FLEXTEGRITY

# Advanced Icosahedral Materials

## Overview

Flextegrity, Inc. is developing advanced structural materials that comprehensively address the requirements for multi-axial loading, shear resistance, fracture resilience, and localized impact containment. Our technology strategically anticipates a new generation of emerging applications.

Creative exploitation of the properties offered by improved materials is increasingly critical to design and engineering innovation. Given this technological and economic impetus, materials and the processes to shape them are now developing faster than at any time in history. And, the challenges and opportunities they present are greater than ever. For example, recent catastrophes on all continents point to the need for structural materials that will perform well under increasingly extreme stress conditions. Advanced materials must be anticipatory of emerging needs in their design, and offer comprehensive solutions to real-world problems.

Flextegrity's applied geometry optimizes resistance to axial compression by using polyhedra in an array coupled with orthogonally, biased, or radially ordered tension to achieve higher performance and significantly enhanced properties using existing materials. Specifically, the patterned array utilizes polyhedral elements as naturally superior structural compression elements and interconnecting tension members. The resulting architecture produces omni-extensible 'hybrid' arrays and lattices comprised of 'micro-icosahedral cells' in macromolecular clusters. These units can 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.

Tension and compression optimally co-exist to form a self-stabilizing integrity suitable for construction of larger load-bearing 3-dimensional shapes, flexible structural blocks, hybrid material sheets, and geo-textiles. This radically simple yet elegant technology can provide innovative solutions to existing material needs using conventional resources. As a far-reaching horizontal technology, it possesses the inherent capability to impact and feed multiple vertically integrated technologies.

## The Invention

Flextegrity's invention is an omni-extensible array comprised of icosahedral elements held in a tensile matrix. The invention is the architecture itself, independent of the materials from which it may be formed, and is inherently stable, permeable and ordered. In the abstract the geometry can be expressed without regard to size or location, therefore it is scalable from the very small to the very large.

As an omni-extensible patterned array that can be assembled or deconstructed without loss of integrity, the material can be shaped or molded into many forms. The icosahedral elements are not 'close-packed' at equilibrium, and as such the array is permeable.

Our innovative micro-architecture, which capitalizes on the dynamic equilibrium inherent in this complementary coexistence of tension and compression, offers material scientists, architects, structural engineers and product designers a wide range of highly desirable and unique properties:

•**The geometry is infinitely scalable** in unit size (from nano- to mega-scale) and in frequency (number of icosahedrons in all three spatial planes of the material matrix).

•**The array is omni-extensible**—the repeating pattern of the geometry may be extended in all directions to achieve material dimensionality that is not limited by the 'natural' dimensions of the raw materials from which it may be manufactured. In addition, an existing array can be increased in size by connecting additional discrete polyhedrons to existing polyhedrons with additional connections, without requiring other modifications to the existing array.

•Like the strongest 'traditional' materials (wood, steel, and reinforced concrete), the geometry has significant **strength both in tension and compression**, affording greater freedom and efficiency in design and use.

•Response to applied stress is one of **local deformation while maintaining global stiffness** due to integrity of compression/tension synergy within the material. Toughness and permeability are not compromised.

•**Strength-to-weight ratio** is inherently high even before material choice. "Open" yet strong geometry efficiently reduces weight, material requirements, and transportation costs.

•Material applications of the technology are **permeable without sacrificing toughness**.

•Material/product **design can be implemented in virtually any category of materials** (plastics, metals, textiles, wood products, etc.).

•A wide range of **non-homogenous characteristics can be custom-engineered within a single product** even when manufactured of a homogenous material, making product performance local and site-specific. Omni-directional control of material and size also enables **customized 'hybrid' solutions using components of differing raw materials**.

•**No limitations on inherent stiffness or flexibility!** A precisely defined flexibility and/or expansion "gradient" or "zone" can be created across a single plank or sheet in any plane or combination of planes. Omni-directional flexibility potential enables a wide and unprecedented range of functional and aesthetic applications.

•Multi-layer, multi-component material structures are possible without mixing materials or binding agents, which **significantly enhances recycling potential** of component materials.

•Open 3-D geometry creates **regular, stable matrix with increased internal "active" surface area, capable of being "loaded" with functional elements** (i.e., chemical "beads," wired or wireless address-able locations, circuitry, lighting/heating elements, solar cells, seeds, phase-change materials, barrier layers).

•The capability for **'uni-body' construction of large, integrated, multi-functional structural components in a controlled manufacturing setting** ensures a higher level of quality assurance, and can significantly shorten on-site construction/installation times and processes.

•**Prescriptively localized stress loading** can be pre-engineered within the structure to optimize strength to weight metrics and increase resistance to shear.

## Background: Material Evolution

The foundation of Flextegrity's intellectual property is a unique and innovative geometry for assembled materials. Over centuries of material science, new ways of processing, structuring and assembling product components have revolutionized the role and functionality of even the most traditional materials.

