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Design Characteristics of the IsoTruss Geometry

Introduction

The patented IsoTruss geometry was originally invented by Dr. David W. Jensen, a professor at Brigham Young University (Provo, UT), with funding from NASA in 1994. The novel geometry optimizes the use of composite materials to reduce weight without compromising structural strength. Dr. Jensen continued to research IsoTruss over the next 26 years at BYU, with research projects to advance manufacturing[1,2], predict failure modes analytically[3] and numerically[4,5], and analyze specific use cases. The IsoTruss geometry was applied to various applications including reinforced concrete beams[6,7], piles[8], and columns[9], bicycle frames[10,11], and bridges[12,13].

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[1] McCune, David Thomas. "Manufacturing Quality of Carbon/Epoxy IsoTruss-Reinforced Concrete Beam Columns." Thesis for the Department of Civil Engineering, Brigham Young University (Provo, UT). 2005.

[2] Hansen, Steven Matthew. Influence of Consolidation and Interweaving on Compression Behavior of IsoTruss Structures." Thesis for the Department of Civil Engineering, Brigham Young University (Provo, UT). 2004.

[3] Weaver, Thomas J. "Mechanical Characterization of a Composite IsoTruss in Flexure, Torsion, Tension and Compression." Thesis for the Department of Civil Engineering, Brigham Young University (Provo, UT). 1999.

[4] Opdahl, Hanna B., and David W. Jensen. "Dimensional Analysis and Optimization of IsoTruss Structures with Outer Longitudinal Members in Uniaxial Compression." *Materials* 14.8 (2021): 2079.

[5] Winkel, Lamar D. "Parametric Investigation of IsoTruss Geometry Using Linear Finite Element Analysis." Thesis for the Department of Civil Engineering, Brigham Young University (Provo, UT). 2001.

[6] Ferrell, Monica. "Flexural Behavior of Carbon/Epoxy IsoTruss-Reinforced Concrete Beam Columns." Thesis for the Department of Civil Engineering, Brigham Young University (Provo, UT). 2005.

[7] Jarvis, David. "Development of a Rectangular IsoTruss for Reinforced Concrete Beams." Thesis for the Department of Civil Engineering, Brigham Young University (Provo, UT). 2001.

[8] Richardson, Sarah. "In-Situ Testing of a Carbon/Epoxy IsoTruss Reinforced Concrete Foundation Pile." Thesis for the Department of Civil Engineering, Brigham Young University (Provo, UT). 2006.

[9] Earl, Jason S. "Concrete Columns Reinforced with Advanced Composite Gride Structures." Thesis for the Department of Civil Engineering, Brigham Young University (Provo, UT). 1998.

[10] Phillips, Joseph K. "IsoTruss Bicycle Frame Design Using Beam Theory and Shear Flow Analysis." Thesis for the Department of Civil Engineering, Brigham Young University (Provo, UT). 2001.

[11] Yoder, Jacob A. "IsoTruss to IsoTruss Connections and Small Scale IsoTruss Design for Mountain Bike Frames."

[12] Gaufin, Tamera. "Design of a Composite Bridge for Aspen Grove." Thesis for the Department of Civil Engineering, Brigham Young University (Provo, UT). 1999.

[13] Walker, Mary S. "A Rational Basis for Designing Advanced Composite Bridge Structures Based on Existing Standard Specifications." Thesis for the Department of Civil Engineering, Brigham Young University (Provo, UT). 1996.

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IsoTruss Inc. was founded in 2015 when Mr. Nathan Rich purchased the IsoTruss patent portfolio from BYU. Since its founding, IsoTruss Inc. has worked with clients in various industries including NASA, Nike, Raytheon, Northrup Grumman, AT&T, and major telecom tower owners in the US and Asia.

