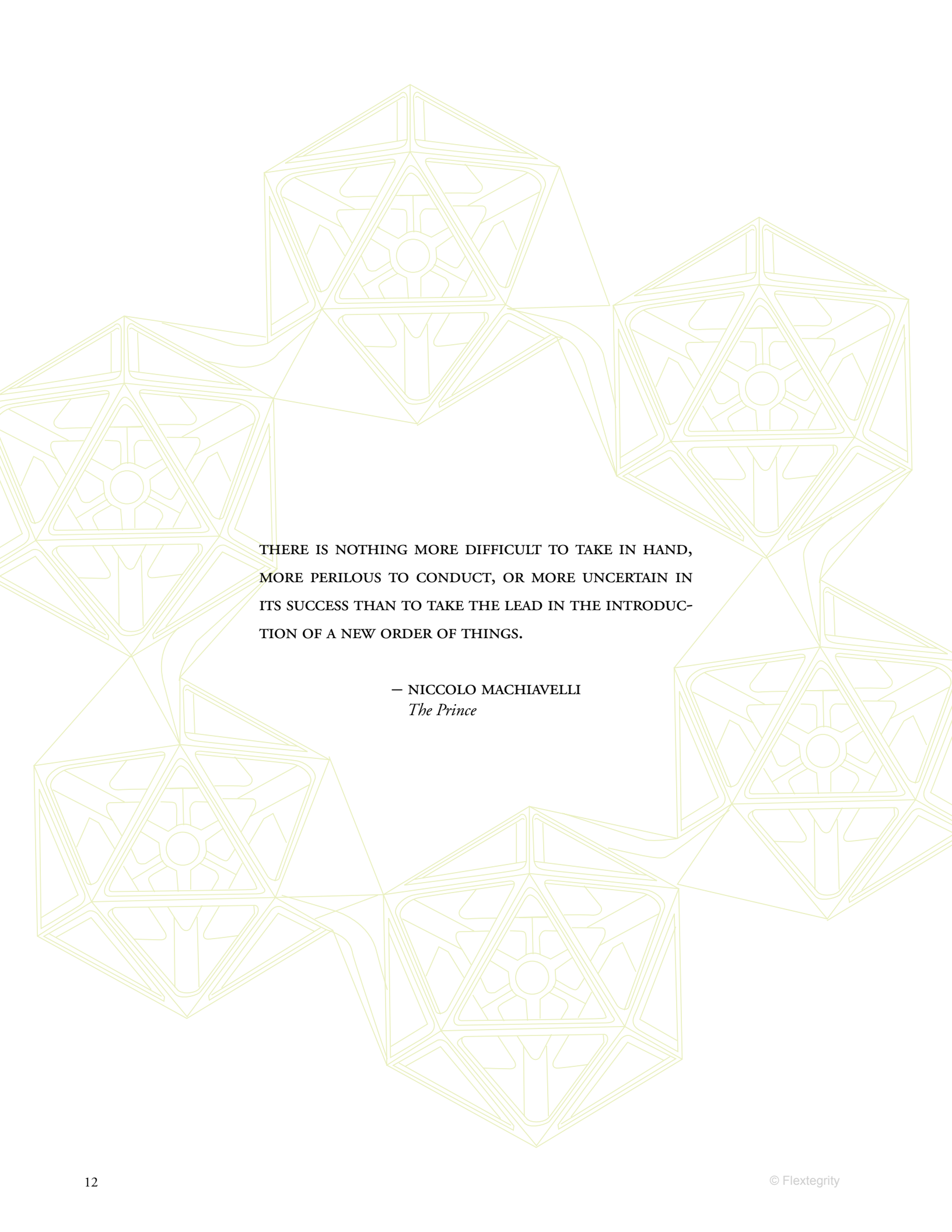




CHAPTER 2

The Geometry of the Invention



THERE IS NOTHING MORE DIFFICULT TO TAKE IN HAND,
MORE PERILOUS TO CONDUCT, OR MORE UNCERTAIN IN
ITS SUCCESS THAN TO TAKE THE LEAD IN THE INTRODUC-
TION OF A NEW ORDER OF THINGS.

— NICCOLO MACHIAVELLI
The Prince

The Invention

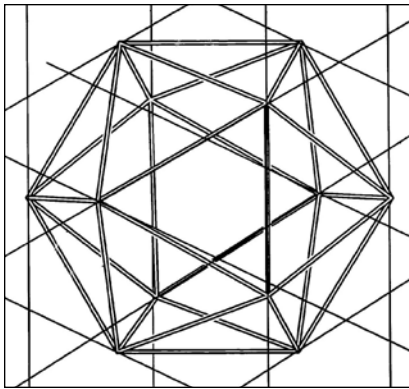


FIGURE 2.1
Icosahedron

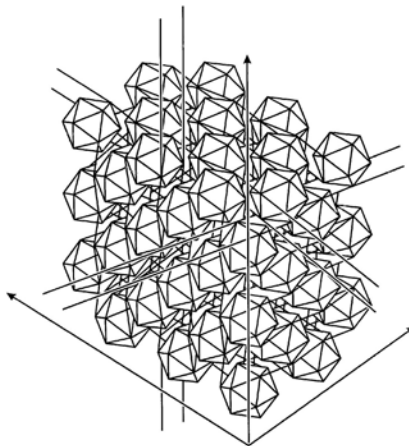


FIGURE 2.2
Icosahedron array

FLEXTEGRITY'S PATENTED GEOMETRIC APPROACH uses well-proven engineering principles in new ways to leverage inherent compression and tension forces of standard materials to their optimal natural performance. The geometry optimizes resistance to compression and shear by using polyhedral elements, in an array assembled with interconnecting tension members. The polyhedrons are naturally superior for omni-axial loading. The material is inherently stable, permeable, and ordered. In the abstract, the geometry can be expressed without regard to size or location; it is scalable from the very small to the very large.

In its most basic form, the omni-extensible Flextegrity array consists of multiple discrete polyhedrons positioned within a tensile connective network. Each polyhedron, by definition, is comprised of edges, faces and vertices, and may be solid, hollow, or 'wireframe' in structure. Each discrete polyhedron is a finitely closed entity having structural integrity independent both of the connection network and of other discrete polyhedrons in the array, and occupies a unique location that can be specified with Cartesian coordinates. And, as you shall learn, these properties can vary prescriptively throughout the array.

From the 'catalog' of all polyhedrons, icosahedrons or truncated regular icosahedrons are specifically and preferentially employed to achieve a fundamental structural integrity with a minimum use of materials. These five-fold symmetric polyhedrons also provide critical edges and faces lying in mutually orthogonal parallel planes, so that three-dimensional lattice structures might be formed. The icosahedral elements are not 'close-packed,' and as such the array is permeable. The resulting architecture produces omni-extensible 'hybrid' arrays and lattices comprised of 'micro-icosahedral cells' in 'macromolecular' clusters. These units may be further assembled into quasi-periodic assemblages to form hybrid materials with superior strength-to-weight ratios and precisely definable flexibility/stiffness gradients, among other characteristics.

According to the invention, interconnecting elements are used to tie the icosahedral elements together along the three Cartesian coordinate axes, forming a structural ‘fabric.’ The term ‘fabric’ is used in its broadest sense to refer to a structure that may be essentially entirely rigid, essentially entirely flexible, or may have any combination of rigidity and flexibility along any combination of axes.

The characteristics of the tensile ‘mesh’ connection network can modify the properties of the array as well. The interconnecting elements carry the tension within the array. Connections can be ‘discrete,’ bridging only two icosahedrons, or extend in a long, continuous fashion from a first polyhedron, to a second polyhedron, etc., on to an nth polyhedron. The connections serve to interconnect the polyhedrons, and when the array is in equilibrium, i.e., at rest and not under an applied load, to maintain them in a spaced apart configuration. The material from which the interconnecting elements and the icosahedral elements are formed may be flexible or rigid, or any combination of the two.

These micro-structured materials may be thought of as discrete new materials and combined with a macromolecular shape factor to create even more comprehensive hybrid materials. Arrays can be derived from sequential combinations of specific raw material stuffs, micro- and macromolecular shapes, connecting ligatures and the periodic ordering of space into lattices. The lattices can be organized into ‘bending’ and ‘stretch’ dominated types with further assignment of properties such as axial strength and flexural stiffness.

The normal state of Flextegrity’s arrays is not ‘solid state’ but a state of static equilibrium—‘equilibrated,’ the shorthand term I use to describe this important quality. ‘Equilibrated’ describes the basic state of the array at rest. Tension and compression are at a net zero. The components are at rest, the sums of the parts are at rest—the system is equilibrated.

