Grid Shell Structures on Freeform Surfaces

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Company Introduction

Novum Structures - Design & Build Specialty Contractor for Architectural Steel, Cable, Glass & Membrane Structures

- Wrigley’s R&D Center Chicago, USA
- Dali Museum St. Petersburg, USA
- Tours Shopping Mall, France
- Seattle Airport, USA
- Yueda 889 Shopping Mall Shanghai, China
- Old Castle Dresden, Germany
Company Introduction

Novum Structures is a Design & Build Specialty Contractor for Architectural Steel, Cable, Glass & Membrane Structures.

Holding Company:
Menomonee Falls, WI
San Francisco, CA
Sarasota, FL
Texas, TX

Diss, UK
Farnham, UK
Wurzburg, Germany
Kocaeli, Turkey
Shanghai, China
Dubai UAE
Bangalore, India
Johannesburg, S. Africa

Selection of Novum Component Systems for Building Structures & Envelopes

KK-System
BB-System
BK-System
FF-System
CCG-System
ECG-System
AFP-System
SSM-System
DoubleTree Hotel, Tower of London, UK
Novum Project References

Ottawa Convention Center, Canada

FF-System

ECG-System

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Novum Project References

Ottawa Convention Center, CAN
Novum Project References

Mall of Africa Midrand, SA

FF-System

AFP-System

© Zak World of Facades, London Conference
Mall of Africa Midrand, SA
Novum Project References

Falcon Tower Hotel, Doha, Qatar

ECG-System

FF-System

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Novum Project References

Falcon Tower Hotel, Doha, Qatar

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Novum Project References

STEVENAGE BIOSCIENCES

AFP-System

AES-System

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Novum Project References

TRINITY LEEDS

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ECG-System

BK-System
1. The General Solution for Panel Geometry in grid shell design
2. Panel Materials – size & scale
3. Automation of production - from model to fabrication
Content

1. **Freeform Surface Typology**
2. Grid Geometry & Analysis
3. Novum FF-System
4. Process Case Study – Salvador Dali Museum
Typology of Freeform Surfaces

**Free-Form Surface Examples**

Foster & Partner: The Sage, Gateshead, UK

HOK: Salvador Dali Museum, St. Petersburg, FL, USA

The Jerde Partnership: Zlote Tarazy, Warsaw, Poland

Studio Fuksas: New Fair, Milan, Italy

Foster & Partners: British Museum, London, UK
Grid Shell Structures on Freeform Surfaces

Typology of Freeform Surfaces

Surface Classification Chart

- Structurally Optimized
  - Minimal Surface
  - Hanging Form

- Structurally Non-Optimized
  - Scale Translation Surface
  - Scale Revolution Surface
  - Ruled Surface
  - NURBS Surface

NURBS = Non-Uniform Rational B-Spline
Typology of Freeform Surfaces

**Minimal Surface**

- Doubly-curved anticlastic surfaces produced by experimental or numerical form-finding process
- Application mainly for cable nets and tension or membrane structures

Fentress & Bradburn: SeaTac Airport Seattle, US
Execution: Novum
Typology of Freeform Surfaces

Hanging Form

- Doubly curved surfaces produced by experimental or numerical form-finding process
- Application mainly for predominantly gravity loaded shell structures

Frei Otto:
Multihalle
Mannheim, DE
Facetted surface produced by a parallel translation and simultaneous scaling (dilation) of a generating polygon (generatrix) along a polygonal guideline (directrix)

Application mainly for glass structures with planar quadrilateral facets
Typology of Freeform Surfaces

Scale Revolution Surface

- Facetted surface produced by a rotation and simultaneous scaling (dilatation) of a generating polygon (generatrix) about an axis of rotation
- Cylinder, sphere, cone and torus surfaces are widely used basic revolution surfaces with an analytically determined generatrix
- Application mainly for glass structures with planar quadrilateral facets

Hadi Simaan & Partner: Aspire Tower Doha, Qatar
Engineer: Arup
Typology of Freeform Surfaces

Ruled Surface

- Practically important ruled surfaces:
  - Hyperbolic Paraboloid / Hypar surfaces
  - Hyperboloid surfaces
- Hyperbolic Paraboloid surfaces are produced by translating a generating line (generatrix) along two skewed guide lines and parallel to a directing plane.
- Hyperboloid surfaces are produced by rotating a generating line skewed to the axis of rotation (each hyperboloid can be generated with two different generating lines).