**History:** There is a long and proven history of structural innovation in materials science. We are surrounded by well-known examples:

- ✓ **Wool:** Natural pelts of animals killed for food were among the earliest known man-made clothing. However, they went largely out of use as humans learned how to cut and use the fleece fibers from live animals as well. Perhaps by accident, it was discovered that the combination of heat, moisture and agitation would cause wool fibers to clump together into a thick and fairly durable felt mat that could be shaped into three-dimensional products such as hats and boots. Humans further learned how to twist short fibers into a long, continuous spun yarn that could be used as a cord or further assembled into two-dimensional textile structures such as woven, knitted, and crocheted fabrics.

- ✓ **Steel:** The original Iron Age knife crafted from a chunk of metal was crude, but it revolutionized hand-cutting tasks for early humans. Centuries later, drawing and rolling steel and other metals out into a wire form enabled creation of lighter more flexible products such as chain mail armor and metal meshes, as well as a means for channeling electrical conduction. The orderly twisting of wires into cables made suspension bridges possible. Development of mass-produced cold-rolled sheet steel made it possible to cover larger surfaces, create larger, lighter objects (ships, locomotives), and enable cutting and shaping of mass-produced parts. With the development of the I-beam, this simple but efficient change in cross-sectional geometry netted impressive increases in strength-to-weight ratios of structural steel members. Today, among the latest advancements in material structure are porous metal “foams”, and nano-scale arrays in which singular metal atoms/molecules perform discreet functions.

- ✓ **Wood:** Early humans’ first use of wood was most likely hunkering under live trees for shelter. Branches and leaves that could be torn off by hands found many utilitarian purposes. Fallen trees were hollowed out with crude cutting tools to form canoes and other three-dimensional forms. With the development of axes, logs could be cut and notched to assemble shelter. The ability to saw logs into strips gave us dimensional board lumber, which could be cut and nailed into an almost infinite variety of shapes and architectural forms. Then came a rash of development of engineered wood products such as plywood, laminated beams, and oriented strand board which leveraged more efficient use of the whole tree by breaking down and then recombining cellulosic elements to create improvements in dimensions and performance. Wood has even been reduced to its constituent chemical ‘building blocks’ (cellulose), then reassembled in a new geometry at the molecular level, and extruded as a fiber of rayon or acetate (new structure). This “wood” textile in turn can be woven or knitted into a soft, elegant silk-like fabric with a whole new set of properties not normally associated with wood. Alternatively, wood-based cellulosic material can now be injection-molded into any geometry/structure of choice.

The quest for new classes and uses of raw materials (such as titanium and carbon fiber) often has been launched only after traditional materials have been structurally exploited to the current technological boundaries of their inherent chemical and molecular properties. For example, conventionally riveted-together aluminum airplanes have reached the limit of their ability to reduce weight, fuel demands and assembly time/complexity. To achieve further increases in structural integrity and safety, current research and development in progress at Boeing involves a radically different method of constructing an entire airplane fuselage out of continuously wound and stabilized ‘ribbons’ of carbon fiber.

Unfortunately, these advanced, state-of-the-art raw materials are too expensive for most applications. Leveraging the performance of existing conventional materials through new and innovative structural geometries, as is Flextegrity’s strategy, has historically proven to be a simpler, more elegant, and infinitely more economical way of extending materials science than the quest to discover and develop whole new classes of raw materials.

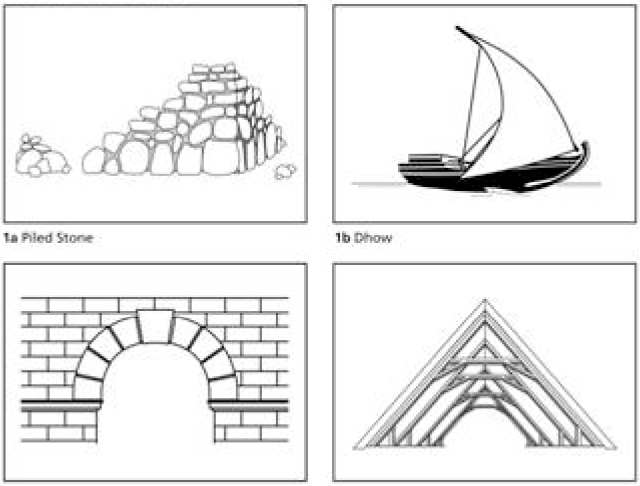
## Background: Evolution of Structure

Humans have been continuously and creatively involved in meeting our inherent need for protection since the beginning of our existence. After first seeking natural shelter in caves and woods, early human-made solutions to the problem of enclosing and roofing spaces included wind shields formed from tree trunks and branches, leather and textile tents, sails (Fig. 1b), snow caves and stone huts with woven or thatched roofs.

Man built, at first heavily and monolithically, and then increasingly by means of ‘tensile’ frameworks and networks. Methods of crude “material-piling” (Fig. 1a) founded on principles of ‘compression’ were developed, based on juxtaposition of heavy, three-dimensional members of stone, clay, ice or wood following the model of natural caves or strata. Centuries of many false starts as well as successful attempts evolved into the beautiful and relatively spacious Roman, Byzantine and Gothic vaults (Fig. 1c).