The Product

The IsoTruss geometry, named for its repeating pattern of isosceles triangles, reduces the amount of material needed to achieve excellent mechanical performance. The innovation comes from aligning the fiber in the composite material with the direction of forces in axial and circumferential directions. The structure is composed of longitudinal and helical members joined together shown in Figure 1. The longitudinal members withstand tensile, compressive, and bending forces while the helical members stabilize the longitudinal members and withstand torsion and transverse shear forces. Based on the application and loading scenario, material can be added to or removed from the longitudinal and helical members where needed to optimize product weight and prevent unnecessary material usage. Thus, for applications where bending or axial forces are most significant, material can be added to the longitudinal members and reduced on the helical members while applications with significant torsion or transverse shear forces can have more material in the helical members.

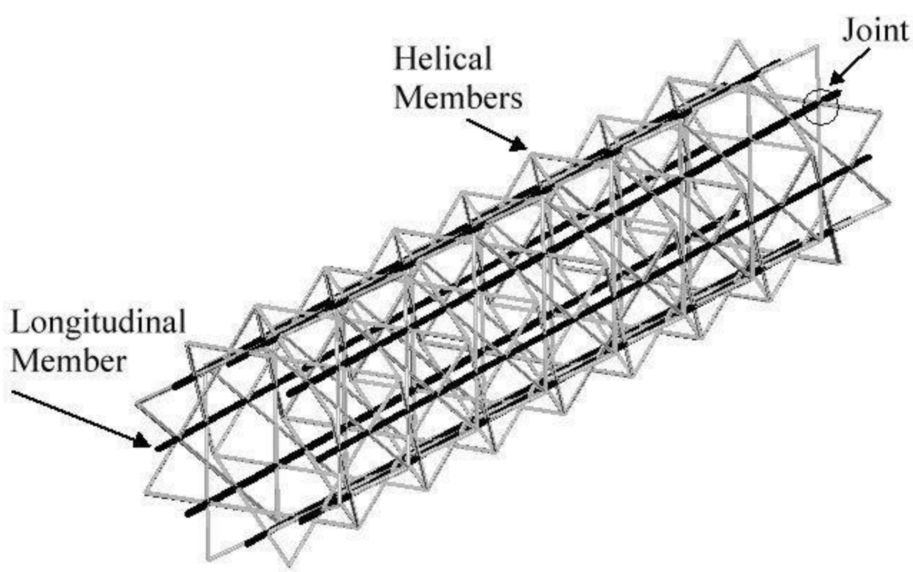

Figure 1. Model of the IsoTruss geometry. Longitudinal members are black and helical members are gray. Longitudinal members counteract tensile, compressive, and bending forces. Helical members counteract torsion and transverse shear forces.

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Applications

The customization potential of the IsoTruss geometry allows it to be widely applicable in various industries including aerospace, recreation, construction, and telecommunications. Specific products and benefits of IsoTruss for each of these industries will be considered.

Aerospace

In the aerospace industry, IsoTruss can be used for fuselage (see Figure 2), wing box, and strut structures in both manned and unmanned vehicles of various sizes. The original intention behind the invention of the IsoTruss geometry was strong and lightweight structures for aerospace. Weight savings result in fuel savings, reducing the impact of the most significant cost of ownership for aircraft[14]. IsoTruss can be customized for each aerospace application, placing materials where needed for specific loading conditions without adding unnecessarily weight. The example shown in Figure 2 shows IsoTruss with a circular cross section, but the geometry can also be applied to a more rectangular wing box shape or a non-uniform diameter fuselage shape such as in unmanned aerial vehicles.