Vladimir Shuchov: Lipezk Tower 1896, RU
Restaurant auf der Zugspitze, DE

Erick van Egeraat: Alphen City Hall, NL
Execution: Oktatube International BV

Coop Himmelb(l)au: BMW World München, DE
Execution: Josef Gartner GmbH

Vladimir Shuchov: Lipezk Tower 1896, RU
Typology of Freeform Surfaces

NURBS Surface

- NURBS surfaces (Non-Uniform-Rational-B-Spline) are analytically defined, double-curved surface areas controlled through the vertices of control polyhedrons
- By manipulating the control polyhedrons, the surface curvature at any location can be diversely influenced (rubber band effect)
- By combining multiple NURBS surface areas (patches) while maintaining the surface continuity along all area interfaces, it is possible to model any arbitrary technically or naturally occurring surface!

Studio Fuksas: New Fair Milan, IT
Execution: Mero GmbH & Co.KG
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Grid Geometry

Grid Generation Methods

- Projection Method
  - Projection of a regular grid pattern from a datum plane onto the freeform surface
  - Typically requires manual grid correction of surface areas with increased curvature or inclination to the datum plane

- Parcellation Method
  - Boundary lines get subdivided into portions of similar length, thus creating "orthogonal" auxiliary grid on surface
  - Final grid is tied into this auxiliary grid
Grid Shell Structures on Freeform Surfaces

Grid Geometry

Grid Generation Methods

- **Projection Method**
  - Resulting grid is usually evenly spaced and balanced.
  - Planar grid projection is not considering boundary lines, thus frequently creating problematic grid zones along boundaries.

- **Parcellation Method**
  - Grid along boundaries is unproblematic.
  - Resulting grid can appear slightly more irregular, although this strongly depends on the perspective of the viewer.

Grid created with planar projection

Grid created with surface partitioning

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Grid Geometry

Elements of Grid Shell Structures
Grid Geometry

**Element Orientation**

Element orientation vectors are generated as follows:

1. Determination of all grid panels (panel finding)
2. Determination of normal vectors for all panels (panel vector)
3. Node vectors are determined by averaging the panel vectors of all panels adjacent to a node
4. Member vectors are determined by either:
   a) averaging the panel vectors of the 2 panels adjacent to a member
   b) averaging the node vectors of the 2 nodes adjacent to a member, both projected into the member cross section plane (thus minimizing twist at both nodes)
Grid Shell Structures on Freeform Surfaces

Grid Geometry

**Element Connectivity Angles**

- **Vertical Angle V**: is the azimuth angle between the node vector and a member axis in the polar coordinate system of a node.
- **Horizontal Angle U**: is the polar angle between adjacent member axes in the polar coordinate system of a node.
- **Twist Angle W**: is the angle between a member vector and a node vector projected into the member cross section plane.
- **Panel Folding Angle F**: is the angle between the 2 panel vectors projected into the member cross section plane.
Grid Geometry

**Element Connectivity Angles – Vertical Angle**

- Vertical angles primarily depend on local curvature parameter 1/R of the surface at this node:
  1. Smaller curvature → vertical angle is close to 90° → smaller V1 (difference to 90°)
  2. Larger curvature → vertical angle significantly deviates from 90° → larger V2 (difference to 90°)

Color plot of the vertical angles for a grid

Vertical angle at a real node
Geometry of Truss Elements

**Element Connectivity Angles – Horizontal Angle**

- Horizontal angles primarily depend on the grid topology:
  1. quadrilateral grid → four way node → larger horizontal angle $U_1$
  2. triangular grid → six way node → smaller horizontal angle $U_2$

[Diagram showing horizontal angles for square grid and triangular grid.
Color plot of the horizontal angles for a grid.
Horizontal angle at a real node.]
Geometry of Truss Elements