Increasingly, these two construction approaches were used simultaneously to perform the complementary functions of compression and tension within a single building: the heavy and solid ‘compressional’ part of the structure was intended to bound the space and edge-support the roofing, and the lighter ‘tensional’ assemblage was employed overhead to cover this space. Even more recently, these two structural types have been combined into unitary constructive systems; for example, brick structures with internal or external ribs (using brick or different materials such as timber and steel), and reinforced concrete structures.

Evolution of Structure



1a Piled Stone

1b Dhow

1c Arch

1d Truss

The desire for ever-larger covered areas free from the constraints of internal supporting columns pushed the quest for new vaulting methods. Early efforts produced sturdy vaults using either discrete (masonry, bricks, etc.) or monolithic (cast) materials. With the introduction of structural iron and steel, followed later by reinforced concrete, sophisticated ‘space frames’ and thin shells not only became possible but helped to reduce both cost and quantity of materials while increasing efficiency of construction.

The enormous self-weight of monolithic load-bearing members and the need to decrease material use and cost drove the development and use of linear spatial ‘truss-and-column’ structures. The plane lattice girder was first developed as a replacement for the solid section beam. However, since the directional diversity of roof loads demanded strengthening systems in several directions, truss systems (Fig. 1d) gradually developed into space-frame structures.

The Mannesmann system, one of the first structural forms evolving towards space frames, consisted of metallic tubes and links using double and triple connectors. Early applications of this geometry included sturdy scaffolds and multi-shaped frames. This system also made it possible to progress from the truss-girder floor and from vaults supported by metallic trusses or meridian-ribs, to space-frame structures for an entire floor or for a curved surface. In the course of development towards a self-supporting framed structure, the spherical dome evolved by way of the Schwedler dome and the Zeiss-Diviag grid, to reach the deceptively simple sophistication of Buckminster Fuller’s isotropic vector matrix and geodesic domes. The skeleton framework of the structures provides outstanding strength for the weight of materials used. Accordingly, the geodesic dome structures are highly, if not supremely, economical.

Subsequently, the true space-frame structures—those which work statically in three dimensions and are made self-supporting by their very shape—received a new impetus from their resemblance to biological structural forms as seen at a microscopic scale. Radiolaria drawn by the naturalist Ernst Haecke and the diatoms studied by means of the electron microscope, as live structures achieving a maximum volume and strength with a minimum of material, have justified and even prompted the development of space-frame structures such as Pier Luigi Nervi’s monolithic and continuous forms. In recent decades, structures employing the principles of ‘tensegrities’ first developed by Kenneth Snelsen and articulated by Buckminster Fuller have been used in dome covers (Fig. 2a). However, there is not yet widespread adaptation of these principles because of the inherent complexity of assembies, issues of scaling, inadequate understanding of the properties of the resulting materials, and the difficulty and reluctanct to perform structural analysis—not to speak of longstanding biases towards “staying the course.”

More recently, with improved manufacturing techniques macromolecular structures have become smaller in scale such that the lattice is now the ‘microstructure’ and the resulting material is in turn ‘macro-shaped’ for specific applications. Most currently and at a much smaller scale, scientists have discovered complex carbon molecules incorporating similar designs, such as the carbon-60 molecule (known as the ‘buckyball’), and carbon nanotubes. Scientists working at the nano scale in the fields of chemistry and crystallography are presently using a variety of methods to create what their disciplines refer to as ‘supra-molecular arrays,’ ‘supramolecular architectures,’ ‘3D coordination polymers,’ ‘metal-organic frameworks (MOF’s)’, ‘structural topologies,’ ‘binary superlattices,’ and ‘porous open-framework solids,’ among other nomenclature. The mostly widely utilized ‘bottom-up’ methods involve programmed construction of extended high-dimensional metal-organic network solids using metal and organic ‘building blocks’ with known and desirable bonding or functional properties. ‘Top-down’ experimental research methods are derived from systematic evaluation of all possible frameworks via application of recent advances in mathematical tiling and graph theory. Other novel methods involve templating against sacrificial templates (‘lost wax’ and other deposition techniques ‘borrowed’ from micro-scale material science).

## The Flextegrity Array

**Beginnings—the icosahedron.** The icosahedron is both simple and complex. Its inherent simplicity makes it an ideal shape to work with, and its rich complexity make the possibilities limitless. Geometrically, the icosahedron is the most complex of the three triangulated Platonic solids. 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. The sphere is often thought to be the optimal shape for robustness to compression. The icosahedron approximates a sphere, which maximizes the volume-to-surface-area ratio and is the key to an efficient solution. Multiple truncations of other polyhedrals can only approximate the theoretical sphere, and will never achieve a spherical distribution as stable as the icosahedron (Fig. 2b).

