RETICULATED STRUCTURES ON FREE-FORM SURFACES

S. Stephan, J. Sánchez-Alvarez, K. Knebel
MERO GmbH & Co. KG, 97084 Würzburg, Germany
Soeren.Stephan@mero.de, Jaime.Sanchez@mero.de, Klaus.Knebel@mero.de

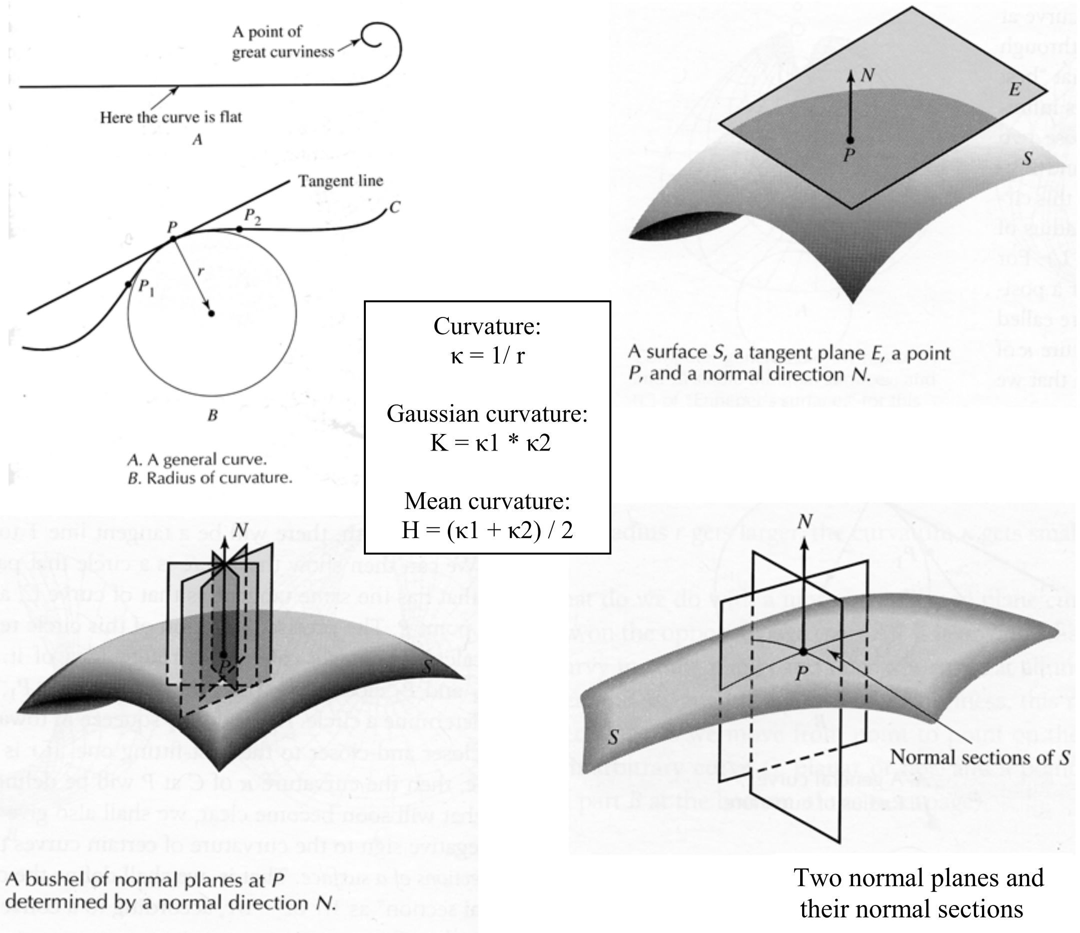
1. Introduction

Promoted by buildings like the DZ-Bank in Berlin (Frank Gehry), the Arts Center in Singapore (Vikas Gore), the British Museum in London (Norman Foster) and recently the New Fair in Milan (Massimiliano Fuksas) with its roofs above the Central Axis and the Service Center, free-form envelopes became more and more popular in recent years.

The paper is a brief review of the geometrical and the corresponding structural problems related to the design of reticulated structures on free-form surfaces.

2. Geometry of Surfaces

Surfaces are the skin of objects. We recognize the form of objects in our environment by visually perceiving their surfaces. Space can be defined and measured in terms of surfaces, which enclose and limit it. Surfaces are two-dimensional continuous shapes contained in the three-dimensional geometric Euclidean space. Thus, a surface constitutes a sort of two-dimensional world, which can carry geometric objects of various kinds, such as points, straight and curved lines and networks.



A. A general curve.
B. Radius of curvature.

Curvature:
$\kappa = 1/r$

Gaussian curvature:
$K = \kappa_1 * \kappa_2$

Mean curvature:
$H = (\kappa_1 + \kappa_2) / 2$

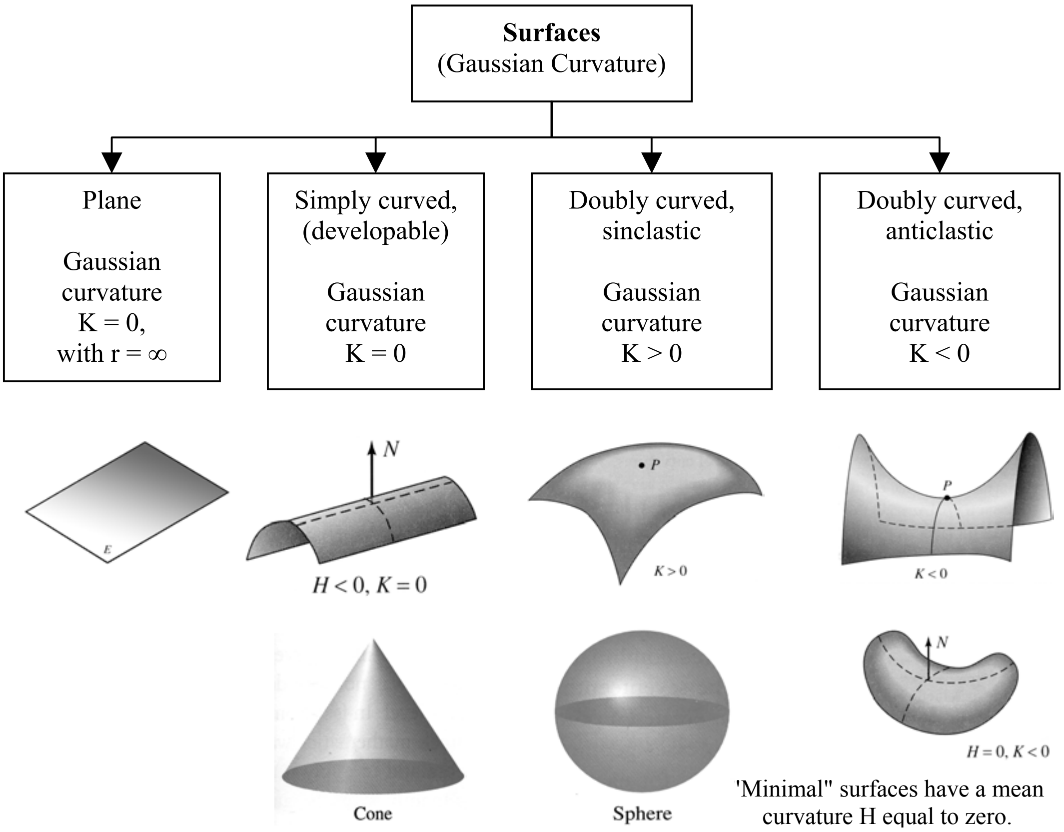
A surface *S*, a tangent plane *E*, a point *P*, and a normal direction *N*.