Element Connectivity Angles – Twist Angle

- Twist angles primarily depend on local curvature parameter $1/R$ of the surface at this node and on the orientation of the member to the principal curvature directions:
  1. Larger deviation from principal curvature direction $G_1$ → Larger twist angle $W_1$
  2. Smaller deviation from principal curvature direction $G_2$ → Smaller twist angle $W_2$

- Twist angle is zero if member axis is parallel to principal curvature direction!
Grid Geometry

Element Connectivity Angles – Panel Folding Angle

- Panel folding angles primarily depend on local curvature parameter $1/R$ of the surface at this node.
Grid Shell Structures on Freeform Surfaces

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Novum FF-System
System Description

- The Novum FF-system is a proprietary end face node connection consisting of:
  - 2 forged steel discs of S355 or C45 material, with individually machined faces as required by the grid geometry
  - each machined face has a threaded hole for a grade 10.9 bolt M24 or M27
  - precision cast steel adapters of steel GS-20Mn5V, with top & bottom faces which can have an offset to each other, with corresponding bolt holes, welded to ends of straight cut RHS members, typically ASTM A500 grade C 6"x3", 8"x3" or 10"x3" or EN 10219 grade S355 150x80, 200x80 or 250x80
  - concealed & pretensioned socket head bolts M24 or M27, fixing the adapters to the 2 node discs

- The structural behaviour of these bolted node connections is semi-rigid and has to be adequately considered in the structural model - typically as a rotational spring stiffness at the end of each grid shell member
Novum FF-System

**Design and Fabrication Data**

- Freeform grid shell structures in general (except for small projects) cannot be modelled, drawn and fabricated using conventional methods due to time, cost, manpower, reliability, accuracy and quality constraints.

- Instead, the design process must be automated by using interconnected parametric component models for all nodes, members & glazing units. Novum is using proprietary software (GSD) for this purpose, which is linking standard Finite Element Analysis software with AutoCAD, Excel and CAM software for CNC machining. The initial parameters for these models have to be established after the grid geometry has been generated and the structural analysis has been done.

- Then, as a substitute of conventional drawing sets, only relevant data and very few parametric drawings are needed to design and fabricate all grid shell components. This process will be illustrated more detailed in a process case study later on.
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1. Freeform Surface Typology
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Workflow Overview

Start: Input

Surface geometry

Generate grid geometry on surface (wireframe)

Find panels, generate node and member vectors

Analysis of grid quality
- Member length too small?
- Cladding panel size too large?
- Angles between adjacent members at nodes
- Vertical node angles, twist angles
- Folding angles between panels on each member → glazing system?
- Water flow on surface → drainage

no

ok?

yes

RSN, RSTAB

Structural analysis incl. global and local buckling check

Member & bolt size

GSD

Manual or automated node size determination

Node size

GSD: Grid import → Panel finding (repeat) → node & member vectors (repeat) → Cladding grid (new) → 3D Model → Fabrication data output/BoM

Fabrication, Installation

RSN

Start: Input

Surface geometry

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RSN, RSTAB

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Fabrication, Installation
Grid Shell Structures on Freeform Surfaces

Process Case Study – Salvador Dali Museum

Architectural Concept

Salvador Dali Museum St. Petersburg, FL, USA:
Architectural design by Yann Weymouth from
Hellmuth Obata & Kassabaum, Inc. (HOK)

Artwork protection concept against hurricane floods w/o evacuation
Workflow Overview

Start: Input

Surface geometry

Generate grid geometry on surface (wireframe)

Find panels, generate node and member vectors

Analysis of grid quality
- Member length too small?
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- Vertical node angles, twist angles
- Folding angles between panels on each member → glazing system?
- Water flow on surface → drainage

no

yes

ok?

RSTAB, RKK

Manual or automated node size determination

GSD:
- Grid import → Panel finding [repeat] → node & member vectors [repeat] → Cladding grid [new] → 3D Model → Fabrication data output/BoM

Structural analysis incl. global and local buckling check

→ Member & bolt size

GSD:

→ Node size

Fabrication, Installation
Surface parcellation generates a dimensionally controlled reference pattern on the surface for various grids while maintaining control of surface edges (thus avoiding sliver facets).