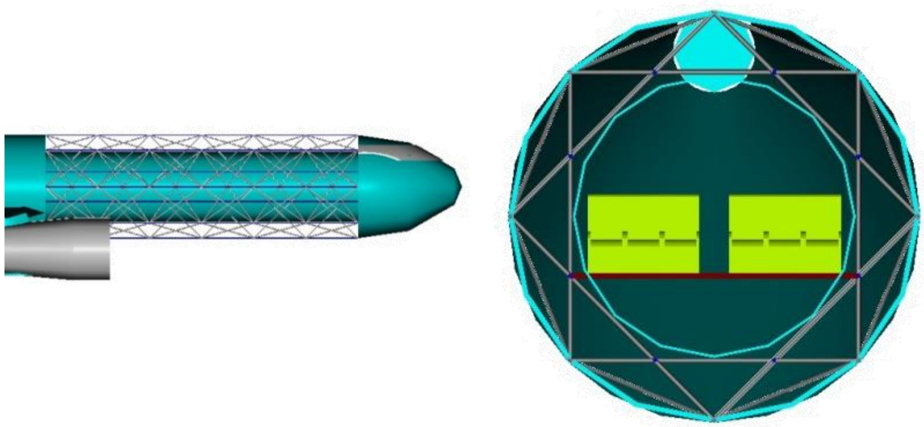

Figure 2. Artist concept of IsoTruss as a fuselage structure showing one example of an IsoTruss application in the aerospace industry.

Recreation

The IsoTruss geometry has also been applied to bicycle frames in the recreation industry. The IsoTruss bike started with university research projects and later evolved to a commercially available product. The weight reduction and durability of IsoTruss structures are beneficial for bicycle frames. IsoTruss frames were found to reduce weight by 51% compared to a standard

[14] Fioriti, Marco, Valeria Vercella, and Nicole Viola. "Cost-estimating model for aircraft maintenance." *Journal of Aircraft* 55.4 (2018): 1564-1575.

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aluminum frame[15]. The IsoTruss geometry was also found to have a lower drag coefficient than a smooth circular geometry[16] which equates to lower wind resistance of the bicycle frame.

Figure 3. Photograph of an IsoTruss bicycle frame. The IsoTruss geometry reduces bicycle frame weight by 51% compared to a traditional aluminum frame.

Construction

IsoTruss is effective in construction applications where reduced weight improves performance such as wall braces and floor beams. Other construction applications benefit from the inability of IsoTruss to rot, rust, or corrode including concrete reinforcement in structural piles, bridges, and roadways. IsoTruss is also valuable for concrete reinforcement because the structure integrates axial and shear members into the same structure, saving time and cost during installation and providing better mechanical performance as members share loads. Typical steel reinforcement has separate members for axial and shear forces which are usually tied together onsite for convenience during installation rather than for the purpose of improving mechanical performance. IsoTruss is currently working on projects to use IsoTruss-reinforced concrete as the foundation for telecom towers, with the hope to expand to additional reinforced concrete projects in the future. Examples of IsoTruss structures for construction applications are shown in Figure 4.

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[15] Yoder, Jacob A. "IsoTruss for Mountain Bike Frames."

[16] Ayers, James T. "Hydrodynamic Drag and Flow Visualization of IsoTruss Lattice Structures." Thesis for the Department of Civil Engineering, Brigham Young University (Provo, UT). 2005.