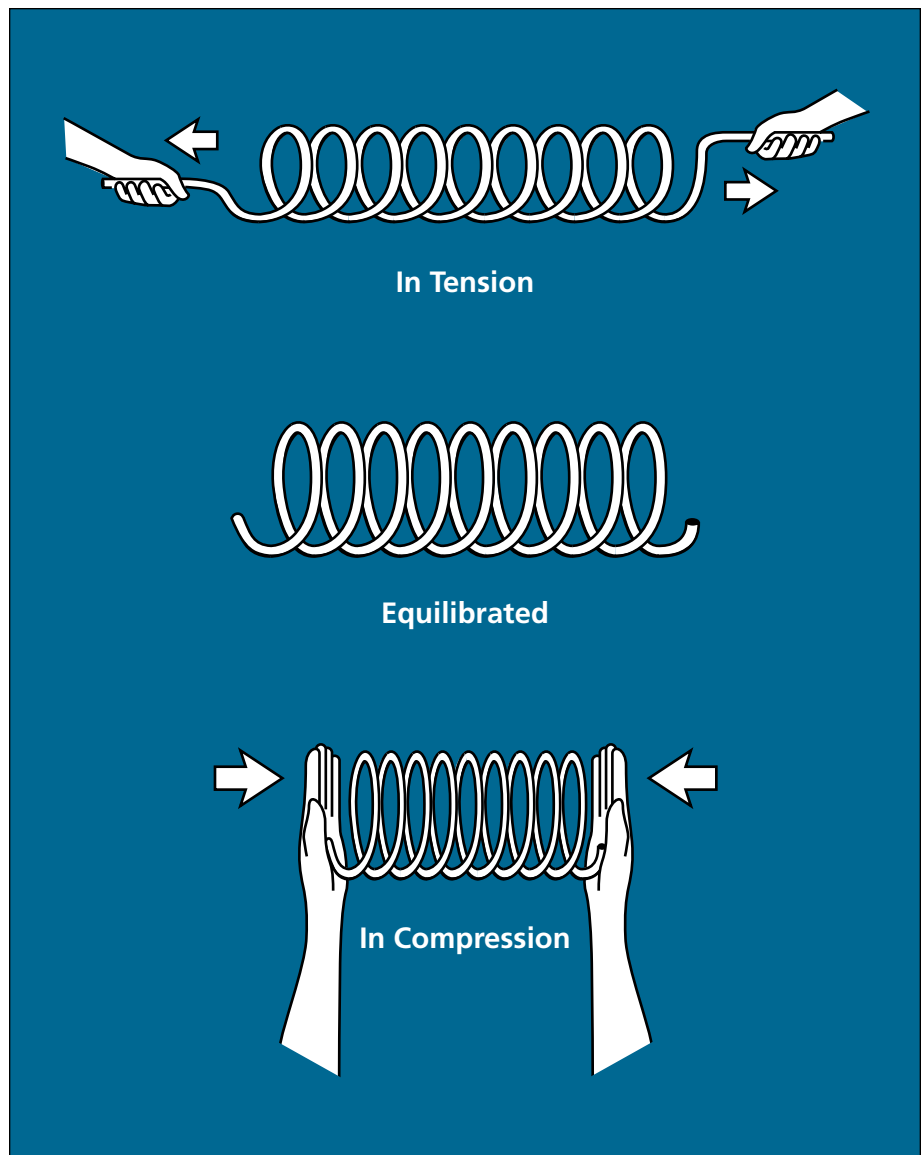


FIGURE 2.3

We can begin to think of the array as an integrated system where local stresses are being broadly distributed throughout the structure in a discontinuous elastic matrix. We may design the system on the assumption that local stresses are shared by all members. A corresponding multi-directional compression-tension network encloses accidental stresses wherever they arise. The tendency toward peripheral or localization of stress is replaced by a strategically engineered, multi-directional stress equilibrium. As an omni-extensible patterned array that can be assembled or deconstructed without loss of integrity, the material can be expressed in many forms.

Materials derived from these arrays may be molded, assembled, arranged and optimally shaped to address forces in axial tension, axial compression, bending, torsion and shear. Micro-analysis of the forces within the shape may also be used prescriptively to add or enhance localized

properties of the material that address problems leading to failure. This, in turn, allows further optimization of the existing macro-shape factor to address issues such as I-beams in torsion, bending and bulging of shapes in axial compression, vibration damping of torsional shafts and other challenges.

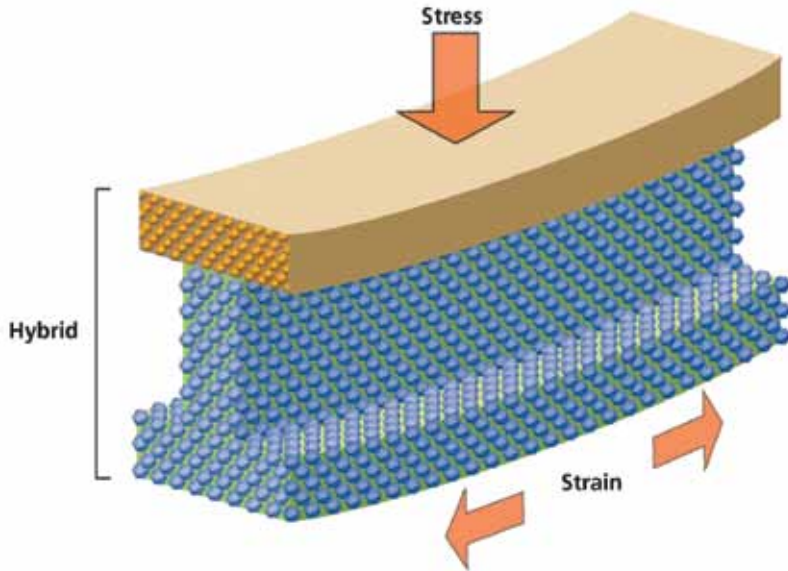


FIGURE 2.4
Micro-structure within an I-beam macro-shape

GEOMETRIC FOUNDATION: THE TRIANGLE

Flextegrity’s geometry begins with the triangle. It is the only polygon that is stable (rigid) by virtue of its pure geometry. It is remarkable how we frequently overlook this simple fact in designing our buildings and structures. Of the Platonic polyhedrons, the tetrahedron, octahedron and icosahedron are stable structures; the cube and the dodecahedron are not. This can be readily demonstrated by the construction of these ‘solids’ with dowels using surgical tubing for flexible pin joints at the vertices. Yes, filling the entire volume of a dodecahedron or cube results in a stable object (bricks!). However, filling a polyhedron’s volume simply to create a basic stability moves us further away from achieving greater strength with less weight.

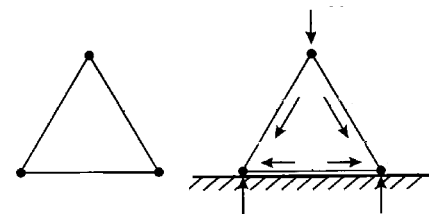


FIGURE 2.5
The triangle’s inherent stability

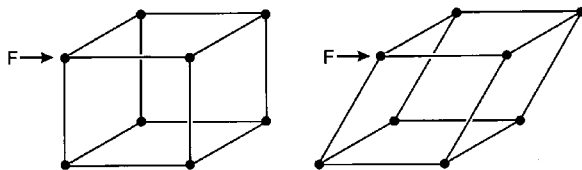


FIGURE 2.6
Cubes are inherently unstable.

It is impossible to overlook the elegant and efficient balancing of both external and internal forces represented in the triangle’s stable integrity. It is in a state of mechanical equilibrium (‘equilibrated’) when the sum of all forces on all vectors of the system is zero. As you will shortly learn, the triangle is also what gives the icosahedron its stability and what makes the omni-triangulated array work.

GEOMETRIC FOUNDATION: THE ICOSAHEDRON

The icosahedron is both simple and complex. Its inherent simplicity makes it an ideal shape to work with because it is stable, symmetrical and has edges and facets for attachments. Of the Platonic solids the icosahedron is the most complex of the three omni-triangulated polyhedron (the tetrahedron and octahedron being the other two). I know this is an advanced text but it is still worth reminding the reader that the cube and dodecahedron are inherently unstable. Its thirty edges belong to five distinct orthogonal sets of six edges each, such that all six edges within one set are mutually parallel or perpendicular to another set. This feature results from the five-fold symmetry of the icosahedron and is the central component in making the ordered tensile array possible. Edges are important to Flextegrity technology, as we shall see, because they provide places to attach other elements. And, as previously mentioned, of the polyhedrons that are members of the 5-fold symmetry group, none are as intrinsically stable as the icosahedron. **EVERYTHING IS TRIANGULATED!**

FIGURE 2.7
The icosahedron

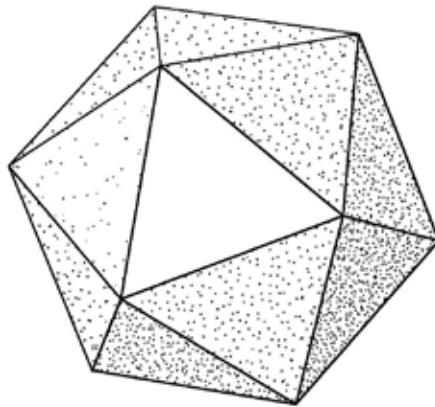
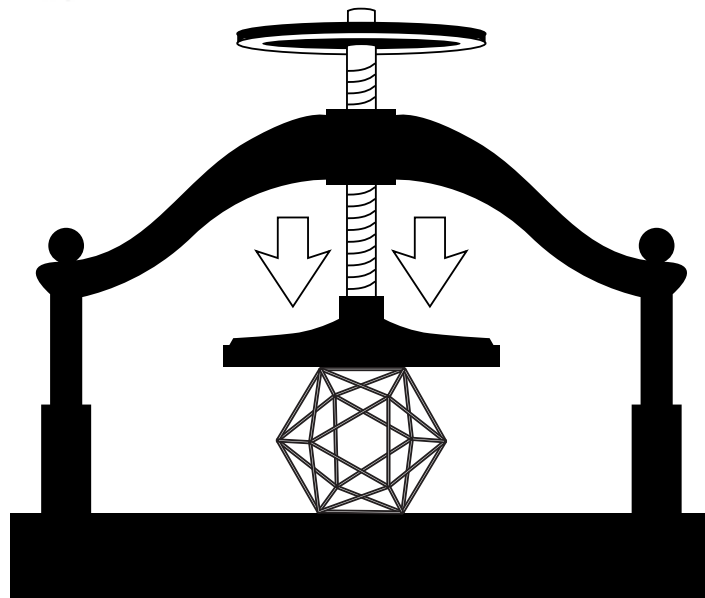