A bushel of normal planes at *P* determined by a normal direction *N*.

Two normal planes and their normal sections

Figure 1. Curvature. Main concepts after [HIL96]

Figure 1 above recalls the main concepts on curvature, which support the classification of surfaces presented below in Figure 2.



'Minimal" surfaces have a mean curvature H equal to zero.

Figure 2. Surface classification. Curvature

Surfaces can be specified and classified in various manners. Following the proposal of Gheorghiu and Dragomir [GHE78] surfaces for the building practice can be primarily classified according to the value of their *Total or Gaussian* curvature and then sub-classified after their mode of generation.

Processes leading to the generation of a surface can be divided into *geometric* modes of generation and *non-geometric* processes involving a form-giving agent, for instance, earth gravity, air pressure or pre-stress. For constructional purposes one of the most convenient methods of geometrically specifying surfaces is to consider them as paths or traces of straight lines and curves, as shown in Figure 3. Here, straight lines are normally used to represent the axes of structural members, while the nodal points of the network of axes represent the midpoints of physical connectors or the theoretical intersections of the structural axes. It is worth mentioning, that a large group of surfaces can be defined in terms of the so called *homothetic* or *dilative translation* transformation [SBP94] [SBP02a] [SBP02b], where a reticulated or facetted surface is obtained by applying suitable combinations of the basic symmetry operations of translation and dilation, the latter in its two forms expansion and contraction, onto the generating elements. A special feature of the homothetic transformation is that it can be used to generate reticulated structures with perfectly plane meshes by keeping the straight generating lines called *generatrices* parallel in 3D-space. *Revolution* surfaces can even be defined from a homothetic viewpoint if the circular polygons around the surface axis are seen as generatrices, which can be obtained from each other by centrally dilating with respect to the rotation axis and sliding along the same line. A large number of *ruled* surfaces, in addition, involve a further transformation, namely rotation, leading to reticulated surfaces with non-planar facets, such as the hyperbolic paraboloid generated by translating a straight line along two skew lines in 3D-space, while remaining parallel to a *directing* plane.

The more general group of surfaces is that of *free forms*, whose geometric specification relies on the special mathematics and procedures summarized under the name of *NURBS*, where this term stands for *non-uniform rational B-splines*. NURBS-surfaces and -techniques allow the specification of practically any imaginable form. Unlike the algebraic surfaces, like the cylinder, the sphere or the various paraboloids, which can be directly specified by fixed equations, free forms or NURBS-surfaces require a complex construct of mathematical objects, like lines, curves and planes, formula and procedures, which interact to specify or even create a new a form in an iterative way. The practical form designer very seldom gets involved in the lengthy and complex mathematics of free-form surfaces, but he makes use of specialized programs [RHI03] where the abstract objects and functions of the mathematical system have been implemented as CAD-tools. Thus, these tools are used, even intuitively, to develop, geometrically construct and manipulate free-form surfaces.

The lower part of Figure 3 shows in a schematic way various geometric components, which are involved in the NURBS-modelling of a free-form surface. The designer normally starts by defining the boundary lines of the whole surface and then divides it into smaller simpler areas or patches, with the aid of lines and curves, to form a rough framework. Although simple lines and curves can be used to define the segments of the internal framework, a most frequently used curve is the *spline*, because it allows describing any shape. The density of the framework is usually determined by the complexity and smoothness of the surface to be modelled. The internal patch boundaries are, in general, significant cross sections of the surface and they are instrumental for the modelling of the patches. Form smoothness or “fairness” is the usual criterion to shape the curves segments and connect them at the nodes of the framework. The individual surface patches are then generated with the help of surface generating functions or tools, which potentially cover the whole inventory of individual geometric shapes. Once the surface patches are generated, the next action is to relate or connect them at their common boundaries in terms of curvature smoothness, tangency or simple vicinity. In the end, the complete surface should appear as a continuous shape. Free-form surfaces in the design of building envelops are usually complex and the definition of a *final* form, more than a simple modelling action, is a relatively long, iterative process of form modelling, function checking, correction and improvement.

Networks on free-form surfaces for reticulated structures can be obtained in various ways, for instance by extracting networks of intrinsic curves from the surface, by parallel projection of an external planar network onto the surface or by any other kind of mapping or geometric construction on the surface, as it is suggested in the lower part of Figure 3.

The non-geometric modes of generating surfaces for structures are referred to by most authors [SFB96] with the term *form-finding* methods, which can in turn be subdivided into *experimental* and *analytical* or numerical methods. Hanging of physical nets or fabrics, which is the traditional form giving source for compression grid shells; and soap bubbles, which point the way to shape pneumatic and pre-stressed textile membranes and cable nets with a minimal surface are well known examples of experimental form finding methods. The analytical form-finding methods, such and the “force-density” method and the "dynamic relaxation" method to produce analytical minimal surfaces, are mainly numerical counterparts of the physical, experimental methods. Figure 4 shows a brief summary of the non-geometric form finding methods.