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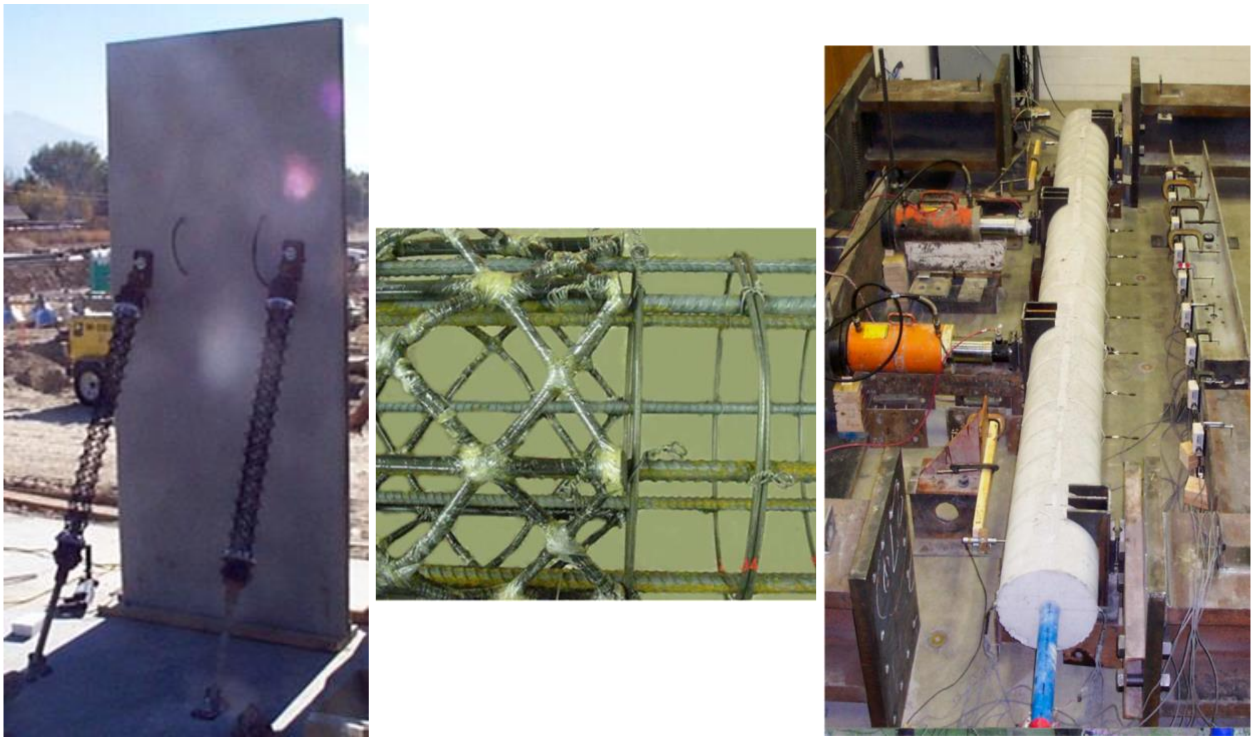

Figure 4. IsoTruss geometry for construction applications: wall braces (left), concrete reinforcement replacing steel (middle), concrete pile (right) [17]. The strength-to-weight ratio and durability in extreme weather conditions allow IsoTruss structures to outperform steel in numerous applications.

<u>Telecommunications</u>

Telecommunications applications such as cellular network towers, mobile cell sites, and wireless internet service provider towers (WISP) are also a good fit for IsoTruss technology because the reduced weight and patented design decrease delivery, installation, and maintenance costs. The lack of corrosion or rot also make IsoTruss ideal for specific locations for telecom towers including coastal regions with high humidity, hurricane-prone regions, and areas with difficult maintenance and repair access. In areas with extreme weather conditions, steel towers can need replacement after only 5 years where IsoTruss structures can last 25 years or longer. The lattice structure of IsoTruss lends to many practical benefits for tower applications such as the structure itself being climbable rather than needing an additional ladder structure. The lattice structure also allows modularity with attachments allowing for equipment to be modified as technology advances. Network hardware needs change over time with innovation and network updates, and IsoTruss structures allow existing structures to be modified with updated hardware rather than needing tower replacement. IsoTruss also has the potential to be radio frequency transparent allowing for unique telecommunication applications. Network access towers are one

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[17] Richardson. "In-Situ Testing".

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of the primary current commercial focus areas for IsoTruss and towers are deployed through the US and Asia (Figure 5).

Figure 5. Photos of IsoTruss telecom towers in the USA (left), Philippines (center), and Vietnam (right). All three towers pictured are 40' tall. The tower in the USA was a greenfield deployment and the Philippines and Vietnam deployments were rooftop applications.

