicular floor system, Block Research Group (2016-)
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Design for Manufacturing
Design for Manufacturing

Self-alignment, explicitness

Self-alignment strategies

Non-obvious alignment

Explicit alignment

Schodek et al.
Design for Manufacturing

Reduction of parts, complexity in the building part

Reduction of parts

Complexity: assembly < parts

Schodek et al.
Design for Manufacturing

Adjustment, Access and handling

Statically determinate adjustment

Access and handling

Schodek et al.
Design for Manufacturing

Incorporating fabrication constraints

Armadillo Vault, Block Research Group (2016)

5-Axes Milling
Productivity in various industry sectors 1995 – 2012

- Manufacturing: 155.1
- Average: 113.3
- Building Sector: 100.7

Index: 1995=100

Productivity in various industry sectors 1995 – 2012, (Bundesamt für Statistik)
Know your tools
and
use them wisely…

Many Thanks!