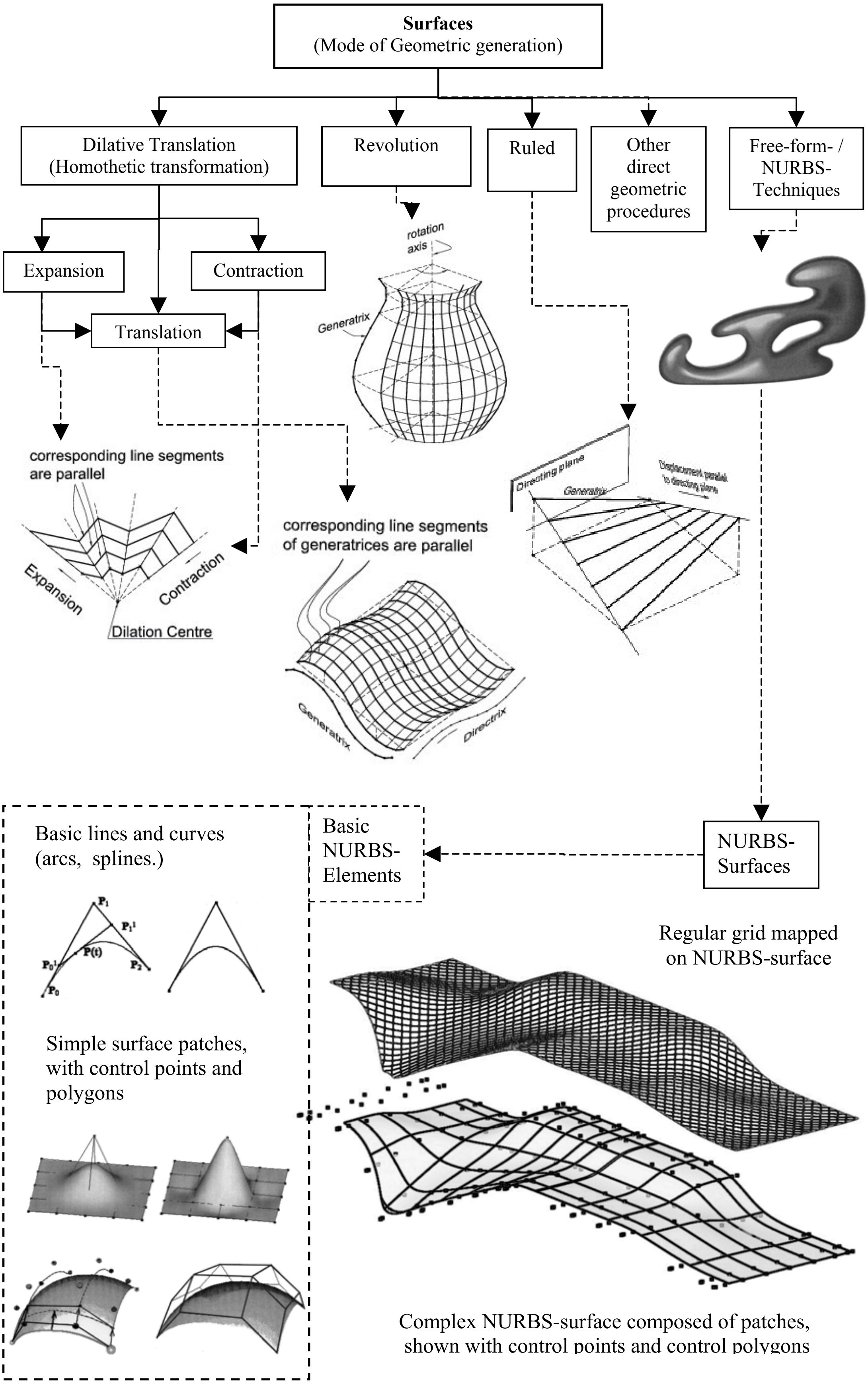


Figure 3. Surfaces. Geometric modes of generation.

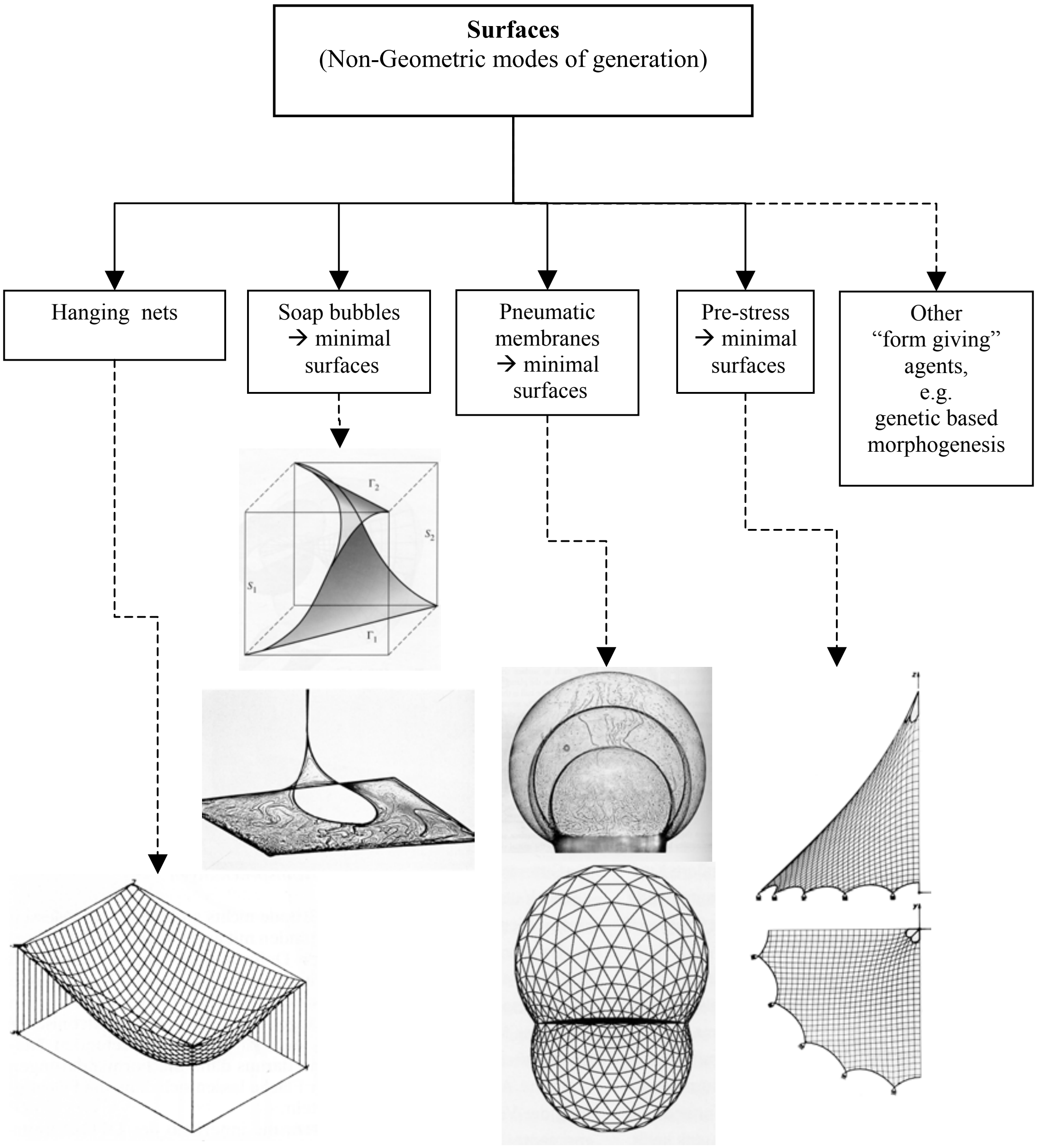
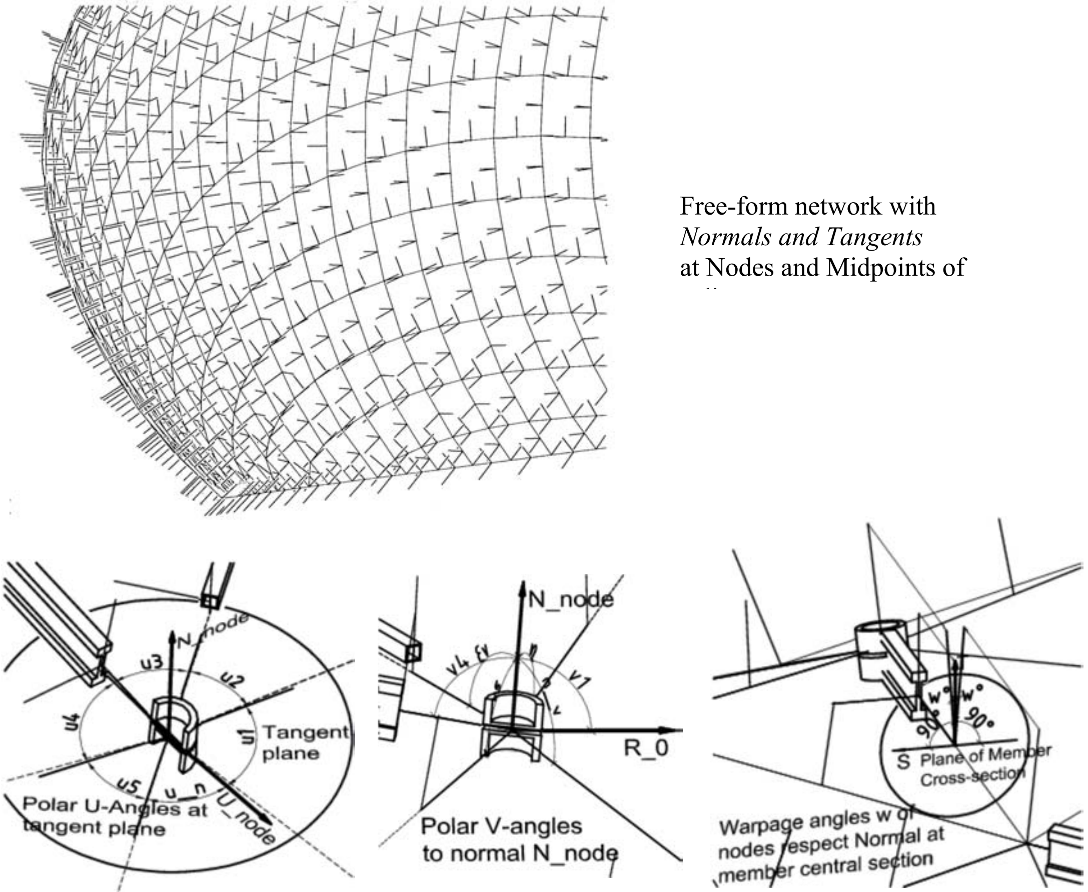