Key Findings

Material Advantages

IsoTruss structures use composite materials such as carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP). Composite materials show significant advantages over other materials in both mechanical and chemical performance. While there are ranges for property values of composite materials and metals depending on the manufacturing method and desired application, the discussion below will compare high modulus CFRP/GFRP with high modulus aluminum and steel[18].

High Strength

Composite materials have a higher strength-to-weight ratio than steel and aluminum which means that less material can be used to achieve the same mechanical performance. This phenomenon occurs because CFRP has a significantly lower density – 0.05 lb/in^3 for CFRP while steel is 0.3 lb/in^3 and aluminum is 0.1 lb/in^3 – while still retaining high mechanical

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[18] Niu, Michael C. Y. Airframe Structural Design: Practical Design Information and Data on Aircraft Structures. Adaso Adastra Engineering Center (1999).

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properties like strength and stiffness. Strength-to-weight ratio is calculated by dividing ultimate tensile strength by material density. CFRP has a strength-to-weight ratio of $30x10^5$ inches compared to $10x10^5$ inches for steel and $7x10^5$ inches for aluminum.

The exact weight reduction for IsoTruss versus aluminum depends on the specific loading case of the application. In buckling conditions, IsoTruss structures are 12% the weight of a comparable steel structure. In bending conditions, the most common loading condition for telecom towers, IsoTruss structures weigh 8% of comparable steel structures.

The lighter weight of IsoTruss structures consequently reduces fuel costs for transport and makes installation easier. 20-ft IsoTruss sections – the standard size for telecom tower sections – can be lifted and maneuvered by hand rather than needing cranes or other heavy machinery (see Figure 6). One application benefitted by the lack of heavy equipment to deploy IsoTruss structures is rural broadband. One of the factors behind lack of network access in rural areas is hard-to-reach places like mountains and forests make it difficult and expensive to deploy traditional steel towers. IsoTruss, on the other hand, can be transported by light-duty trucks or even carried to deployment site by hand if needed.

Figure 6. 20-ft IsoTruss sections can be carried and maneuvered by hand rather than needing additional heavy machinery for deployment.

High Stiffness

Carbon fiber composite materials are also higher than aluminum and steel in stiffness-to-weight ratio calculated by dividing Young's modulus by material density. Stiffness-to-weight for CFRP is $400x10^6$ inches verses $100x10^6$ inches for steel and aluminum. Therefore, CFRP is 4x stiffer on a per weight basis. In applications where preventing or minimizing deflection is important, IsoTruss structures can meet deflection goals with less material than required for a steel or aluminum structure.

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Transversely Isotropic

Metals such as steel and aluminum are isotropic with mechanical properties identical in all directions. Composite materials are significantly stronger in the direction parallel to the fibers. The quality of properties being symmetric about a single axis of symmetry is called transversely isotropic. Transversely isotropic materials are beneficial because the design can be tailored to put material exactly where it is needed, thus reducing the overall amount of material used. The IsoTruss geometry takes advantage of the transversely isotropic property of composite materials by aligning the fibers with the direction of axial forces with longitudinal members and torsional forces with helical members (see Figure 1).

High Durability

Not only do IsoTruss structures give significant weight savings, but they extend product lifetimes with chemical and mechanical durability. Composite materials reduce or eliminate the effects of corrosion and rust. Exposure to water, humidity, and salinity can drastically reduce the product lifetime for steel structures. For example, one telecom tower company required replacement of steel towers after only 5 years in humid, coastal areas rather than the expected 25+ year lifespan seen in other areas. IsoTruss towers installed in the same locations do not have shortened product lifespans due to corrosion. Another example is corrosion of steel-reinforced concrete bridges over waterways due to the spray from jet skis and other water vehicles after 25 years while a composite-reinforced bridge in the same location was rated for a 100-year life. Corrosion damage is costly to prevent and repair in steel structures. IsoTruss structures, on the other hand, are made of composite materials that do not corrode even in the most extreme environments. Therefore, IsoTruss structures reduce the total cost of ownership by reducing maintenance and repair costs and greatly extending product lifetime.