FIGURE 2.8
Omni-axial loading under
compression



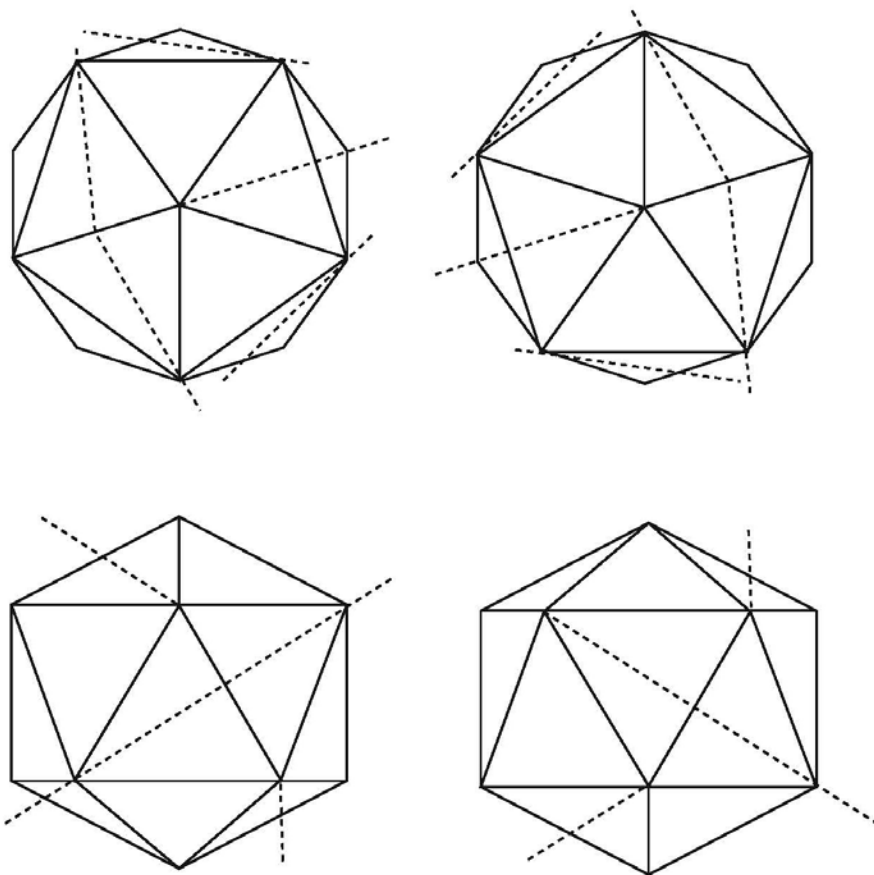


FIGURE 2.9
5-fold symmetry

ROTATIONAL SYMMETRY

In the world of biology some of the ever-economical viruses employ icosahedral symmetry for the construction of a shell made of identical units. Requiring a minimum of effort, this arrangement can arise automatically and satisfies nature's pervasive requirement of achieving maximum volume with minimum material. The icosahedron's sturdy triangulated functionality is also ideally suited to load-bearing functions. Rotationally 5-fold symmetric clusters of atoms embedded in a lattice are already a prevalent feature in the literature, especially since the discovery of buckminsterfullerene and icosahedral twin-bowties in the 1980s. Most, if not all inquiry has dealt with issues of clustering and close packing, which seems almost unnatural (in my view alone) because the icosahedron informs us otherwise. Others have attempted to get icosahedrons to close-pack and take advantage of the intrinsic arrangements of molecules under certain conditions. Atoms that typically form a cubo octahedral (FCC) arrangement compress to an icosahedral shape, possibly two or three layers thick, called MacKay shells. These clusters may then arrange themselves in a larger Flextegrity-type arrangement (see 'Florets').

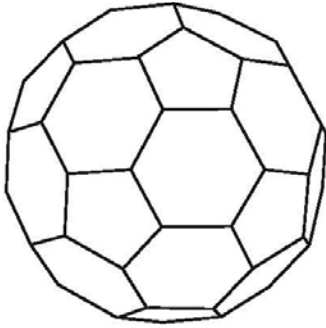


FIGURE 2.10
Truncated icosahedron

Furthermore, of the Platonic polyhedrons, the icosahedron most closely approximates the sphere, having the highest ratio of volume-to-surface-area. Multiple truncations (slicing off the ‘points’ of vertices) of other polyhedrons can approximate the theoretical sphere but will never achieve a load distribution as stable as the icosahedron. It has been noted earlier that all the faces of the three most stable Platonic structures are made up of triangles. However, introducing more truncations to simply try to approach the high volume-to-surface-area ratio of the sphere means more edges, more vertices and fewer stable triangulated polygon faces so there is no net gain after all the trouble.

So why not just use spheres? The sphere is often thought to be the optimal shape for robustness to compression. However, it is an amorphous shape. As Peter Pearce puts it, “It’s simply too symmetrical.”¹ When adding connecting features, the basic shape is compromised. The other problem comes when you want to lighten a sphere—it then becomes a shell. The compromised surface and the excavation necessary to lose weight eliminate any perceived advantages of the sphere over the stable polyhedrons. A natural advantage of the icosahedron is simply an artifact of its physical geometry: It provides natural facets and edges for attaching things. Limitless connector types can be designed for edges or faces, and vertices can also be connected using pin joints.

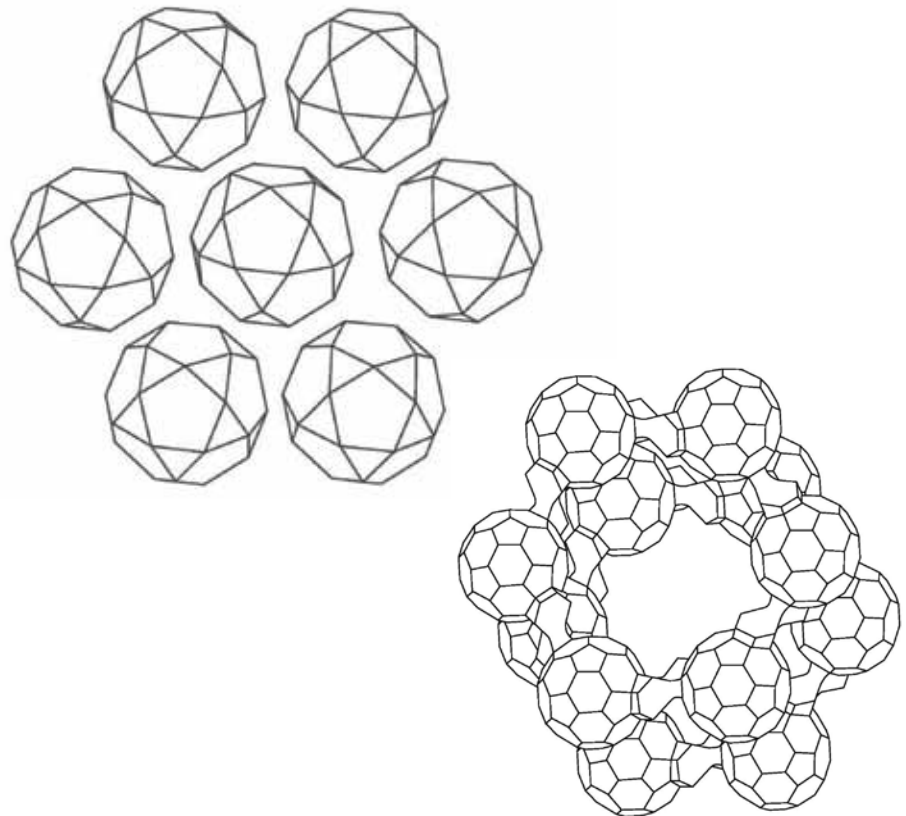


FIGURE 2.11
Truncated icosahedrons and
Icosidodecahedron

¹ Peter Pearce, *Structure in Nature Is a Strategy for Design*, The MIT Press, 1990

All things break, no matter how revered (this is particularly true of belief structures!). The icosahedron responds to external forces by first bending along the primary face bounded by three edges closest to the point of the load and then translating the loads to the vertices. The faces of the icosahedron do relatively little work according to structural analysis (and can readily be left ‘open’ with little decrease in performance). The vertices of the icosahedron resist the natural tendency to dimple and consequently the icosahedron is predictable from a structural standpoint: It breaks along the midpoint of an edge.

Analysis also reveals that to optimally resist loads on the surface and throughout the icosahedron, internal scaffolding is required to efficiently transfer the loads. In fact, internal support is structurally desirable rather than relying solely on the strength of the edge. Optimal design is not only about triangulating the surfaces, but the whole structure in multiple dimensions wherever possible.

There you have it! A triangulated, symmetrical object that is supremely economical for load carrying. The icosahedron IS the optimal stable geometry for applications in materials and structures.

6 | 12 DEGREES OF FREEDOM

Fuller has written, “Every ‘event’ in space is six-vectored. The resulting six positive and six negative vectors are symmetrically arrayed around this ‘event location’ in space. These universal degrees of freedom represent nature’s most economical movements of energy.” (*Synergetics*, Sec. 400.661) There are six positive and six negative exercises of the motion freedoms, but the freedoms themselves come from the fact that the minimum structural system in the Universe—the tetrahedron—consists of six vectors. Hence, as Fuller states, these are the six active and the six passive degrees of freedom, and they are always there. They operate in a plane: they are omni-directionally interarranged. Fuller’s entwinement of metaphor, a description of mechanical forces, and actual physical constraints on an object such as the icosahedron itself gets a little obtuse. I confine myself to talking about the physical model.

Think of the icosahedron as the event location, infinitesimally small. If I were to attach lines that extend from the center of

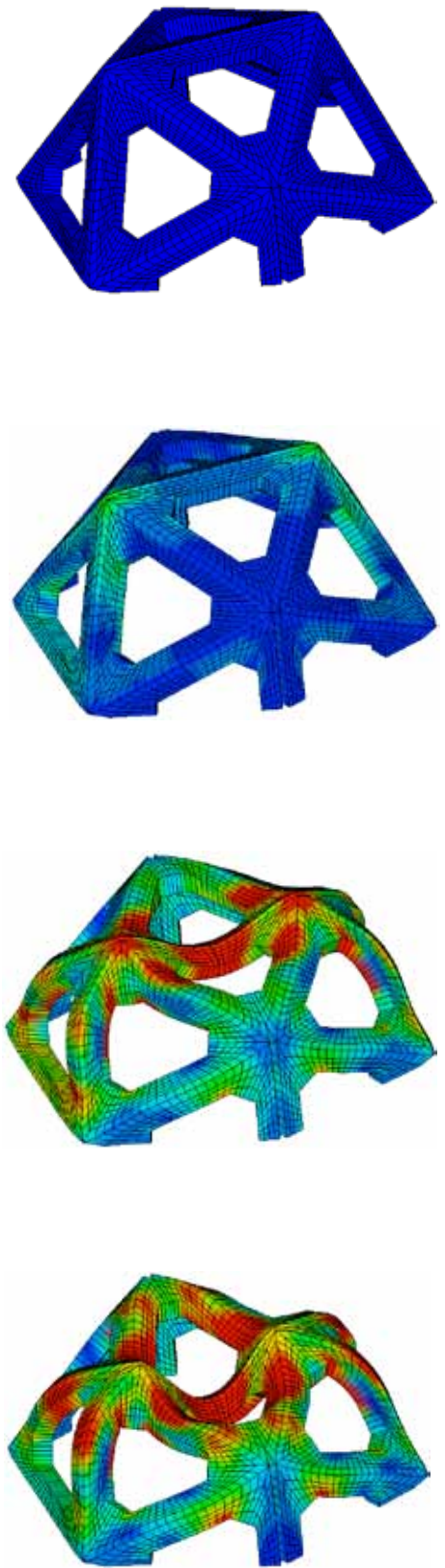


FIGURE 2.12
Icosahedral failure pattern

¹ R. Buckminster Fuller, *Synergetics 1*, Sec. 400.661, Macmillan Publishing Co., 1975

the icosahedron to an external restraint and to do so six times such that the lines intersected at the centers of the planes of a circumscribing cube. The cube is comprised of three sets of parallel orthogonal planes that provide by the six bounding planes. The icosahedron is now constrained in the six directions (Up, Down, Front, Back, Left, Right). Because the object is infinitesimally small the restraint itself is nominally the same size. The problem is that objects (structures) are not infinitesimally small and have volume that needs to be constrained across the surface. The challenge is restraining the object from rotating if ever so slightly because the object can still rotate somewhat. Pilots describe these rotations as 'pitch,' 'yaw' and 'roll.' Hence the object needs to be further constrained across its surface (as determined by volume) or from side-to-side, essentially creating parallel planes of restraint (see figure 3.2). The icosahedron provides the perfect solution with parallel edges suitable for making easy connections to tensile components.