Buckminster Fuller, in his inimitably exhaustive style, characterizes the exceptional energetic equilibrium of the icosahedron as “dramatically manifesting the half-positive, half-negative, always and only coexisting, universal non-mirror-imaged complementarity inherently permeating all systems, dynamic or static, despite superficial disorder, whether or not visibly discernible initially.” (*Synergetics*, p. 181). Ever economical, some 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.

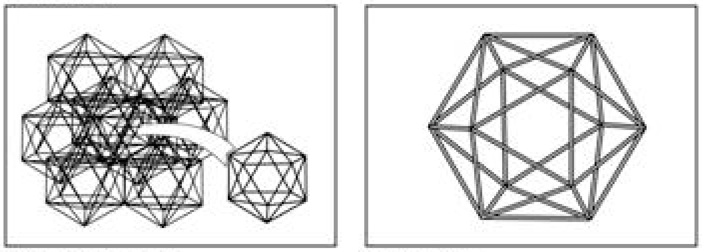
The icosahedron inherently possesses several mechanical advantages over the sphere. The solid sphere under a load, a ball bearing for example, distributes the applied forces throughout its interior and across its surface. A more careful analysis at the atomic scale reveals an uneven distribution of those forces related to the manufacturing process itself and the inherent randomness of bonding subject to heat and pressure. These flaws inevitably lead to cracking, fracturing and failure, and are hard to predict. Advances in analytical instrumentation have more recently allowed us to observe these properties of materials.

Another problem of the spherical shape is commonly referred to as localization. The hollow and, surprisingly, the solid spheres are prone to dimpling and are inelastic, based on the materials used. This is most easily evident when pushing on the surface of a highly elastic balloon. A similar flattening occurs close to the failure point even when the sphere is solid, and the atomic bonds are sheared apart.

The icosahedron responds differently to external forces by first bending along the primary edge and transmitting the forces to the vertices. The faces of the icosahedron do relatively little work. The vertices of the icosahedron resist the natural tendency to dimple and consequently the icosahedron is more predictable from a structural standpoint.

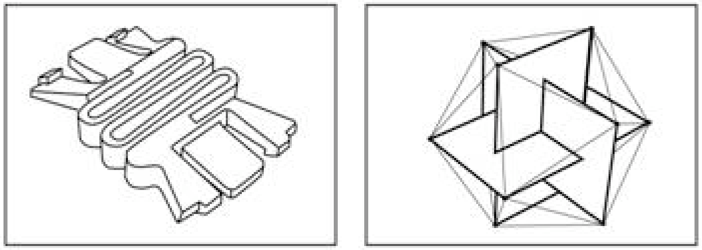
Another highly practical advantage of the icosahedron vs. the sphere is simply the physical geometry. It provides natural facets and edges for attaching things. Limitless connector types can be designed for edges or faces; vertices can also be connected using pin joints. Further enhancing the connective potential of the icosahedron is its symmetry: it can be circumscribed within a cube with any of its faces, edges or vertices oriented in the plane of the cube providing naturally orthogonal attachment surfaces. Although the opposing faces of the truncated icosahedron are not identical—one a pentagon and the other a hexagon—both faces can easily accommodate identical post connectors, making it adequately uniform for machine assembly.

Icosahedron



2a Octahedral Tensegrity

2b Icosahedron



2c Tension Connector

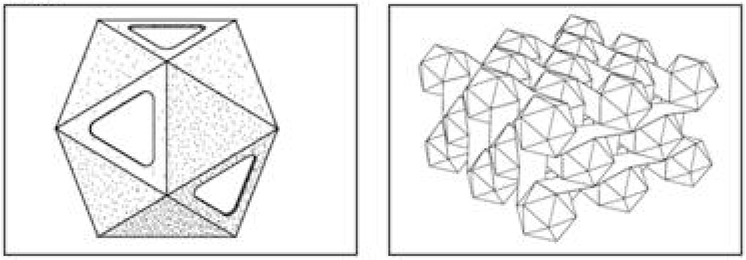
2d Circumscribed Planes

**The Array.** Flextegrity's patented omni-extensible permeable array uses icosahedron and truncated regular icosahedron forms to achieve a fundamental structural integrity with a minimum use of materials, enhanced strength-to-weight ratio and corresponding load-bearing efficiency. These specific polyhedrons also provide critical edges and faces lying in orthogonal planes, so that three-dimensional lattice structures can be formed with the standard Cartesian symmetry that is most useful in many applications.

In its most basic form, the Flextegrity array consists of multiple discrete polyhedrons precisely positioned within a tensile connection network. Each polyhedron, by definition, is comprised of edges, faces and vertices, and may be solid, hollow, or 'wireframe' in structure. Each is a finitely closed entity having structural integrity independent both of the connection network (for example, a spring connection as in Fig. 2c) and of other discrete polyhedrons in the array, and occupies a unique location that can be specified with Cartesian coordinates (Fig. 2d).