IsoTruss structures can also replace wood structures in certain applications such as utility poles and floor beams. In outdoor applications coatings are often applied to reduce the possibility of rot, however, the coatings are toxic and can seep into the ground potentially harming plant and animal life[19]. On the other hand, IsoTruss structures are impervious to rot or corrosion without the need for added coatings.

Radio Frequency Transparent

Glass fiber is uniquely transparent to radio frequencies. IsoTruss structures made of GFRP can be used for situations where radio frequencies need to pass through the structure. For example, 5G cellular network towers are sometimes combined with other utilities and disguised to look like streetlamps in cities. With an IsoTruss structure the network hardware can be enclosed inside the tower so that the outward appearance matches aesthetics of a typical streetlamp.

Structural Advantages

The IsoTruss geometry amplifies the advantages of composite materials and creates superior structures compared to other composite structures. The lattice pattern of the IsoTruss

[19] Matthews, Robert Guy. "Poles Apart: Steel Take on Wood." *The Wallstreet Journal* (March 2, 2000).

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geometry places the fibers in the composite in the direction of forces to withstand axial, bending, and torsional forces with less material. This minimizes the use of material while giving high strength and stiffness and overall lowers the product cost.

For purposes of comparison, the IsoTruss geometry will be compared to a solid-wall tube structure made of the same composite material with identical diameters, heights, and loading scenarios. A 3D representation of these two geometries is shown in Figure 7.

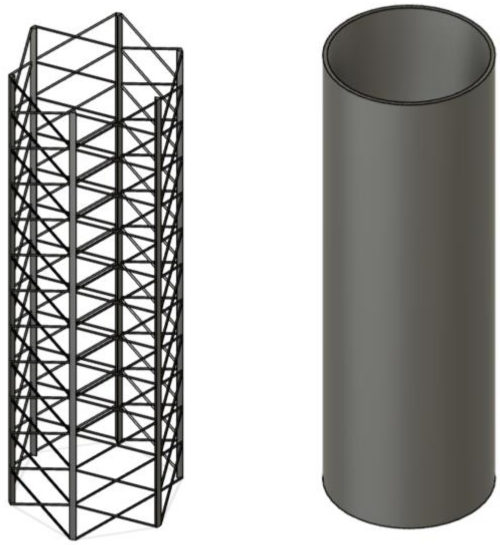

Figure 7. Representation of the IsoTruss lattice geometry (left) and solid-walled cylindrical tube (right). The project area, and therefore drag force, is lower for the IsoTruss geometry than for the solid tube.

Resists Shell Buckling

Shell buckling occurs under axial compression loading of thin-walled cylinders such as pressure vessels, storage tanks, aircraft skin, poles, and towers. Shell buckling can be mitigated by increasing the shell thickness or adding ribs, however, these measures either increase material usage and product weight in the case of increasing thickness or increase the complexity of manufacturing in the case of adding ribs. IsoTruss structures, particularly 6-sided IsoTruss structures are inherently stable in shell buckling conditions due to the repeating pattern of triangles in the geometry[20] and do not need additional material to prevent shell buckling conditions.

Lighter Weight

The IsoTruss geometry optimizes the amount of composite material for the desired mechanical performance and results in structures that are reduce material by up to 50%

[20] Opdahl, Hanna Belle. "Investigation of IsoTruss Structures in Compression using Numerical, Dimensional, and Optimization Methods." Thesis for the Department of Civil Engineering, Brigham Young University (Provo, UT). 2020.

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compared to traditional solid-wall composite structures. The reduction in weight is especially beneficial because material costs can be a large part of manufacturing costs compared to other more traditional engineering materials.