Figure 4. Surfaces. Non-Geometric modes of generation [SFB96].

3. Design of Free-Form Reticulated Structures

Prismatic structural members, such as T- or I-sections and rectangular or square sections, normally need to be properly placed and oriented with respect to the carrier surface. A network of lines usually defines the member axes in a reticulated structure and the nodal points the midpoints of physical connectors or theoretical intersections between the axes of the members. A plane surface is obviously the simplest case and the so called local systems of the non-symmetric members can be readily set parallel or normal to the plane of the structure. If the carrier surface has a unique reference point or axis, like a point for a sphere or a straight line for a regular cylinder, then the non-symmetrical members and connectors can be oriented in a way that one of their local coordinate axes point to a single reference point or drop perpendicularly to the reference axis. In the general case of free-form (NURBS) surfaces with a permanently changing curvature, the process of orienting non-symmetric components on the surface turns to be much more complex. Here, the local properties of surfaces, in particular, tangents and normals provide a consistent means to place and orient prismatic members with respect to a surface. The *Normal* at a node in a reticulated or facetted structure is usually obtained as the average vector of the facets Normals at the node. The *Normal* defining the local *vertical* axis of a prismatic cross-section is frequently obtained as the bisecting line of the angle between the two adjacent facets at the longitudinal axis of the section. The direction of this bisecting line can in turn be determined by the vector addition of the Normals of the adjacent facets.

The upper part of Figure 5 illustrates a line model of a free-form reticulated structure, which has been complemented with *normals* defining connectors axes at the nodes and *normal and tangents* at the midpoints of lines to define the local coordinate systems of structural sections. The lower part of the figure shows in some detail the way in which local entities are used to place and orient structural components on the carrier surface.



Free-form network with
Normals and Tangents
at Nodes and Midpoints of

a) Connector orientation and Members layout on the Tangent Plane around the Normal N_node

b) Members inclinations with respect to the Normal N. Positioning out of the Tangent Plane

c) Members twist specification at central cross-section with respect to the Normals at the end nodes

Figure 5. Application of local geometric entities: Normals and Tangent Planes

For simplification the polar angle U_i of a structural member on the node tangent plane is called “horizontal angle” of the member at this node (Figure 5a). The polar angle V_i of a structural member with respect to the node normal is called “vertical angle” of the member at this node (Figure 5b). The angle W_i between the normal plane of a structural member and the plane defined by the node normal and the longitudinal member axis is called “twist angle” of the member at this node (Figure 5c).

Hence the local geometry of a surface can be described through the set of local geometrical parameters U_i V_i W_i of all structural members connected to a certain node. These local geometrical parameters strongly depend on two main factors – the surface curvature κ and the member grid configuration.

The horizontal angle of a member at a certain node depends mainly on the grid configuration. Figure 6 shows exemplary two different grids – a quadrangular grid [1] with a bigger horizontal angle U_1 and a triangular grid [2] with a smaller horizontal angle U_2.

The vertical angle of a member at a certain node depends primarily on the surface curvature $\kappa = 1 / R$ in longitudinal direction of the member. Figure 7 shows exemplary two different curvatures – a small curvature $\kappa_1 = 1 / R_1$ with a smaller vertical angle V_1 [1] and a bigger curvature $\kappa_2 = 1 / R_2$ with a bigger vertical angle V_2 [2].

The twist angle of a member at a certain node depends on the grid configuration and the surface curvature. Figure 8 shows exemplary two different grid configurations (surface curvature remains constant) – the alignment angle G_1 results in a bigger twist angle W_1 [1] and the alignment angle G_2 results in a smaller twist angle W_2 [2].