FIGURE 2.13

v.3 icosahedron with multi-axial inter-connecting spring system, constrained twelve degrees of freedom

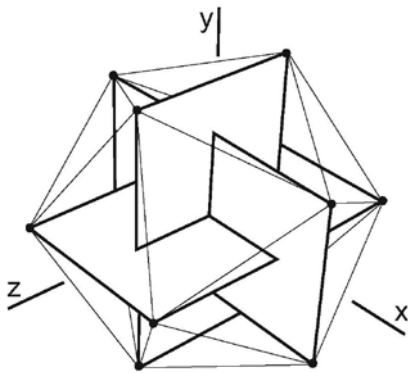
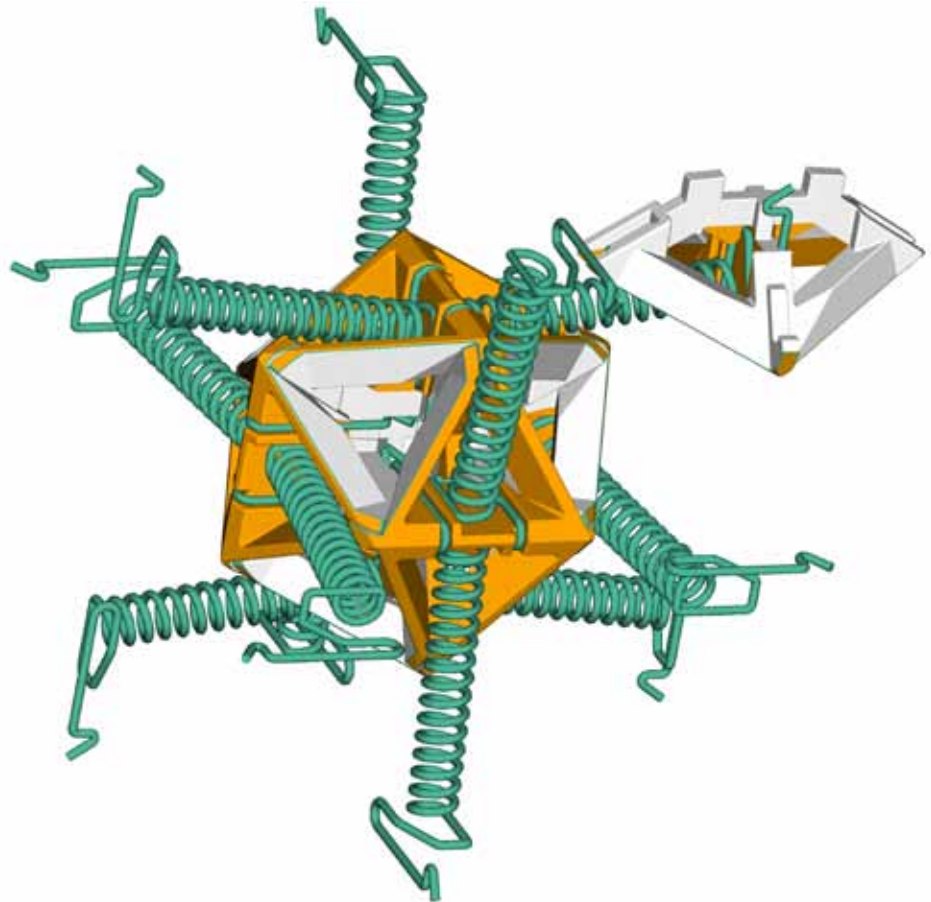


FIGURE 2.14

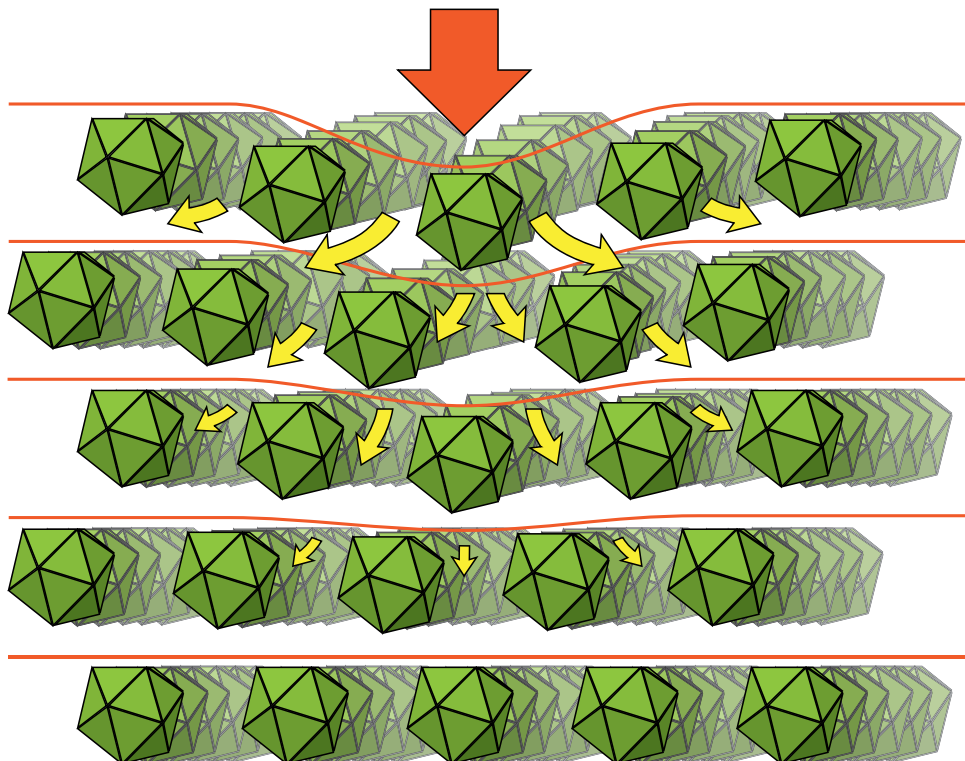
Each polyhedron in the Flextegrity array, like an object in space, can be described by the coordinating forces within these six degrees of freedom, namely the ability to translate in the X, Y and/or Z directions as defined by a fixed coordinate axis and/or to rotate about one or more of these axes. Because an icosahedron has volume it requires twelve restraints, as does the next icosahedron in the array and so forth. With the exception of the boundary layers, all polyhedrons in the interior

of the array are constrained by the twelve degrees of freedom. The connections are intended to constrain some or all of each polyhedron's twelve degrees of freedom completely.

The forces corresponding to the vectors are transmitted through the interconnecting members, which hold the icosahedrons in their relative positions within the ordered patterned array. While the force represented by one plane tends to displace the icosahedron to which it is applied in one direction, the interconnecting members in the two orthogonal directions tend to hold the other icosahedrons in place, preventing their relative displacement. Similarly with forces that tend to rotate the icosahedron, the other icosahedrons resist the rotation, preventing relative rotations of the central icosahedron.

When the array is subject to an external load such as an applied force or torque, one or more of the polyhedrons may be moved in response to the influence. In some implementations, at least one polyhedron, although constrained by its connections, may move from its equilibrium position into contact with an adjacent polyhedron. Depending on the specific implementation, the polyhedron's movement may be a translation, a rotation, or a combination of a translation and a rotation. The ability of a polyhedron to move within the array but remain connected to its neighboring polyhedrons allows the array to have 'flexibility' under compression and resist the forces being applied.