Low Drag

The IsoTruss lattice geometry experiences less drag in air and water than a solid cylindrical tube. The comparison with a solid cylindrical tube or solid-walled tube is informative because it is a common geometry used for composite materials in various applications. The drag force for any geometry is proportional to the projected area which is significantly smaller for a lattice geometry than for a solid-walled geometry. Therefore, the aerodynamic and hydrodynamic drag is lower for IsoTruss than for solid-walled composite geometries.

The exact percentage decrease in drag force for IsoTruss over a solid-walled tube depends on the wind speed and geometrical parameters of the IsoTruss such as the thickness of the members and the number of sides. Regardless of the IsoTruss geometry, however, the solid-walled tube always experiences higher drag. Figure 8 shows test data of an aerodynamic flow simulation comparing several IsoTruss geometries to a solid-walled tube. In the figure, 6-node and 8-node refers to the number of sides of the IsoTruss, double versus single refers to there being a single diameter or two diameters for the IsoTruss geometry, and thick versus thin refers to the thickness of the individual members of the IsoTruss. The smooth circular cylinder (red line with circular points) experiences higher drag than any configuration of IsoTruss for all wind speeds.

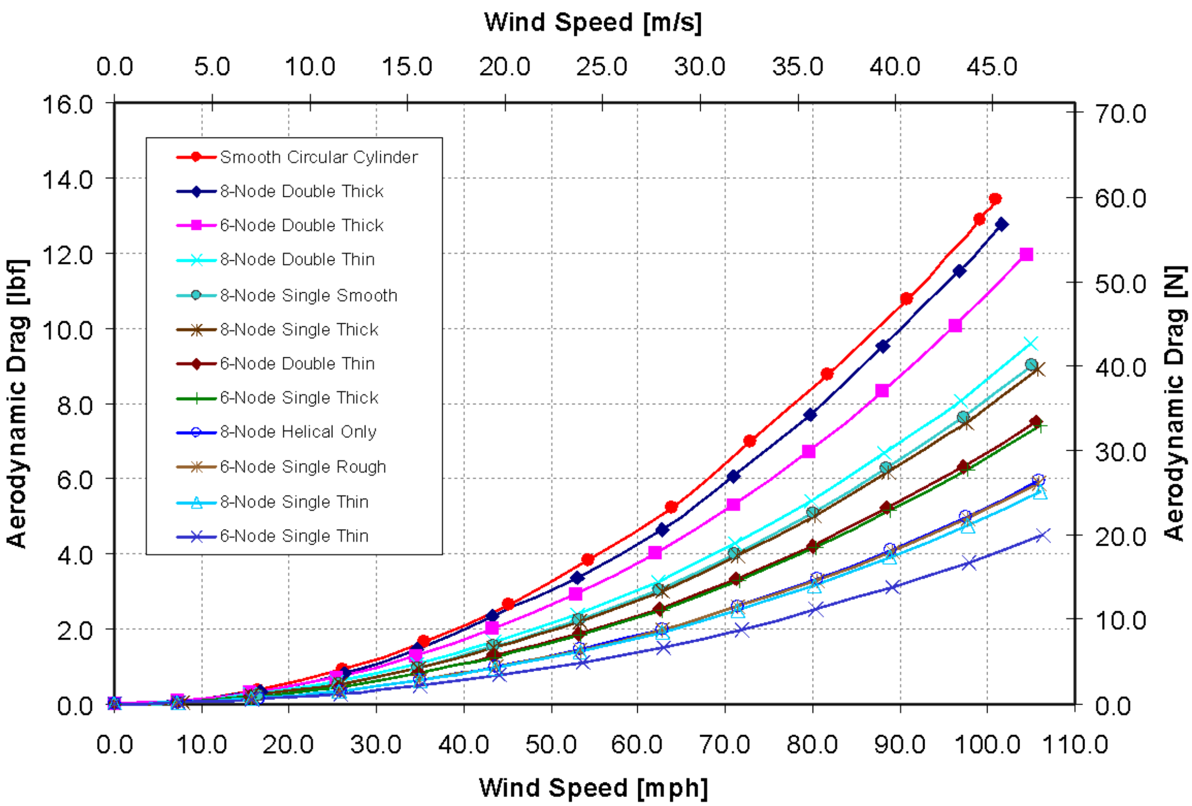

Figure 8. Test data for aerodynamic drag of a solid-walled cylindrical tube (smooth circular cylinder) and various IsoTruss geometries. The IsoTruss is lower than the cylindrical tube for every geometry configuration and wind speed. See the red line with circle data points for cylindrical tube data. All IsoTruss geometries have less drag than the cylindrical tube. Data from Ayers[21].

Damage Tolerant

IsoTruss structures are more damage tolerant than other geometries because the members provide layers of redundancy for better structural integrity. If one member of the IsoTruss is damaged or breaks, the load can still be carried by other members without catastrophic failure. This concept was tested by loading an IsoTruss structure to an initial failure (breakage of one member) and then reloading the same structure again until a second breakage occurred. The second breakage occurred at approximately 75% of the initial maximum load, proving that there is redundant structural integrity of the IsoTruss structure rather than a catastrophic failure after a single breakage.

[21] Ayers, James T. "Hydrodynamic Drag and Flow Visualization of IsoTruss Lattice Structures." 2005.

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Aesthetics