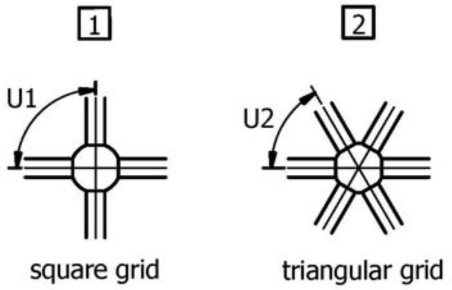


Figure 6. Horizontal angle for different grids

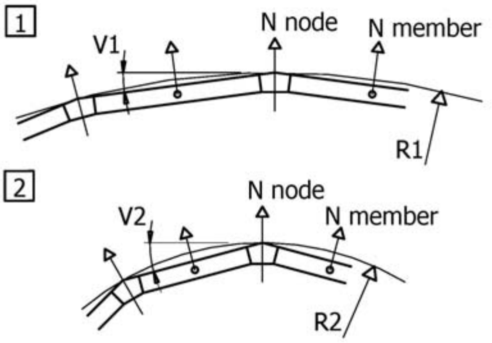


Figure 7. Vertical angle for different curvatures

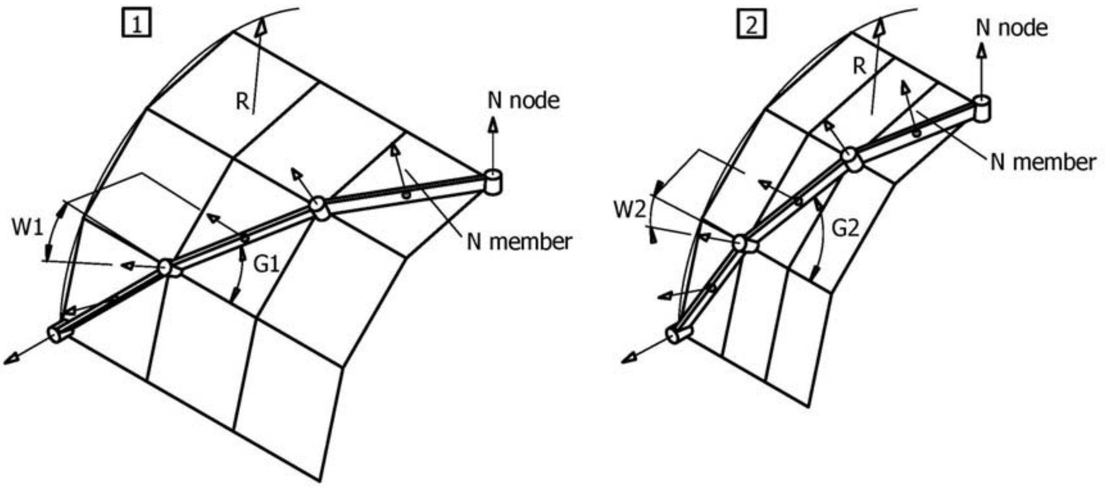


Figure 8. Twist angle for different grid configurations

The design of any non-optimized free-form, reticulated structure is complex by two reasons:

- The structural behaviour is generally not predictable. Mainly in single layer structures, the stress in the structural members can range from solely tension or compression stress to predominantly bending stress.
- The local geometrical parameters of structural members can vary widely in a structure. Even the local geometrical parameters of adjacent structural members at one node can be extremely different.

In principle, the form-finding methods mentioned above can be seen as optimization methods to influence the structural behaviour of free-form reticulated structures (structural optimization). The generation of reticulated structures using e.g. homothetic transformations to ensure perfectly plane quadrangular facets between the structural members or to avoid major variations of the local geometrical parameters, can be understand as an optimization method as well (geometrical optimization).

Despite the complex design, the number of non-optimized free-form structures has increased in recent years, primarily caused by the availability of CAD-programs with powerful NURBS-functions and architectural preferences for formal design without consideration of technical limitations.

Under these circumstances, the only way out is the design of a flexible node connector, capable to cope with the changing structural behaviour and the varying geometrical parameters of the structural members.

4. Node Connectors for Double Layer Free-Form Structures

Among others, there are two main concepts for the realisation of free-form structures – single layer structures and double layer structures. The latter concept is well known since many years. Comprehensive comparisons of node connectors for double layer structures are published in [EBE75] [LAC77] [OCT02].

The classical node connector for double layer structures is the ball node connector (Figure 9). This type of connector was adopted in space frame systems like MERO, Krupp-Montal, Zueblin, Tuball (Octatube) and other. Design and calculation of this connection type is systematically described in [MER03] [OCT02]. Cladding elements are preferably connected to the ball node elements via point supports, e.g. spider connectors with rotules are often used as fixings of glazing elements. If cladding elements require linear support, secondary frames or purlins have to be connected to the ball nodes.

Figure 9. MERO Ball Node Connector

The complementary element to the ball node in double layer structures is the bowl node (Figure 10), which was developed by MERO GmbH, Wuerzburg, Germany. The bowl node allows the use of structural members with prismatic cross sections (e.g. RHS) in the outer layer as a direct support of cladding elements. The design of this connection type is described in [MER94]. In the last few years the combined application of ball node and bowl node connectors has enabled the successful realization of several double layer structures with ambitious or free-form geometry like the Stockholm Globe Arena [KLI89], the Eden Project [KNE01] and the Singapore Arts Center [SAN02].

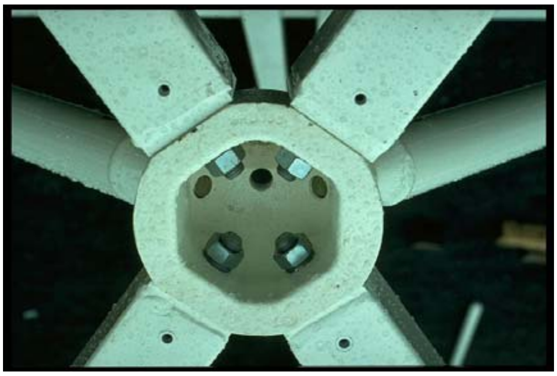


Figure 10. MERO Bowl Node Connector

5. Node Connectors for Single Layer Free-Form Structures

The grown importance of single layer structures in the recent years was induced by the architectural preference for transparent building envelopes. Node connectors for single layer structures can be divided in two fundamental groups – splice connectors and end-face connectors. A first comparison of node connectors for single layer structures was done by K. Fischer in [KFI99]. Below most of the hitherto established node connectors will be described and compared among each other.

5.1. Splice Connectors

These node connectors are characterized by the following:

- The contact surface between the node and the connected structural member runs along splice plates in the longitudinal axis of the member
- The fixing can be realized as a bolted splice with shear-stressed bolts or by welding.

In 1988 Schlaich Bergermann & Partner, Stuttgart, Germany, published the basic principles of a reticulated structure with a splice connector [SBP88], whose first implementation SBP-1 is shown in the Figures 11 and 12. The node connector consists of two flat plates that are connected by a single central bolt. Simultaneously, a clamp for cable bracings can be connected to the node through the central bolt. Each structural member is connected to the horizontal splice plates by two or more bolts in single shear. The central bolt allows for an easy adjustment of the horizontal angle U_i between the structural members. Vertical angles can be accommodated by folding the splices plates. Twist angles can be adjusted only the in very limited range of imperfections. In consequence of the small section height of the splice plates, this node connector can transfer only limited bending moments.