FIGURE 2.15
Behavior of array under load

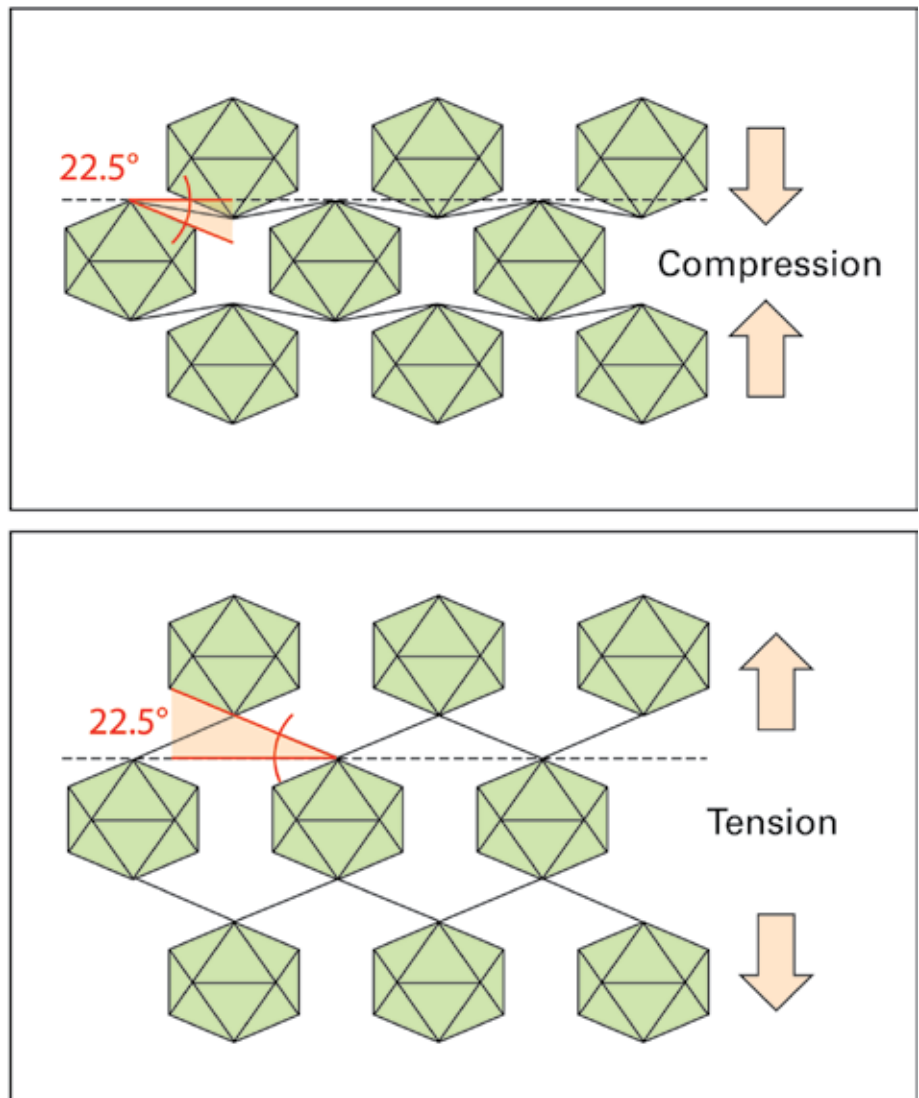


THE DIHEDRAL ANGLE

The array is allowed to contract uniformly along the three orthogonal planes. If you place two icosahedrons on a table with an edge up orientation, a board resting on the uppermost edges stretching between the two defines a horizontal plane (see diagram 2.16). The dihedral angle we're interested in is the angle between the horizontal plane just described and the angle of the face of the icosahedron. The angle can vary by 22 degrees. Decreasing the angle does have a limited effect on the array's response to loading. An alternative to the contraction is allowed but remains unexplored. Essentially, the material would expand as the components move farther apart from one another.

The encroachment into the plane of the adjacent icosahedron is a defining characteristic of the materials (Fig. 2.16). The contraction further stabilizes the array. The orthogonal planes of the interconnecting elements undulate to embrace its objective from all sides. Tension is continuous or can terminate.

FIGURE 2.16
Dihedral angle: between horizontal
plane and icosahedral face



BASIC UNIT: THE CUBO-OCTAHEDRAL CLUSTER

In its simplest form, each interior icosahedron has a connection to each of twelve surrounding icosahedrons, including the six surrounding icosahedrons in the same layer, three icosahedrons in the immediately adjacent upper layer and three icosahedrons in the immediately adjacent lower layer as depicted in the illustration. The distribution of icosahedrons involved in the resultant 'macromolecule' form a cubo-octahedron. In essence, each icosahedron forms the nucleus of a cubo-octahedral cluster or 'cell.' The adjacent icosahedron becomes the nucleus for the next 'cell.' Not surprisingly neither the icosahedron, nor the cubo-octahedral clusters they form, close-pack. It is this single cell that propagates in all directions.

There are essentially three 'layers' represented by the vertices of the cubo-octahedral geometry when the icosahedron is in the 'face up' orientation (more on this later). This is a useful way to organize the structure around what becomes five 'layers' when the interconnecting elements are included: the top layer of three icosahedrons; the interconnecting layer; the middle layer of seven icosahedrons; another layer of interconnecting elements; and the bottom layer of three icosahedrons. Again, think abstractly. The points do not need to be icosahedrons, simply points in space representing the center points of any polyhedron. Nonetheless, the underlying form is cubo-octahedral geometry.

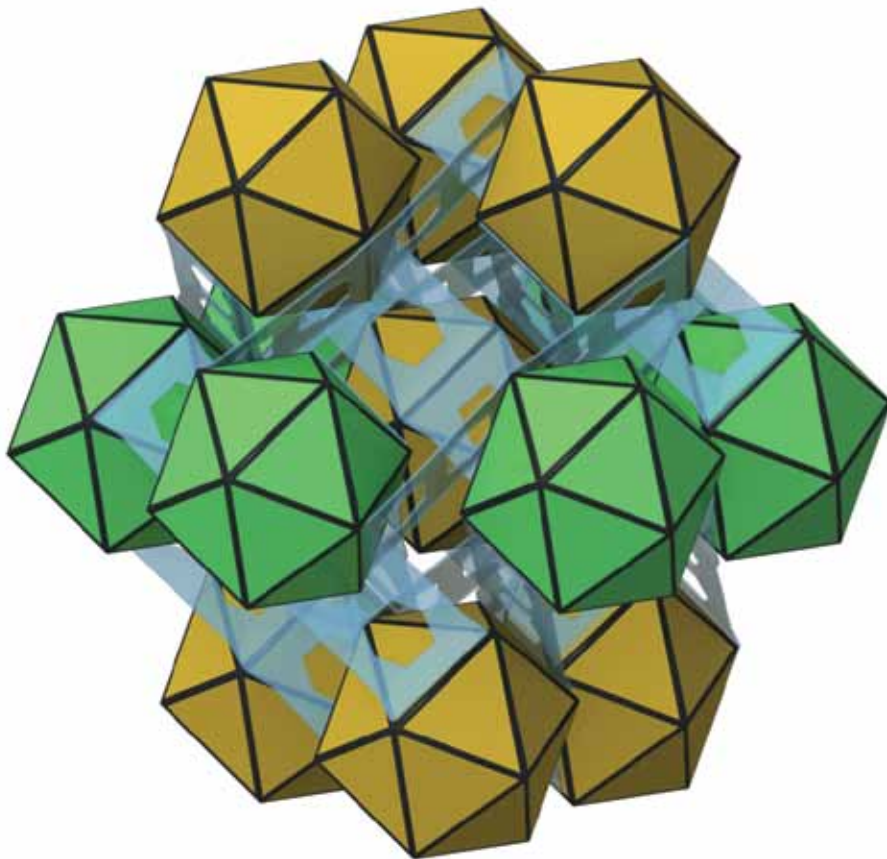


FIGURE 2.17

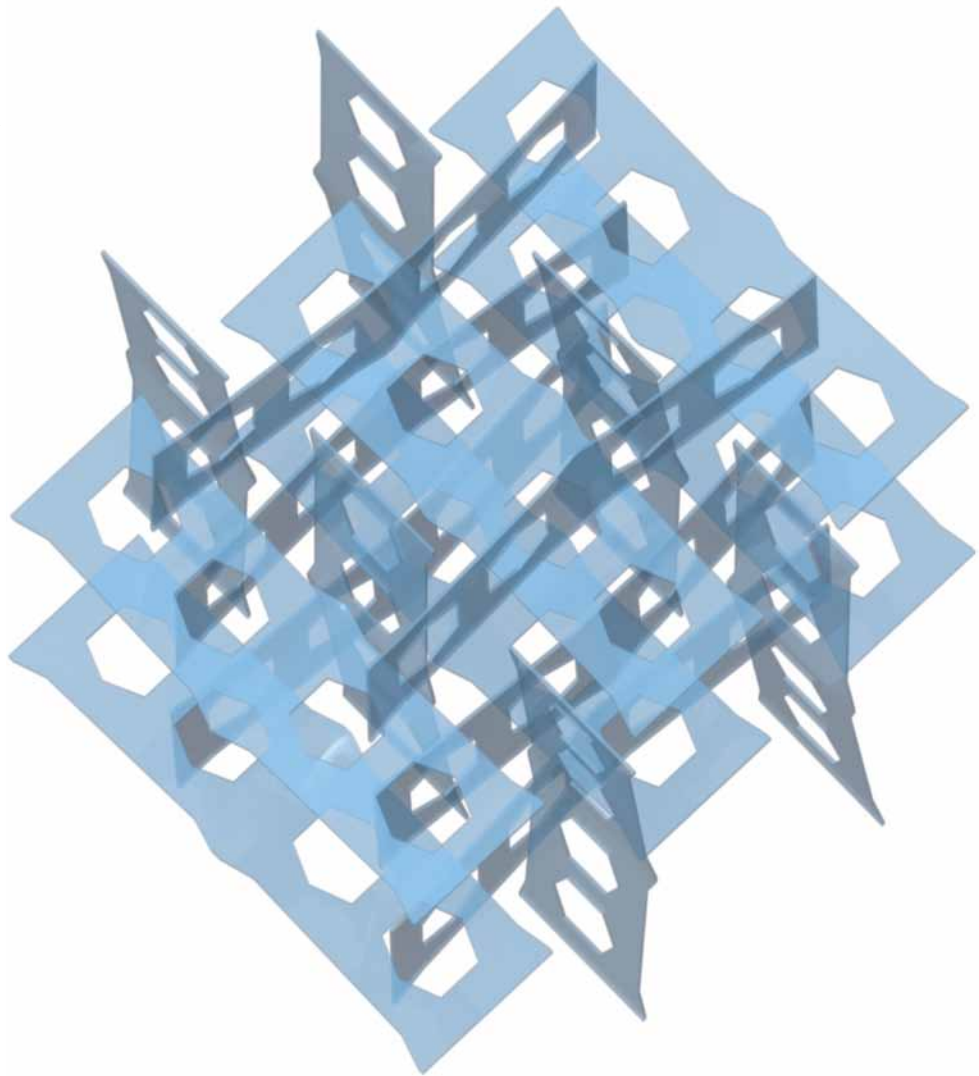
BASIC GEOMETRIES OF FLEXTEGRITY ARRAYS

Starting from the basis of the fully intact cubo-octahedron, four configurations or variations of the basic geometry can be described:

1. The first is the 'whole' fabric whereby 12 icosahedrons surround a central icosahedron—the fully constrained 12 degrees of freedom extended ad infinitum in any or all directions.
2. A second configuration reverses this idea and drops the icosahedron from the center of the middle layer, creating a regular periodic lattice structure.

FIGURE 2.18

The interconnecting elements form orthogonal planes



3. A third adaptation is the ‘hexaphorous’ ring assembly (see figure 2.33), which eliminates all icosahedrons in the top and bottom layers as well as the central icosahedron, leaving just six of the original thirteen (or essentially the middle layer minus certain central icosahedrons).