Initial NURBS freeform surface (Enigma)

Manual definition of intersecting planes for surface parcellation

Generated grid on freeform surface
Process Case Study – Salvador Dali Museum

Grid Visualization

Final grid of Enigma and Igloo
Workflow Overview

Start: Input

- Surface geometry
- Generate grid geometry on surface (wireframe)
- Find panels, generate node and member vectors

Analysis of grid quality
- Member length too small?
- Cladding panel size too large?
- Angles between adjacent members at nodes?
- Vertical node angles, twist angles?
- Folding angles between panels on each member → glazing system?
- Water flow on surface → drainage

 découplage

RSTAB, RKK

Manual or automated node size determination
- GSD:
  - Grid import → Panel finding (repeat) → node & member vectors (repeat)
  - Cladding grid (new) → 3D Model → Fabrication data output/BoM

RSN, RSTAB

Structural analysis incl. global and local buckling check
- Member & bolt size
- Node size

Fabrication, Installation
Process Case Study – Salvador Dali Museum

**Structural Design & Glazing System Impact Testing**

- Design component & cladding wind pressure per wind tunnel test results: ±100 psf (± 4.79 kN/m²)
- Florida Building Code requires rigorous testing of glazing systems:
  - water penetration tests as per ASTM E 331 & AAMA 501.1
  - structural tests as per ASTM E 330 for 200% design wind load
  - small / large missile impact tests & subsequent pressure cycling as per ASTM E 1886 and E 1996 (above / below 30 ft or 9.1 m)
Process Case Study – Salvador Dali Museum

Bending Capacity & Stiffness Tests of Node Connection

In order to establish the bending stiffness and verify the connection capacity of various combinations of FF-system components, series of methodical 4-point bending tests have been realized.
Process Case Study – Salvador Dali Museum

**Finite Element Analysis of Node Connection**

- In order to verify those 4-point bending tests of FF-system components, series of finite element analysis of the test specimen have been performed.
- Semi-rigid connection behaviour is a combined effect of the bolted connection stiffness and reduced bending stiffness in the mounting hole zone.
- The observed mid span deflections of the FE models were only 80% of the average measured values, apparently due to small initial settlements of the real test specimen under loads.
- This ratio is being used to calibrate FE models of FF-system node connections in any structural analysis.
Process Case Study – Salvador Dali Museum
Calculation of Node Connection Capacity

- The varying bending moment capacity of the bolted node connection in dependency of the axial connection force is typically determined using an iterative numerical calculation method assuming planarity of member end section [Space Structures 5, Telford Publ. 2002, p. 759-773]

- Calculation results shown below performed for 3 limit states – elastic, plastic and failure limit – of RHS 250x80 S355 with adapter FFA1036-0-26 and M24-10.9 bolts

- Results from methodical 4-point bending tests are conservatively close to the failure limit bending moment
In addition to local member buckling and capacity checks, a global buckling analysis is conducted to ensure structural integrity of the grid shell frame.

To account for imperfections due to fabrication and installation tolerances, an “imperfect geometry” model is generated and analyzed according to all appropriate load cases and combinations.

The imperfect geometry is generated by deforming the structure to the node locations of critical buckling modes.

The magnitude of the maximum nodal shift is scaled to an imperfection tolerance, which is generally derived from steel design code imperfections.
Grid Shell Design

Workflow Overview

**Start: Input**

- **Surface geometry**
- **Generate grid geometry on surface (wireframe)**
- **Find panels, generate node and member vectors**
- **Analysis of grid quality**
  - Member length too small?
  - Cladding panel size too large?
  - Angles between adjacent members at nodes
  - Vertical node angles, twist angles
  - Folding angles between panels on each member → glazing system?
  - Water flow on surface → drainage

**RSN, RSTAB, RKK**

- Structural analysis incl. global and local buckling check
  - Member & bolt size
- Manual or automated® node size determination
  - Node size

**GSD**

- Grid import → Panel finding [repeat] → node & member vectors [repeat] → Cladding grid [new] → 3D Model → Fabrication data output/BoM

**Fabrication, Installation**
Process Case Study – Salvador Dali Museum

Parametric Component Modelling – System Line Wireframe

The final structural model contains all information about member profile & bolt dimensions. Information about node types & dimensions needs to be added. Novum’s grid shell design software GSD is importing this information & connecting it with the grid shell system database.
Process Case Study – Salvador Dali Museum

Parametric Component Modelling with GSD – Element Orientation Vectors

GSD is now performing an automated panel search for all selected members of the generated wireframe in AutoCAD. Then GSD is establishing the element orientation vectors for panels, nodes and members as presented earlier.