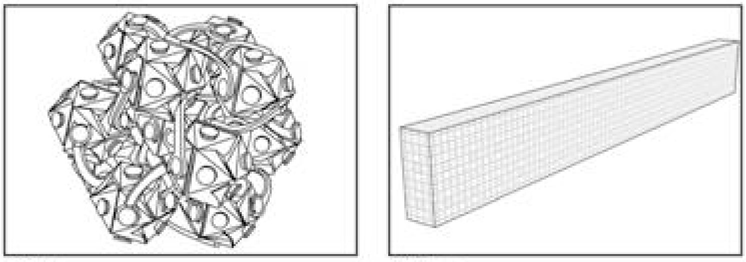
At equilibrium, the polyhedrons are spaced apart from each other in a predetermined, generally regular or periodic pattern. In creating material implementations of the Flextegrity architecture, the polyhedrons in the array are arranged in multiple parallel layers comprised of alternating rows of icosahedrons. The regular pattern in which the polyhedrons are arranged can include spaces occurring at uniform or periodic intervals. The array forms in a straightforward fashion as each polyhedron is stabilized or constrained within the prescribed weave (Fig. 3b). This is accomplished through the design of the inherent network that 'connects' the tensile elements with the compressive elements. 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.

Arrays



3a Cell

3b Array



3c Macro

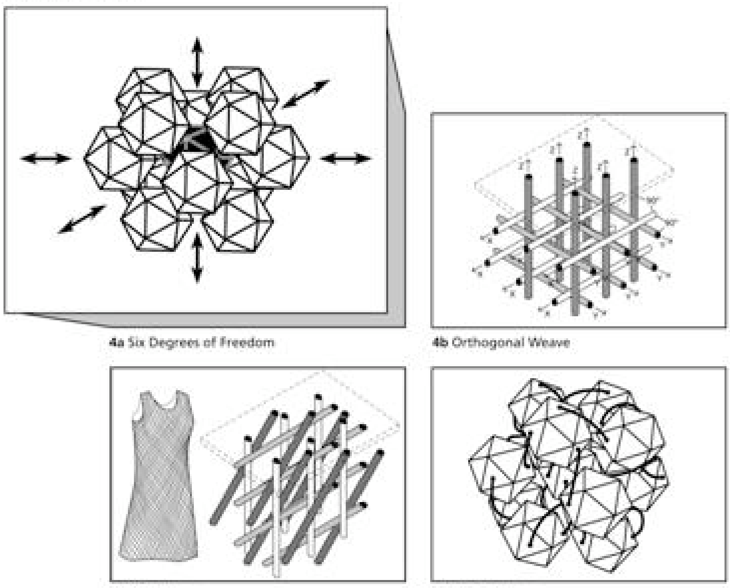
3d Shape

Fuller has said, “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.” For our ordered array to maintain stability it must secure the polyhedral elements in relationship to these vectors. The Flextegrity connection network strategically and selectively constrains the discrete polyhedrons with respect to each one's six ‘degrees of freedom’ according to the requirements of the material’s end use (for example, the beam in Fig. 3d). These degrees of freedom (up, down, left, right, front, back) correspond to the same six planes of the cube that circumscribe the icosahedron (Fig. 4a).

Within the network, the connection element ‘planes’ are orthogonal to one another along the x, y and z axes. This network may extend in regular orthogonal directions relative to the material’s surface, along bias directions, or in radial directions to interconnect the polyhedrons.

**Regular Orthogonal Array.** When one plane of connection elements is parallel to the direction of an applied force (Fig. 4b), 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.

Weave Patterns



4a Six Degrees of Freedom

4b Orthogonal Weave

4c Bias Weave

4d Radial Weave

**Bias Array.** Another interesting and somewhat more compelling approach to the internal architecture is to rotate the entire array such that all three axes are at 45° to the direction of the applied load. This coincides with what we know two-dimensionally in the garment industry as a ‘bias’ cut, and a variation in more complex textile structures is sometimes referred to as a ‘tri-axial’ weave (Fig. 4c). In this orientation, there is no one plane ‘superior’ to another by virtue of position, and therefore they all share the compressive load initially. Subsequently, they offer less individual resistance and as a consequence the icosahedrons quickly form the uniform close-packed array and assume the primary bearing of the compressive load. As we have created material and computer-simulated models of Flextegrity arrays, we have noted natural advantages to this pattern. Ease of assembly is facilitated and it provides a ‘face-up’ orientation to the icosahedron, creating a flatter and more extensive contact surface for attaching an external ‘skin’ if desired. Our own theoretical efforts and intuition suggest that the applied load is distributed across the array of icosahedrons similar to stones in an arch.

Within a bias-oriented array, the multi-layered polyhedrons are secured by a connection 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 tension and compression stresses produced by shear loads in directions at 45° to the plane of the shearing.

**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’ (Figs. 3c and 4d) 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. This common practice of constructing intersecting freeways at different heights and connecting them with ‘translational’ links eliminates major congestion, hazards, and traffic lights. The structural advantages this configuration brings to the Flextegrity array are discussed below.