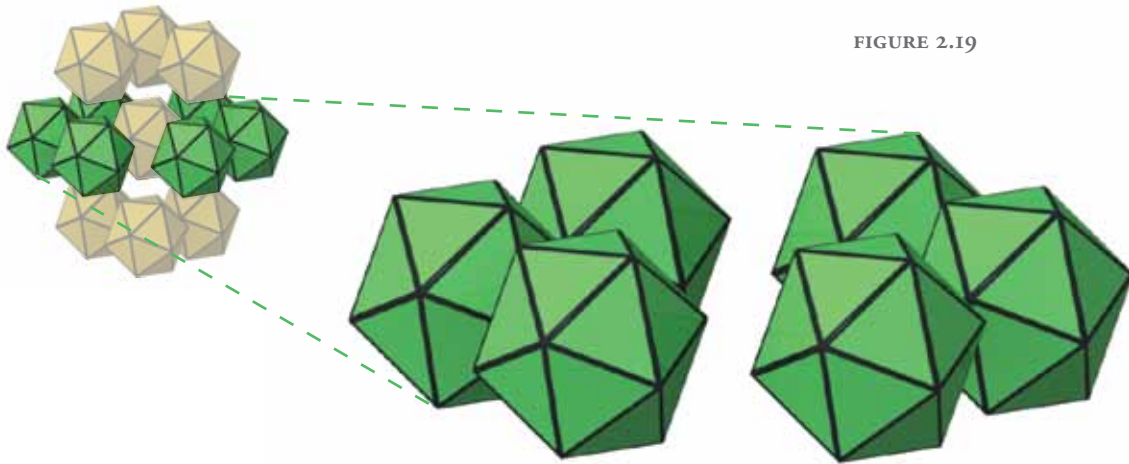
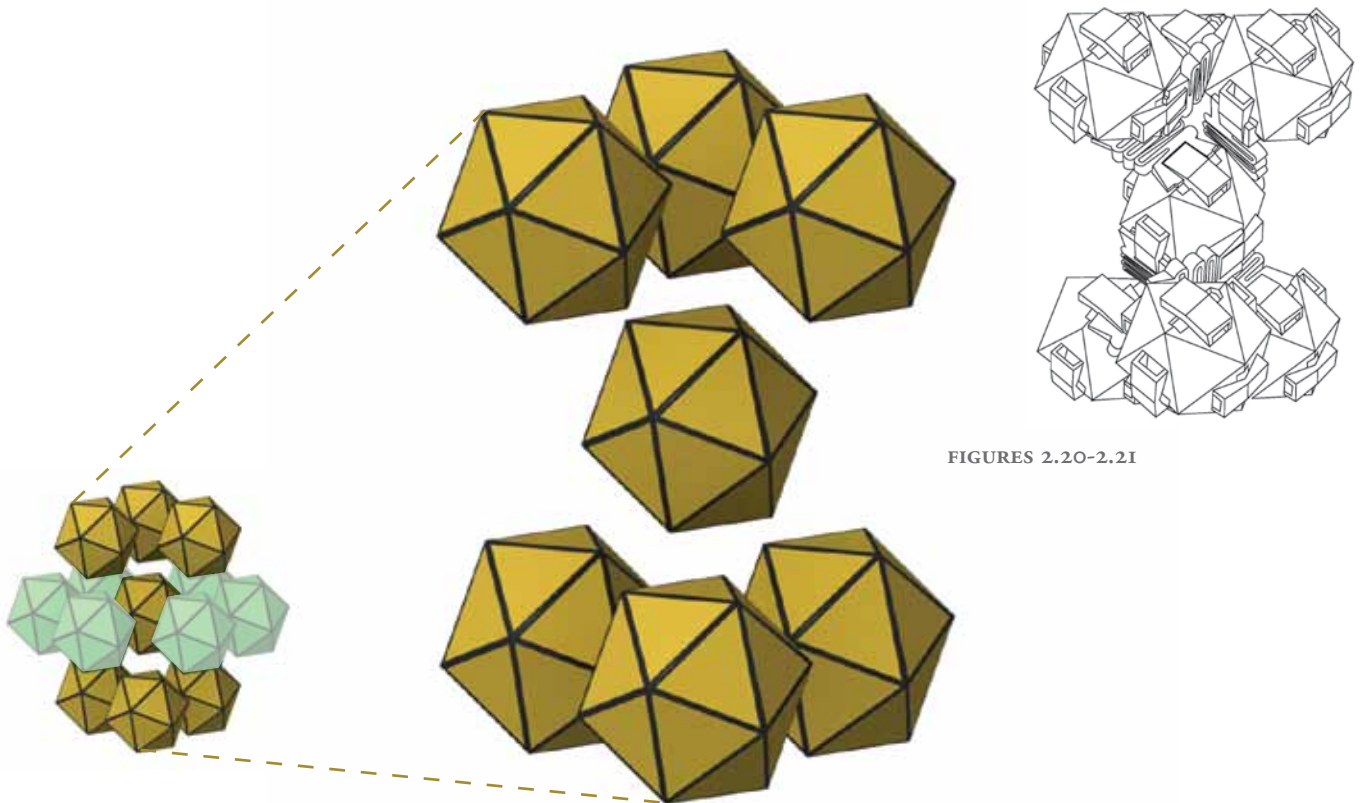


FIGURE 2.19

4. A fourth variation is somewhat opposite of the third, retaining three equilaterally positioned icosahedrons in the top and bottom layers and eliminating the six around the perimeter of the middle layer, with the resultant icosahedral cluster resembling an hourglass. This is similar to the ‘bowtie’ icosahedral twin crystal.



FIGURES 2.20-2.21

‘WHOLE FABRIC’ VARIATIONS

Even in its most basic, omni-extensible ‘whole’ array configuration, multiple geometries with varying properties based on tensile network orientation have been identified and studied:

Regular Orthogonal Array: When one plane of connection elements is parallel to the direction of an applied force then these particular elements respond and behave as ‘compression columns.’ The two remaining planes are perpendicular to the lines of force and are thus not directly in compression. Instead, they act in an assistive tensile fashion to resist the bending moments of the plane in compression. Another way of looking at this orientation is to make the orientation of the icosahedron ‘edge-up’ to the direction of applied force.

Bias Array: A more compelling approach to the internal architecture is to rotate the entire array such that all three axes of the tensile network are at 45° to the direction of the applied load. In this orientation, the icosahedron are face up. This coincides with what we know two-dimensionally in the garment industry as a ‘bias’ cut, and a variation in more complex textile structures sometimes referred to as a ‘tri-axial’ weave. Within a bias-oriented array, the multi-layered polyhedron are secured by a connective network whose extending elements are inclined about 45° in all three planes relative to the expected direction of an applied load on the surface of the array. This specific architecture promises particular robustness against the tensile stress produced by shear loads in directions at 45° to the plane of the shearing.

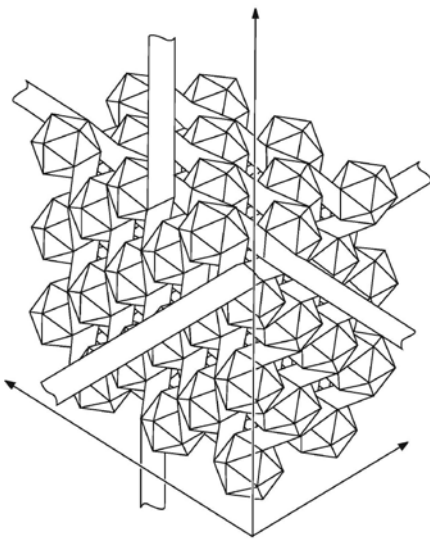


FIGURE 2.22
Regular orthogonal array

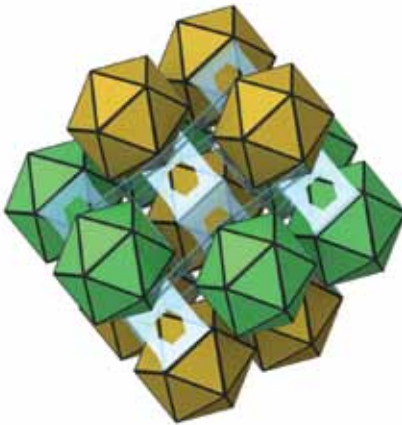
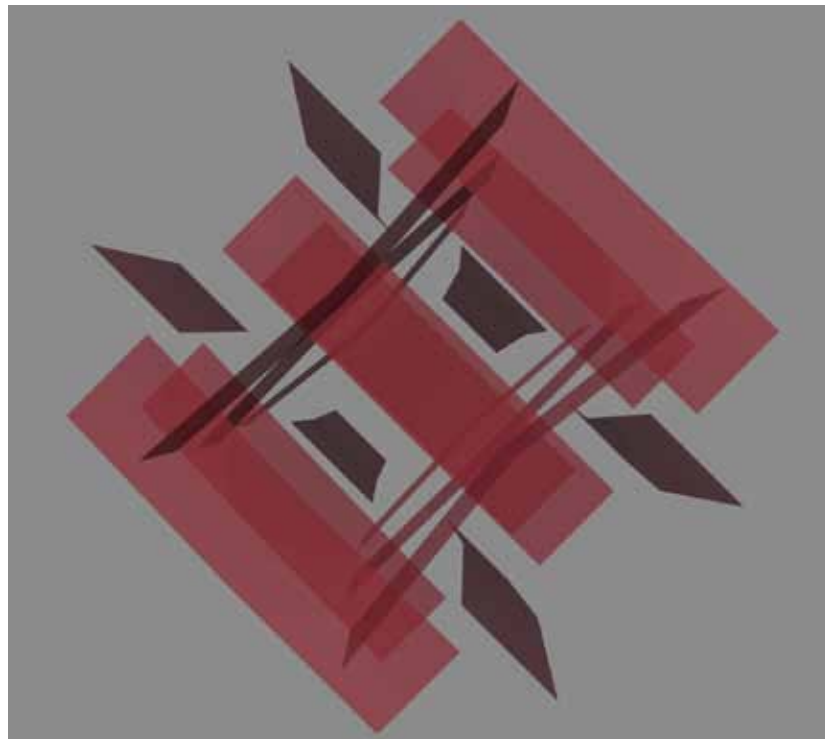


FIGURE 2.23
Bias array

FIGURE 2.24
Bias array connecting elements



The bias array provides other natural advantages. In this orientation, no one plane is ‘superior’ to another by virtue of position, and therefore they all share the load initially. The interconnecting elements are never in pure compression, which is the case in the orthogonal orientation. Consequently, the icosahedron—rather than the interconnecting elements—acting in compression, takes on a much larger share of load-bearing, which is how it should be. The icosahedrons start stacking into a closer-packed array and assume the primary bearing of the compressive load. This ‘face-up’ orientation surprisingly makes assembly easier and creates a flat and more extensive contact surface for attaching an external ‘skin’ if desired.