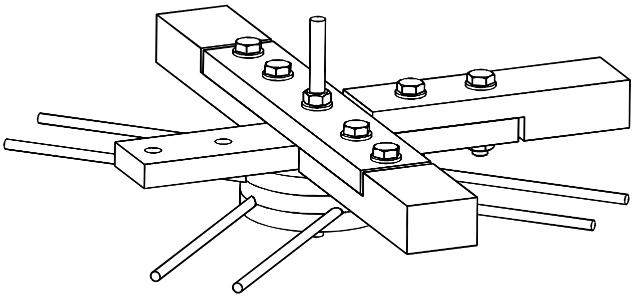


Figure 11. Splice Connector SBP-1

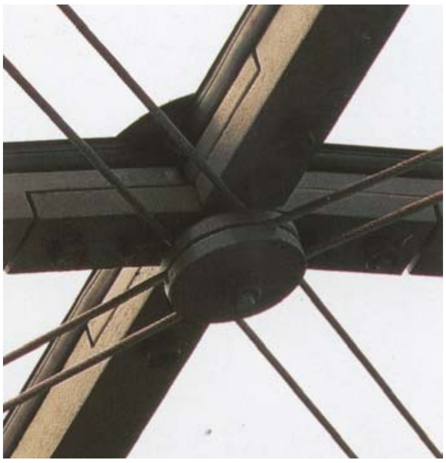


Figure 12. Splice Connector SBP-1

This implementation of the splice connector was successfully used in several free-form structures, such as the courtyard roof of the City History Museum in Hamburg or the roof of the indoor swimming pool in Neckarsulm [SBP92a] [SBP92b][SBP03].

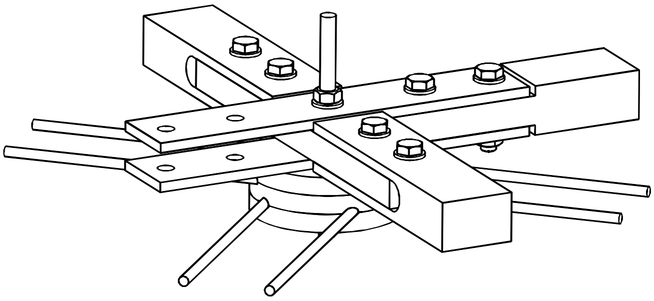


Figure 13. Splice Connector SBP-2

Figure 13 shows the subsequent modification SBP-2 of the original splice connector. The modified node connector consists of three flat plates that are connected by a single central bolt as in the previous version. The two outer horizontal splice plates are connected to machined lug fittings at the end of the structural members by two or more bolts in double shear. The inner splice plate is connected to machined fork fittings at the end of the other structural members by two or more bolts in double shear. The limits for the horizontal, vertical and twist angles are the same as for SBP-1. Due to the double shear connection higher bending moments than with SBP-1 can be transfered. Among others this version of the splice connector was proposed for the roof structure of the railway station Berlin-Spandau [SBP99].

Figure 14 shows the implementation HEFI-1 of a splice connector, which was published in 1999 by Helmut Fischer GmbH, Talheim, Germany [HFI99] [KFI99]. The node connector consists of two flat discs with a circular groove and four holes. The structural members have machined fittings with shear tongues at their chamfered ends. The shear tongues are plugged into the grooves of the two discs. The discs and the structural member are fixed together by bolts.

Horizontal, vertical and twist angle of a structural member at a node could be accommodated by the geometry of the machined fittings at the corresponding end of the member within certain limits. The splice connector HEFI-1 was applied for the courtyard roof in Berlin Friedrichstrasse no. 1991-1992 and the Hippopotami House of the zoological garden in Berlin [KNA98] [SBP03].

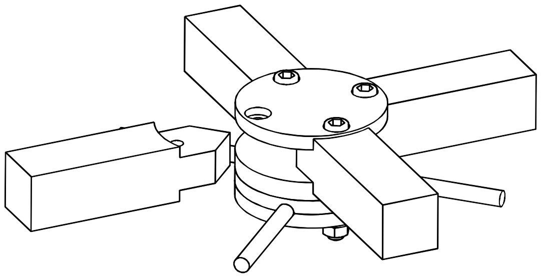


Figure 14. Splice Connector HEFI-1

Figure 15. Splice Connector SBP-3

Figures 15 and 16 show the implementation SBP-3 of a splice connector developed by Schlaich Bergermann and Partner in 1996 for the inner court roof of the DZ-Bank in Berlin [GAR99] [SBP03].

The node connector consists of a solid plate with up to six horizontal finger splice plates. The structural members have machined fork fittings at their ends, which are connected to the finger splice plates of the node by two or more bolts in double shear. Horizontal, vertical and twist angles of a structural member at this node can be accommodated to a certain extent by the geometry of the machined finger splice plates.

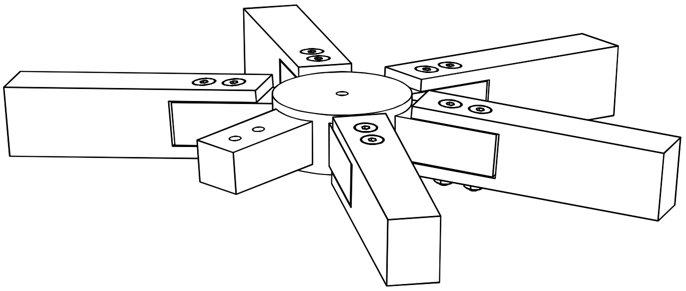


Figure 16. Splice Connector SBP-3

Figure 17 shows the principle design of a splice connector with vertical splices POLO-1. A similar node design was developed by Polonyi & Fink, Cologne, Germany, for the canopy roof of the railway station in Cologne [WOE88].

This node connector consists of a cylindrical or prismatic core and up to six vertical splice plates. The structural members have vertical fork fittings at their ends, which are fixed to the splice plates by two or more bolts in double shear.

Optional the splice plates can be realized as fork fittings – in this case the structural members will have lug fittings at their ends. Horizontal, vertical and twist angles of structural members at a node can be accommodated by the geometry of the splice plates. Due to the more favourable orientation of the splice joint higher bending moments can be transfered.

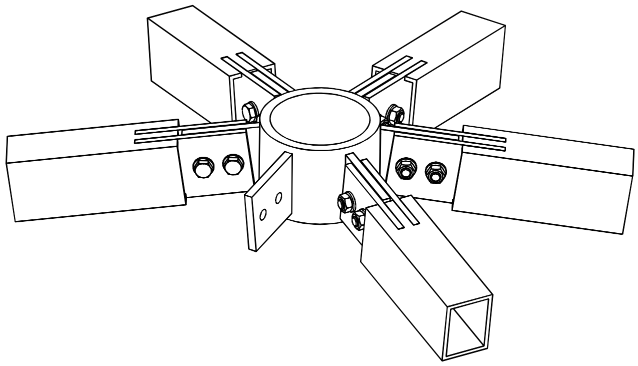


Figure 17. Splice Connector POLO-1

A basically similar node connector was developed by Schlaich Bergermann & Partner for the vestibule roof of the Deutsche Bank building in Berlin [GAR98].

5.2. End-Face Connectors

These node connectors are characterized by the following:

- The contact surface between the node and the end-face of the connected structural member is transverse to the longitudinal axis of the structural member
- The connection can be realized as an end-plate connection with tension-stressed bolts or by welding.