Panels on the system line wireframe model in AutoCAD generated by GSD

Close-up of panels with panel, node and member vectors
Novum FF-System

**Parametric Component Modelling with GSD – Glazing Joint Wireframe**

With all element orientation vectors determined, GSD is generating a glazing joint wireframe model on a predefined stand-off distance to the system line wireframe. The intersection points of glazing joints are always located on the node vectors.

![Glazing joint wireframe model in AutoCAD generated by GSD](image1)

![Close-up of glazing joint wireframe model (yellow color)](image2)
Process Case Study – Salvador Dali Museum

Parametric Component Modelling with GSD – 3D CAD Model of Nodes & Members

Using all initially established component parameters on basis of the grid shell system database, GSD is then generating a full 3D CAD model of all grid shell nodes and members. Simultaneously the corresponding node and member fabrication data is being determined.
Process Case Study – Salvador Dali Museum
Parametric Component Modelling with GSD – 3D CAD Model of Glazing Units

With the earlier established glazing joint wireframe, GSD is now generating a full 3D CAD model of all glazing units. Simultaneously the corresponding glazing fabrication data is being determined.

![3D CAD model of glazing units in AutoCAD generated by GSD](image1)

![Close-up of 3D CAD model of glazing units](image2)
Process Case Study – Salvador Dali Museum

**Parametric Component Modelling with GSD – 3D Assembly Plan**

In order to enable the correct installation of the grid shell structure, GSD is finally establishing a 3D assembly plan with orientation marks for all grid shell nodes, members and glazing units.

3D assembly plan in AutoCAD generated by GSD

Close-up of 3D assembly plan with element orientation marks
Grid Shell Structures on Freeform Surfaces

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Fabrication Data Output – Nodes and Glazing Units

Fabrication data for nodes and glazing units is being generated in comprehensive Excel spreadsheets.

- Node fabrication list generated by GSD
- Glazing unit fabrication list generated by GSD

Process Case Study – Salvador Dali Museum

Fabrication Data Output – Members

Fabrication data for members is being generated in comprehensive Excel spreadsheets.

- Member fabrication list generated by GSD
Grid Shell Design

**Workflow Overview**

**Start: Input**
- **Surface geometry**

**Generate grid geometry on surface (wireframe)**

**Find panels, generate node and member vectors**

**Analysis of grid quality**
- Member length too small?
- Cladding panel size too large?
- Angles between adjacent members at nodes
- Vertical node angles, twist angles
- Folding angles between panels on each member → glazing system?
- Water flow on surface → drainage

**ok?**
- yes
- no

**RSN, RSTAB**
- Structural analysis incl. global and local buckling check
  → Member & bolt size

**RSTAB, ® RKK**
- Manual or automated © node size determination
  → Node size

**GSD**
- Grid import → Panel finding (repeat) → node & member vectors (repeat) → Cladding grid (new) → 3D Model → Fabrication data output/BoM

**Fabrication, Installation**

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Node Fabrication

Typical fabrication procedure:

• CAD model data transfer into CNC software & check
• CNC machining and marking
• Quality control
• Electroplating & painting
• Crating and shipment
Process Case Study – Salvador Dali Museum

Member Fabrication

Typical fabrication procedure:

- CAD model data transfer into parametric drawings & check
- Automated profile length and mounting hole cutting
- Quality control
- Hot dip galvanizing & painting
- Wrapping, crating and shipment
Grid Shell Structures on Freeform Surfaces

Process Case Study – Salvador Dali Museum

Installation

Typical installation procedure:

• Calibration of proprietary bolt pretensioning devices using Skidmore-Wilhelm units
• Preassembly of "node fans", single nodes with several members attached, on multiple ground stations
• Lifting & mounting of "node fans" as extensions of already installed grid shell structure
• Final bolt pretensioning
• Glazing installation & caulking
Process Case Study – Salvador Dali Museum

Installation