Radial Array: As the most complex and perhaps most bio-mimetic of Flextegrity’s design efforts to date, the sinuous interconnecting elements of the ‘radial assembly’ extend perpendicularly from a line drawn from the center of the icosahedron in one plane and then ‘translate’ to an adjacent orthogonal plane where they connect again in a radial but nonparallel fashion to an adjoining icosahedron.

To better visualize this tensile network, consider that, in fact, our bodies trace a similar path each time we drive on a ‘cloverleaf’ ramp connecting two intersecting freeways. In this maneuver, our vehicle not only changes direction (say, from north to west), but the ‘cloverleaf’ also translates us in elevation, either up or down depending on which freeway is in the ‘overpass’ position (See version #2- chapter 3).



FIGURE 2.25

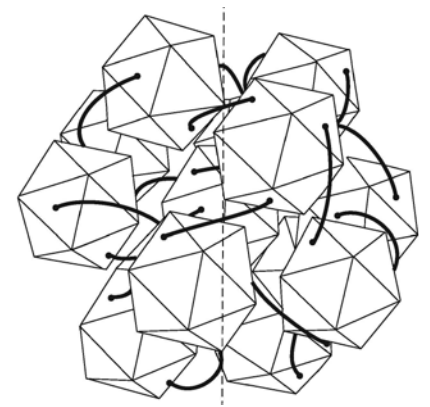


FIGURE 2.26
Radial array ‘cell’

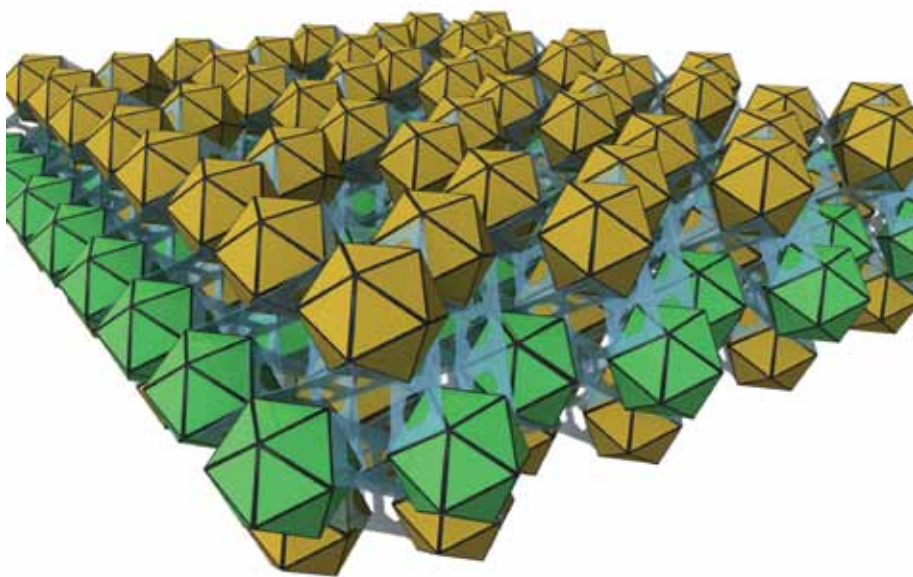


FIGURE 2.27
Omni-extensible bias array

GENERAL CHARACTERISTICS OF FLEXTEGRITY ARRAYS

Ordered: Flextegrity arrays are formed in a ‘structured and ordered’ manner, that is, each element is designed, positioned, placed, or otherwise formed in a non-random manner. The regular pattern in which the polyhedrons are arranged can include spaces occurring at periodic intervals. Arrays are assembled in a straightforward fashion as each polyhedron is stabilized or constrained within the orthogonal tensile network.

The ordered nature of the array means that it will perform more predictably than structures formed with non-ordered elements (such as concrete). In addition, the array’s ordered nature results in a failure resistance that limits structural damage to the location of the damage, preventing it from spreading to other areas of the array. Deformation, damage, and/or other failures can be localized and controlled, thereby maintaining the integrity of the array as a whole.

Open: As pointed out previously, the array is not ‘close packed.’ In fact, it might best be called ‘open ordered.’ Thus, each polyhedron is separate from the other polyhedrons, and adjacent polyhedrons do not share common vertices, edges or faces.

Three-dimensional: In general, the array is three-dimensional and comprises multiple layers depending on the application and the characteristics desired for the application. Each layer is planar, and the layers are parallel to each other. The connections extend to adjacent polyhedrons in the same layer and to other layers.

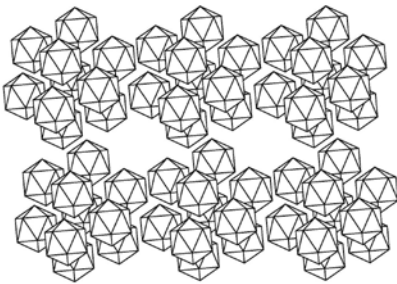


FIGURE 2.28

Isotropic | Anisotropic: A polyhedral array can be configured to be isotropic, i.e., to have the same properties in all directions. Alternatively, the array can be designed with a predetermined anisotropy. The relative rigidities of the polyhedral elements and the connective elements can be tailored for a given application. For example, connections extending in the Z direction may be made less or more rigid than the interconnecting members in the X and Y directions where the anticipated loading configuration differs in the Z direction as compared to the X and Y directions.

While most commonly the icosahedral elements and the interconnecting elements recur in the array with a spatial periodicity, polyhedral arrays can deviate from perfect regularity without compromising the overall function and behavior compared to a ‘regular array.’ In some cases, a selected polyhedral element may be omitted to achieve a

more desirable outcome. Slight departures from perfect regularity in response to specific local conditions can, in fact, be desirable. Recent iterations of Flextegrity arrays have successfully capitalized on this characteristic. Alternatively, it may strengthen the structural fabric to intentionally introduce irregularities by analogy to the methods used to strengthen crystalline materials such as metals.

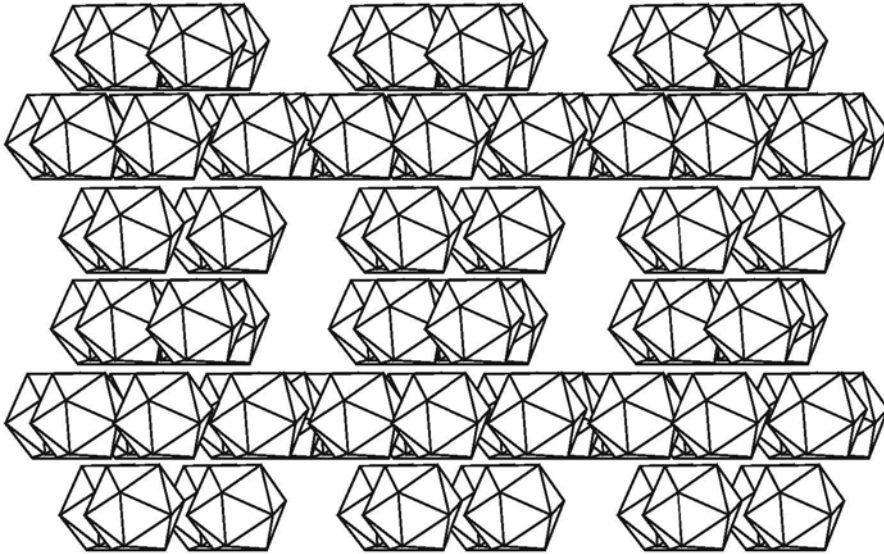


FIGURE 2.29
Array with spatial periodicity

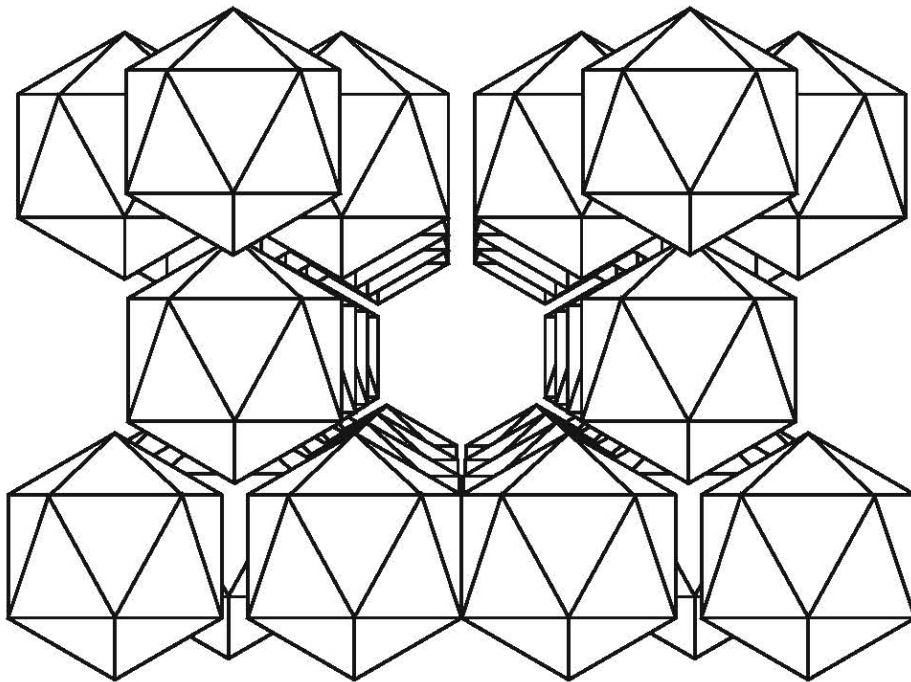


FIGURE 2.30
Array with spatial periodicity

Prescriptive: Arrays can be configured to have different portions exhibiting different properties. For example, the polyhedrons occupying the edge positions in an array could be formed of a material more resistant to environmental conditions, or specifically adapted for receiving a thin covering layer, or attaching to a conventional adjacent structure. Polyhedrons having different physical properties, including elasticity, density, melting point, strength in compression, etc., to name a few, could be substituted in the array to achieve a desired result. Connections can be adapted in the same way, with their properties varied according to their location in the array, their orientation relative to the expected load, their specific configurations and materials from which they are made. Connections can also be designed to exhibit varying properties along their length.