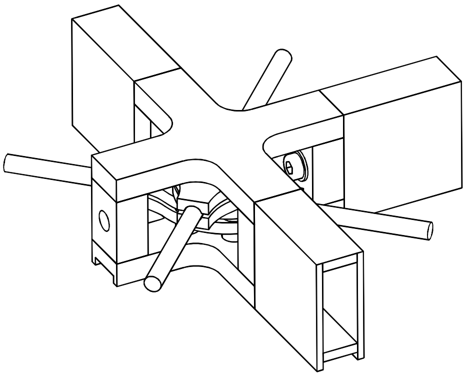


Figure 18. End-Face Connector SBP-4

Figure 18 shows the implementation SBP-4 of an end-face connector developed by Schlaich Bergermann & Partner for the Schlueterhof courtyard roof of the German Historical Museum in Berlin [SBP03]. The node connector is made of two cross-shaped plates and four end plates that are welded together. The structural members are connected to the node end-faces with butt welds. During erection, the structural members can be provisionally fixed to the node end-faces by bolts. In the cavity between the two cross-shaped plates, a clamp for cable bracings is connected to the top plate by four bolts. Horizontal angles of structural members at this node can be accommodated only by the prefabricated geometry of the cross-shaped plates. Vertical angles can be adjusted to a certain extent by the geometry of the machined node end-faces. Twist angles can be accommodated only in the limited ranges of imperfections. In consequence of the considerable section height of the node end-faces, high bending moments, up to the full member strength, can be transferred.

The node, shown in the figures 19 and 20, is the welded end-face connector WABI-1, which was developed by Waagner-Biro AG, Vienna, Austria, for the courtyard roof of the British Museum in London [WAB00] [WAB01]. The node consists of a star-shaped plate with 5 or 6 arms.

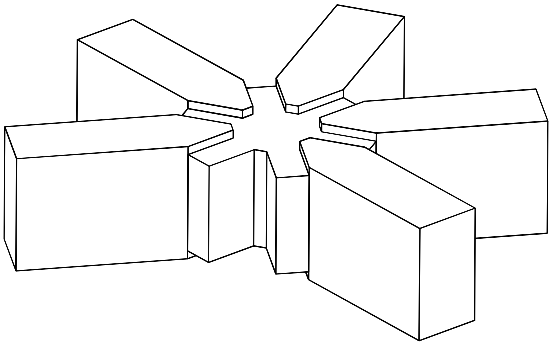


Figure 19. End-Face Connector WABI-1

Figure 20. End-Face Connector WABI-1

Each arm runs between adjacent structural members. These nodes are made from thick plates by cutting perpendicular to the plate surface. The end-faces of the structural members have a double mitre cut to match with the corresponding node gap between adjacent arms. The thickness of the node plate is less than the height of the connected structural members. Top and bottom surface of the node plates are connected to the members by fillet welds, the side surfaces are connected by butt welds. Horizontal, vertical and twist angles of structural members at this node can be accommodated by the geometry of the double mitre cuts at the end of the members. High bending moments, up to the full member strength, can be transferred.

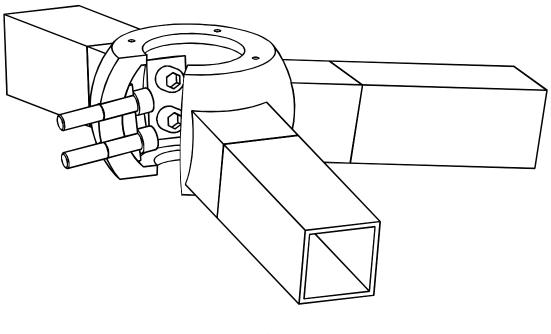


Figure 21. End-Face Connector OCTA-1

Figure 21 shows another end-face connector OCTA-1, that was developed by Octatube Space Structures BV, Delft, Holland, as a modification of the Tuball node system [OCT02].

The node is made from a hollow sphere with openings at the top and the bottom. Each structural member is connected to the node sphere by two bolts, which are mounted from inside of the hollow sphere. Horizontal, vertical and twist angles of structural members at this node can be accommodated by the geometry of the two bolt holes for each member. A direct support of cladding elements by the members across the node connector is not feasible.

In 1994 MERO GmbH, Wuerzburg, Germany published a series of end-face connectors along with the bowl node, which was called “MERO Plus” [MER94]. One of these node connectors is the cylinder node MERO-1, which is shown in figure 22 and 23. The node is made from a hollow cylinder with openings at the top and the bottom. Each structural member is connected to the node cylinder by two bolts, which are mounted from inside of the hollow cylinder. Horizontal, vertical and twist angles of structural members can be accommodated by the geometry of the machined plane surfaces at the node. The connection enables the transfer of relatively high bending moments.

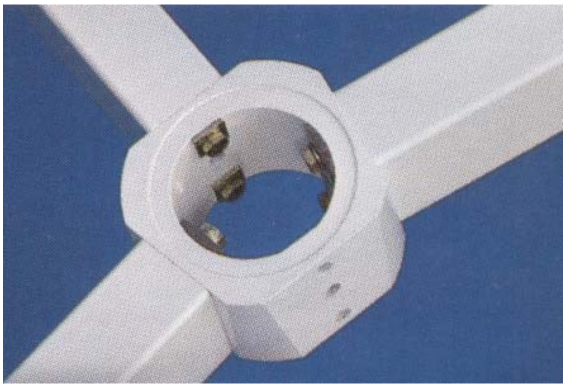


Figure 22. End-Face Connector MERO-1

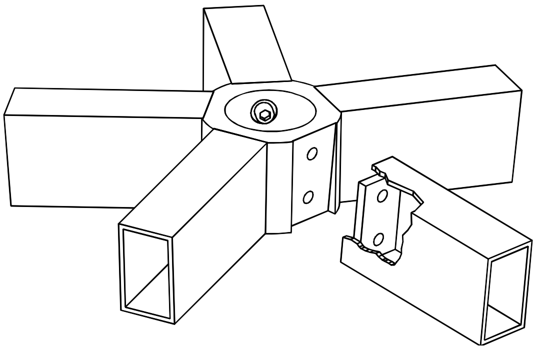


Figure 23. End-Face Connector MERO-1

Another “MERO Plus” connector is the block node MERO-2, which is shown in figure 24. The node is cut from a thick plate. Each structural member is connected to the block node by one or two bolts, which are mounted from inside of the structural member. Hence, the member must be a hollow section profile like RHS, SHS or CHS. Alternatively, the members can be welded to the node. Horizontal, vertical and twist angles of structural members can be accommodated by the geometry of the machined plane surfaces at the node. The bending capacity is similar to the capacity of the cylinder node MERO-1.

Another “MERO Plus” connector is the dish node MERO-3, which is shown in the figures 25 and 26. This node consists of a dish, i.e. a hollow cylinder with a bottom plate. The structural members are connected to the node by only one bolt. Horizontal, vertical and twist angles of structural members can be accommodated by the geometry of the machined plane surfaces at the node. The bending capacity of the connection is rather small.