The radial array derived from a challenge that arose in the other assembly patterns. The problem was that when the icosahedrons are in compression, the interconnecting elements can ‘clutter’ or ‘interfere’ with the maximum ability of the icosahedron to seat on the ‘hip’ or ‘face-to-face’ with that of its nearest neighbor in the array. In addition to resolving this issue, using our experience and intuition we believe that the radial approach provides improved resistance to shear forces.

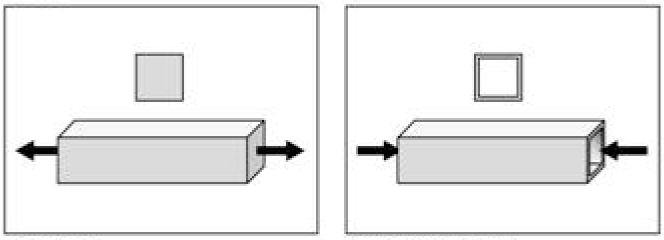
**Observations on Mechanics.** From our initial engineering studies on regular orthogonal arrays (please see our available downloads), we have observed that when a plane of tensile connection elements is said to be in ‘compression’ with an orientation parallel to the lines of force, the interconnecting ‘mini-columns’ with orientation at 90° to the applied load are predominately in tension within the array. ‘Predominately’ suggests that overall the shape or structure is being squeezed locally, and as the icosahedral elements grow closer together, then the tension elements start acting more in compression. Stated differently, the orthogonal tension members and adjacent compression elements became the ‘bracing’ components preventing the column from buckling. Therefore, when designing for loads one should consider stiff interconnecting elements that work well in compression for the array plane that is parallel to the applied load (presuming the designer fully understands the direction of the load). This principle is not unlike dimensional lumber which works better in one axis over another for a given type of applied force.

Further, the interconnecting elements would ideally be designed so that when they are fully compressed, the icosahedrons can begin to stack against one another and start to behave as compression columns in their own right. While they neither stack directly on top of one another nor close-pack as in a tetrahedral/octahedral array, they do form a uniform and stable column (see Ross Engineering report).

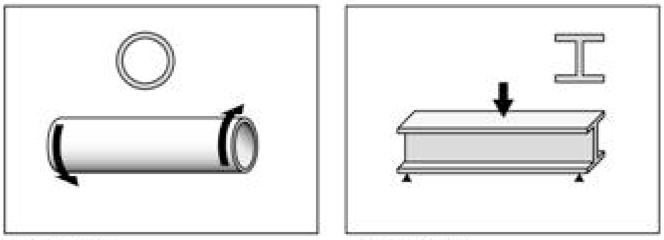
The array is more than the sum of its components. The array can be shaped into common elements: sheets of materials, Z-beams, cylinders and 2X4’s, to name a few familiar objects. The array can further be made into macromolecular structures, sub-assemblies that become the building blocks for larger assemblies. The array can be limitless and extensible in any desirable direction. Lattices can be designed to add additional lightness and porosity to the fabric.

For the engineer or designer it is important to consider the predominate forces applied to the structure and especially the shapes of the components themselves. The resulting arrays and lattices are subject to the same Newtonian mechanics as traditional materials and shapes: Tension (Fig. 5a), compression (Fig. 5b), torsion (Fig. 5c) and bending (Fig. 5d) exist simultaneously within all load-bearing materials. Now, we can begin to prescriptively localize the effects of these forces with the structure. And, if the design requirements require flexibility, the applied forces can be prescriptively dissipated with the structural.

Forces



**5a** Tension: Tie **5b** Compression: Column



**5c** Torsion: Shaft **5d** Bending: Beam

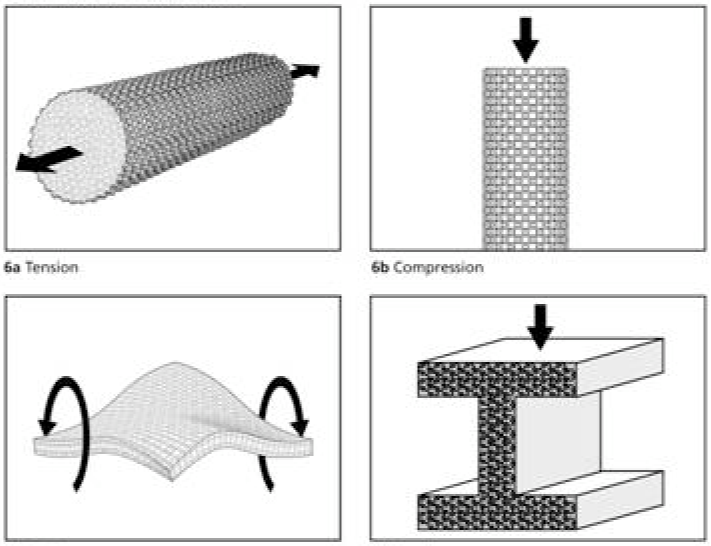
## Shapes, Materials and Lattices

Micro-structured materials can be thought of as new material and combined with a macromolecular shape factor to create hybrid materials. Arrays continue that sequence resulting from combinations of materials, 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 of axial strength and flexural stiffness. We can begin to think of an array as an integrated system where local stresses are being broadly transmitted throughout the structure, and locally absorbed. This principle points toward valuable economies in material. We may instead design the system on the assumption that local stresses are shared by all members. The normal state of the system is not ‘solid state’ but a state of dynamic equilibrium. A corresponding multidirectional compression-tension network encloses accidental stresses wherever they arise. The tendency toward peripheral or localization of stress is replaced by a prescriptive multi-directional stress equilibrium.