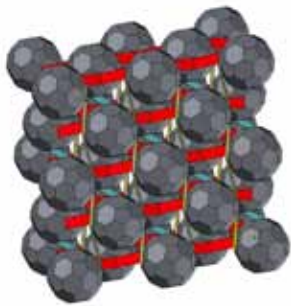


FIGURE 2.31
Array based on Fullerene
(C60) molecule

As described in the opening of this chapter, polyhedral arrays can be designed to withstand loading within a predetermined working range, and forces and torques, including compressive forces, tensile forces and torsional forces applied to the array as well as other forces, such as shear forces, that may be developed internally.

Not constrained by scale: It is also possible to provide very small-scale arrays, such as at the nano-scale or micro-scale. Some molecular forms, in fact, naturally possess specific polyhedral geometry. The C60 molecule is a truncated icosahedron. Assembly techniques, such as atomic force microscopy or self-assembly, could conceivably be used to provide suitable molecules as polyhedral elements. Further, and not appreciated until now, the polyhedral molecules can be arranged into predetermined arrays with connections formed of molecules, ligands or ligatures to give the resulting arrays overall properties useful in the design and fabrication of larger objects.

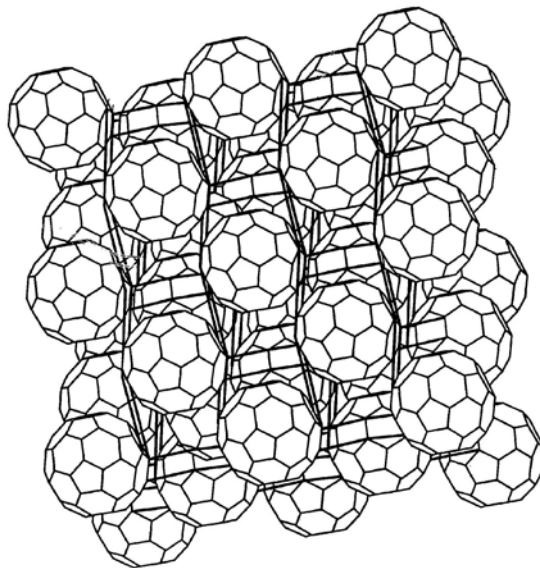


FIGURE 2.32
Fullerene array

HEXAPHOROUS STRUCTURES

Hexaphorous means ‘carried or borne by six’—an archaic term referring to litters carried by slaves. In the realm of Flextegrity, it is the layer comprised of six icosahedrons (the third configuration mentioned above) formed from the perimeter of the middle layer of the cubo-octahedron, absent the central icosahedron. The icosahedrons carry the load. Because of the way it is molded, the ring also comprises tensile elements (see discussion below). The ring below bears the load from the ring above it. In compression, the load is conveyed through the interconnecting tensile ‘mortar.’

Hexaphorous ring assemblies are an example of material designed to be stiff and used predominantly in compression. They are a prototype for an industrial process whereby rings (‘bricks’) and interconnecting elements (‘mortar’) come together in an automated assembly system for final packaging and distribution. The rings can also be designed with a variety of three-dimensional connection interfaces for shear resistant architectures.

What happens when you disregard the discrete boundaries between tension and compression, as in hexaphorous ring assemblies? The ring system uses the tension elements to ‘preconfigure’ the arrangement of the six icosahedrons (compression) around the central plane of the cubo-octahedron. This is part of the design, an artifact of the mold. The distinction between which element is in tension and which is in compression is blurred, as it should be in this iteration, because these functions are shared. Under certain conditions the same element may be called upon to perform both functions. Again, it becomes more useful to think in terms of components being predominantly in tension or predominantly in compression rather than purely so as say in a ‘tensegrity.’ Once the design objectives has been met there is nothing prohibiting additional corruptions to the form. Compromises are made. While there is purity in discontinuous compression and continuous tension structures, the separation into tensile elements and compression elements can impose unnecessary restrictions on the design.

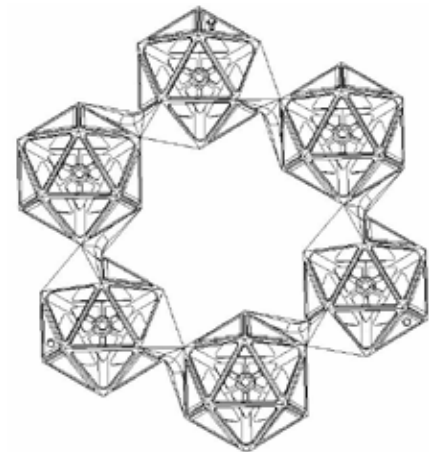
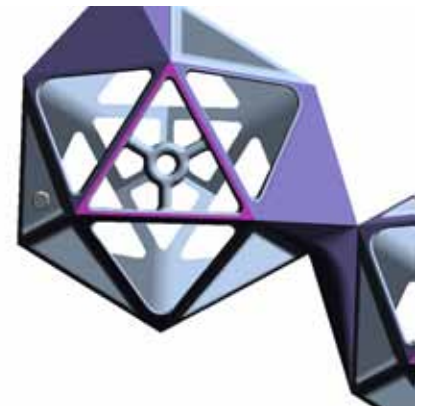


FIGURE 2.33-2.34
Hexaphorous Ring Assembly

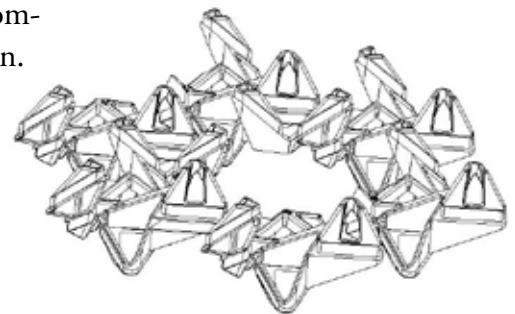


FIGURE 2.35
Molded interconnecting elements

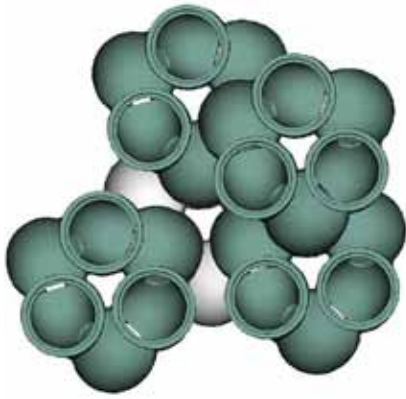


FIGURE 2.36

FLORETS

Returning to the four basic configurations of the cubo-octahedron outlined above, variation #4 employs three upper and lower icosahedrons (tetrahedral bases) plus one in the middle of the center layer for a total of seven. It is comprised of two tetrahedral structures, inverted to each other, sharing a central icosahedron as a common vertex. The upper tetrahedron is rotated 60 degrees relative to the lower. This is a very important relationship because each ‘up’ and ‘down’ element is inherently stable.

Floret structures incorporate both the tension and compression into a single load-bearing element. The sinusoidal waveform is well optimized for omni-axial loading. The Floret informs us that tension and compression need not be thought as discreet elements, that they may indeed be incorporated into the same form. A Floret’s up- and down-extending members enable each component to be joined to as many as three other structural members in the layer above, and three in the layer below. In this manner an omni-extendable array of structural elements can be constructed.

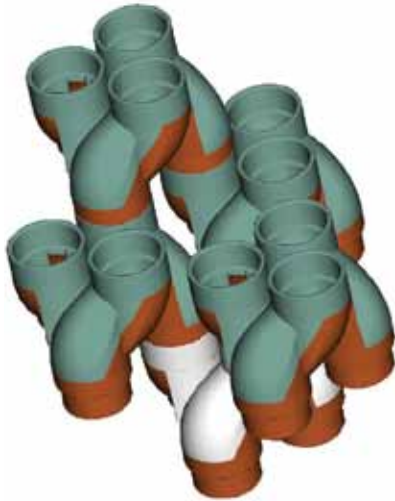


FIGURE 2.37

The integrity of the Floret structural member benefits from the inherent structural stability of an icosahedral array, as described in more detail in U.S. Patent Publication No. 2008/0040984. The angles between the top openings and the bottom openings are equilateral triangles, and the offset between the top and bottom openings can approximate that of the offset between the icosahedrons. Similarly, the passageways between fluidly connected top and bottom openings can correspond to a structural linking member that provides structural rigidity to an icosahedral array. Thus, by approximating the structure of an icosahedral array, this array of tubular members can have increased structural integrity.

Each structural member can be solid or substantially hollow. In some embodiments the openings of hollow extending members can connect with extending members from a second layer forming a passageway, which can extend between each first opening and a corresponding, offset second opening. Each first opening of a first structural member can be fluidly connected to only one second opening of the first structural member and so forth as to create an extended passageway(s). At least one passageway can have a restricted cross-section area along a portion of the passageway. Each structural member can upwards of three ‘in’ openings and three ‘out’ openings.

Openings in the top and bottom surface that are fluidly connected are offset from one another. This offset can provide integrity and strength to structural members. In addition, if a structural member is configured to allow fluids to flow between the top and bottom surfaces, the offset openings can be used to influence or modify the flow of an element (e.g., gas, fluid, or flowable solids) through the passageways. For example, the offset can define a circuitous path between the openings in the top and bottom surfaces that can cause the flowing element to experience non-laminar flow between the top and bottom surfaces. Such non-laminar flow can provide various advantages, such as mixing or blending one or more fluids or other flowing elements. Additionally, at least a portion of one or more passageways can include a restricted cross-sectional area along the passageway to further affect the flow pattern of an element moving through the passageway.



In the beginning I described the concept of a single repeating element that could be both stiff, flexible from which omni-extensible arrays could be manufactured. My journey of discovery had led me to new class of materials I call ‘Equilibrated Polyhedral Structures.’ The cubo-octahedron is the organizing characteristic of the cluster. We can also use this organization to shape our thinking about tension and compression and how loads are carried throughout the cell. But just as important is that these basic building blocks can be cheaply and easily manufactured using a variety of commonly available materials and minimal capital requirements.