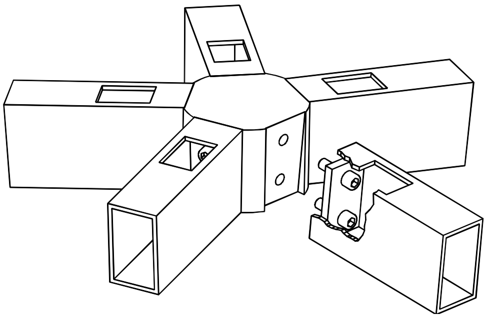


Figure 24. End-Face Connector MERO-2

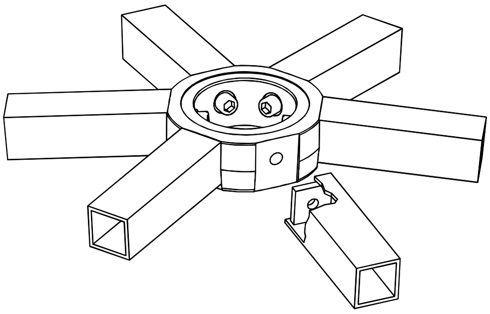


Figure 25. End-Face Connector MERO-3

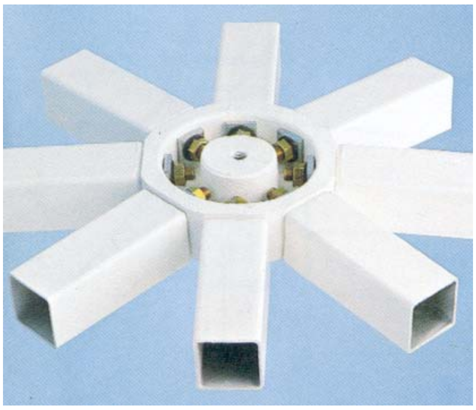


Figure 26. End-Face Connector MERO-3

Figures 27 and 28 show the recent implementation MERO-4[*] of an end-face connector. This node was developed by MERO for the roofs over the Central Axis and the Service Center of the New Fair in Milan, Italy. Both roofs are free-form reticulated structures. The roof over the Central Axis has a length of approx. 1300 m and a width of 32 m. The roof structure is divided into twelve structurally independent parts. Figure 30 shows the first two parts during construction. Totally, the structure has approx. 16000 nodes and 41000 structural members. The structural members are T-profiles with a height of 200 mm and a width of 60 mm. The roof structure is supported by approx. 180 columns. Six spikes at the top of each column are connecting the column with the roof structure.

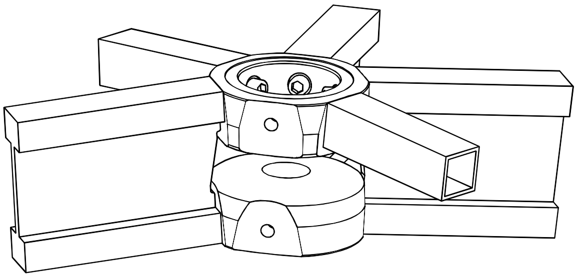


Figure 27. End-Face Connector MERO-4[*]

Figure 28. End-Face Connector MERO-4[*]

The node is in principle made of two dish nodes, one node for the top chord of the structural members, one for the bottom chord at the end of each member. The structural members are connected to both nodes by two bolts or by welding. Horizontal, vertical and twist angles of structural members can be accommodated by the geometry of the machined plane surfaces at the nodes. The connection is capable to transfer high bending moments.

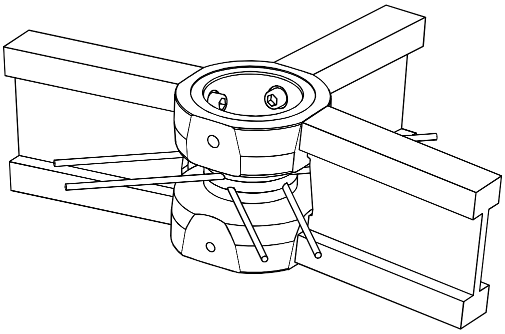


Figure 29. End-Face Connector MERO-4[*]

A further modification of the node MERO-4 is shown in figure 29. In this version a clamp for cable bracings is positioned in the cavity between the two dish nodes. The cable clamp is fixed to the top node by one central bolt.

Figure 30. New Fair Milan, Roof over the Central Axis during Construction

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[*] *Patent Pending*

5.3. Applicability of Node Connectors for Single Layer Free-Form Structures

Summarizing, figure 31 shows the applicability of the different node connectors for single layer free-form structures. Generally, most of the splice connectors require geometrical and structural optimization of the free-form structure, while the end-face connectors are geometrically more flexible and usually do not require a structural optimization.

However, this does not change the fact that non-optimized free-form structures are more complex and thus more expensive than optimized free-form structures.

Node Connector		**Accommodation of Local Geometry**			**Transferability of Internal Forces**		**Applicability**
Version	Connection	Horizontal Angle U_i	Vertical Angle V_i	Twist Angle W_i	Normal Forces	Bending Moments	Free-Form Structure Type
SBP-1	Bolted Splice	+	+	O	+	O	Geom. Optim., Struct. Optim.
SBP-2	Bolted Splice	+	+	O	++	+	Geom. Optim., Struct. Optim.
HEFI-1	Bolted Splice	++	+	+	++	++	Geom. Optim., Struct. Optim.
SBP-3	Bolted Splice	++	++	++	++	++	Geom. Non-Optim., Struct. Non-Optim.
POLO-1	Bolted Splice	++	++	++	++	++	Geom. Non-Optim., Struct. Non-Optim.
SBP-4	Welded End-Face	+	+	O	+++	+++	Geom. Optim., Struct. Non-Optim.
WABI-1	Welded End-Face	++	++	+	+++	+++	Geom. Non-Optim., Struct. Non-Optim.
OCTA-1	Bolted End-Face	++	+++	++	++	++	Geom. Non-Optim., Struct. Non-Optim.
MERO-1 (Cylinder)	Bolted End-Face	++	++	+	++	++	Geom. Optim., Struct. Non-Optim.
MERO-2 (Block)	Bolted End-Face	++	+++	++	++	++	Geom. Non-Optim., Struct. Non-Optim.
	Welded End-Face	++	+++	++	+++	+++	Geom. Non-Optim., Struct. Non-Optim.
MERO-3 (Dish)	Bolted End-Face	++	++	++	++	+	Geom. Non-Optim., Struct. Optim.
	Welded End-Face	++	+++	++	++	++	Geom. Non-Optim., Struct. Non-Optim.
MERO-4 (Double Dish)	Bolted End-Face	++	++	+	++	++	Geom. Non-Optim., Struct. Non-Optim.
	Welded End-Face	++	+++	++	+++	+++	Geom. Non-Optim., Struct. Non-Optim.

Notation	**O**	Limited Suitability	**Geom. Optim.**	Geometrically Optimized Surfaces
	+	Adequate Suitability	**Geom. Non-Optim.**	Geometrically Non-Optimized Surfaces
	++	Good Suitability	**Struct. Optim.**	Structurally Optimized Surfaces
	+++	Excellent Suitability	**Struct. Non-Optim.**	Structurally Non-Optimized Surfaces

Figure 31. Applicability of Node Connectors for Free-Form Structures

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