Flextegrity’s patents describe the arrays that vary anisotropically, omni-topologically creating myriad hybrid materials. The materials themselves can be made of micromolecular cells aggregated into clusters of polyhedra. For example icosahedrons can be ordered into cubo-octahedral macro molecular clusters made from interconnecting icosahedrons to form a larger lattice that in turn is ‘shaped’ into an I-beam for greater efficiency in loading and use of material. Materials can be molded, assembled, arranged and optimally shaped to address forces in axial tension, bending, torsion and axial compression. Micro-analysis of the forces within the shape can 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 so forth.

A defining characteristic of Flextegrity’s material architecture is its anisotropic potential. According to the invention, interconnecting elements are used to tie icosahedral elements together along at least two and preferably 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. The material of which the interconnecting elements are formed may be flexible or rigid, and the material of which the icosahedral elements are formed may be flexible or rigid.

Forces with Icosahedrons



**6a** Tension

**6b** Compression

**6c** Torsion

**6d** Bending

Huge benefit is derived from being able to design and build a ‘micro-structure’ into the material to optimally fit a specific end-use application: The interconnecting network can be configured in a generally repeating pattern, but with tremendously variable functional characteristics due to the ability to vary the materials and micro-design of connecting tensile elements.

## Flextegrity: A Problem-solving Technology

Any new material offers both opportunities and risks to industrial designers and architects. There may be significant opportunities to enjoy radically new or improved technical or aesthetic behavior. The risks lie in incomplete understanding and characterization of the functional properties as well as the lack of previous design or manufacturing history. In architecture, for example, structures can be exceedingly complex in form, and the loads to be applied to the structure are equally complex. Hence, it can be difficult to analyze the loading on a given proposed structure and the resulting stress distribution within it. As a result, material elements and structures tend to be as simple and discrete as possible. Conventional design paradigms are constantly re-purposed even though they may not be optimal, but simply because it is more difficult to create and test new alternatives that will also meet established and traditional building codes.

We have strong reasons to believe that our advanced icosahedral architectures can address a number of increasingly complex material requirements. Flextegrity is presently prosecuting two patents in the field of structural materials that address the opportunities presented in the fields of disaster-resistant housing and environmentally mandated geo-textile solutions.

**Problem: Disaster-resistant housing.** The changing global climate brings more frequent, severe, and disastrous weather events that overwhelm conventionally built structures. Present day housing construction is driven by a short-term cost mentality and traditional uses of materials. It is only as strong as its weakest connection such as the point where rafters join walls and exterior walls intersect, making the structures prone to damage from earthquake and wind damage. We continue to rely on the same materials and designs in hurricane-prone areas even though existing methods often fail to meet the overwhelming stress/force demands on structures. Yet building codes and property insurers' regulations are becoming more rigorous as we speak. We need to re-think our designs and use of materials to anticipate catastrophic events and be resilient in extreme conditions.

**Solution:** Comprehensive custom-engineered solutions leveraging the unique and robust properties of Flextegrity materials. Tough, continuous web-like assemblies for retrofitting existing foundations and walls could be factory-built to custom sizes and exact specifications. In new construction, the structure is designed as a "whole" where the rafters and walls are of the same integral construction to create unprecedented resilience against novel external forces. The diverse design potential of Flextegrity materials could allow for retrofitting and new construction of disaster-resistant structures without sacrificing traditional architecture's look and feel.

**Problem: Environmentally damaging water run-off** is increasing as we pave our suburbs. Simultaneously, water quality is decreasing as current water control methods channel run-off directly into streams and rivers. The more we pave, the less opportunity for water to percolate through the soil before reaching the aquifers and rivers that provide clean water for our cities. Sidewalks, as a familiar example, are relatively easy to apply but the material is impermeable, contributing to polluted run-off into our waterways. Paved surfaces present additional problems, as the material lacks any resilience and breaks under the pressure of a tree root. Successful repair is impossible—we are forced to jackhammer the problem, haul off the debris, and start over. Municipalities and contractors face an increasingly high bar of EPA-mandated stormwater control regulations, and are searching for versatile and effective solutions.

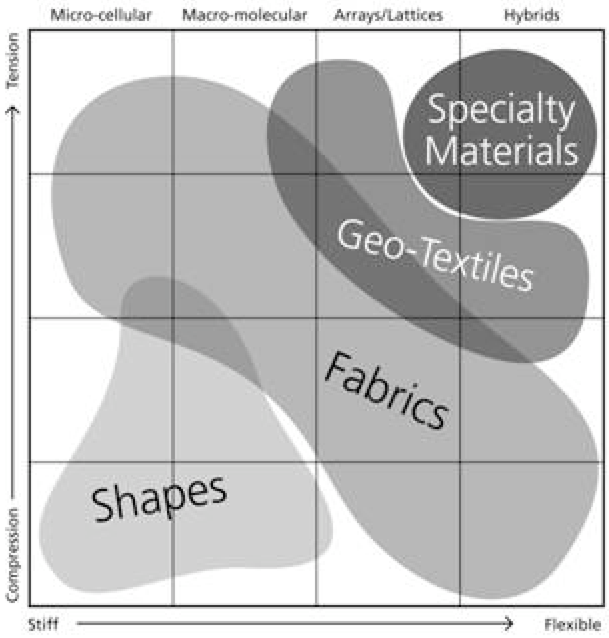
**Solution:** Meet demand for EPA-required soil stabilization and stormwater control products that balance strength and durability needs with environmental requirements. Flextegrity will produce structural 3-D "geo-textiles" that are load-bearing yet permeable, allowing for the controlled drainage of stormwater and natural percolation/de-activation of petroleum-based pollutants,. The assembled array can flex under stress, and the component parts are easily dissembled and reassembled for maintenance. Designers will gain the ability to create natural forms that begin to look and behave more like the natural landscapes they replace. Soil stabilization fabrics, sidewalks and eventually, streets, can be constructed using strong materials that offer the benefits of permeability and ease of maintenance. Intelligent sensors, microelectronics and a variety of unique and responsive properties can be engineered into the material.

**Problem: Inflexible, heavy, non-integrated building materials.** Age-old materials such as brick, steel, and wood don't truly integrate with each other. They are abutted, bolted and otherwise coerced to coexist. Their inherent design forces us to build most structures using 90-degree angles. But we only need to spend more time outside to observe that biological systems (the most supremely efficient in the structure and use of raw materials) do not use Cartesian coordinates to grow and sustain life.

**Solution:** FleXBloX will be the first flexible, permeable, structural material in the marketplace. Flextegrity's geometry mimics natural structural efficiencies and can be integrated to form limitless iterations for landscaping, exterior and interior constructions, architectural motifs, and fencing. FleXBloX, a lightweight, flexible, easy-to-assemble material, will be equally appealing to the contractor and the home handyman.

## Other Prime Applications in Search of Flextegrity's 'New Materials' Solutions:

- ✓ **'3-D Structural Elastics':** strong flexible joints/connectors for 'thick' dimensional surfaces/elements that need to bend or be held in continuous tension; adapts to fluctuations in expansion/contraction due to temperature and pressure changes without damage; self-draining; buildable at any scale



- ✓ **Underlayment/Reinforcement for Longer-lasting Paving/Sidewalks:** tough, resistant to damage by temperature extremes, porous for drainage of storm-water and natural percolation of petroleum-based pollutants, rapid "unibody" installation of panels and rolled goods that can be custom-sized and produced to specifications off-site

- ✓ **Advanced Geo-textiles:** extremely strong web-like structures for stabilization of soil, slopes; permeable and self-draining; 3-D geometry enables embedding of functional elements such as plant seeds, fertilizer, water-storing gels, weed suppressors

- ✓ **Home Landscaping/Paths/Driveways/ Fencing:** strong, porous 3-D scrims to replace heavy, expensive, time-consuming methods of preparing durable self-draining underlayment for hardscape (pavers/bricks) or natural materials (gravel/wood chips); can function as a matrix to stabilize loose materials especially on sloped surfaces; ideal for slight, strong, weather-proof, easily installed fencing material; can be covered with composite "tiles" or a tough continuous "skin" to achieve additional aesthetic and performance effects

- ✓ '**Intelligent' Textiles/Materials:** ability to incorporate functional elements such as circuitry, conductivity, lighting, sensors directly into intrinsic material structure, enables a single integrated layer of material to efficiently perform multiple functions

- ✓ **Systems-Built Housing:** enables ability to "custom-knit" lighter, stronger, safer, more portable structures in a controlled factory setting; customizable for function and aesthetics

- ✓ **Aviation/Marine Applications:** high potential strength-to-weight ratio, flexibility, structural integrity that accompanies the geometry is ideally adaptable to use of state-of-the-art light and strong composite materials

- ✓ **Nano-scale Materials:** potential for extremely thin/strong 3-D membranes, self-assembling at molecular scale by leveraging electro-chemical and other bonds.

- ✓ **Bio-Materials and other Medical Applications:** components for artificial body materials that need to emulate the strength of bone, flexibility of muscles and connective tissue, and physio-electronic conductivity of nerves.

- ✓ **Art/Décor:** ability for amateur and professional artisans to create unique, personalized geometrical constructions that might include conductive connectors, transparent/translucent icosahedron components, and LED/fiber-optic elements for use as a lighting device