The IsoTruss geometry allows for many different aesthetic designs. The lattice geometry blends into the surroundings so that it is difficult to see (Figure 9). IsoTruss structures are also compatible with skins or other coverings if desired. One application of this is to create utility poles that look like streetlamps. The electrical hardware for utilities is encased inside of the IsoTruss structure, and then an outer covering can be applied to match virtually any desired streetlamp. This application is particularly desirable in city locations where standard utility poles detract from the aesthetics of the area.

Figure 9. Photograph of an IsoTruss utility pole structure. The lattice geometry of IsoTruss structures causes them to easily blend into the surrounding area. The arrow on the figure points to the IsoTruss structure.

Environmentally Friendly

IsoTruss structures support efforts to reduce carbon emissions and more carefully consider environmental impact of product lifecycles. Both steel and carbon fiber materials require carbon-intensive processes to manufacture with steel at 2 tons of CO_2 per ton of material and carbon fiber at 20 tons of CO_2 per ton of material produced. The environmental benefit of IsoTruss and carbon fiber comes from the reduced amount of material needed for the design along with the extended lifetime of IsoTruss products. In other words, IsoTruss products use less material in the first place and then need less frequent replacing.

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Conclusion

IsoTruss is a patented composite lattice geometry that reduces weight and material usage while exhibiting excellent mechanical performance. The structure can be applied in many different applications in the aerospace, recreation, construction, and telecommunications industries.

The advantages of IsoTruss structures can be classified into material and geometrical. The composite materials used in IsoTruss structures are extremely high strength-to-weight and stiffness-to-weight ratios compared to metals which allows lighter weight structures to be used to achieve the same mechanical performance. Composite materials are exceptionally corrosion resistant which increases product lifetimes and reduces maintenance costs.

The IsoTruss geometry further increases the inherent benefits of composite materials by taking advantage of the transversely isotropic material and aligning the fibers with the direction of the force. This design allows IsoTruss to be lighter weight than traditional solid-wall composite designs. The IsoTruss geometry is also naturally resistant to shell buckling, a common problem for thin-walled structures, because of the repeating pattern of triangles. IsoTruss is also advantageous in aerodynamic and hydrodynamic situations because the drag force is lower for IsoTruss than solid-walled geometries. The triangle pattern also gives redundancy allowing higher damage tolerance. The lattice design is beneficial for aesthetic reasons – for different applications IsoTruss can blend into surroundings, be radio frequency transparent, or easily interface outer coverings for disguise. Finally, the reduction in material use and extended product lifespan of IsoTruss structures ultimately reduce the environmental impact and provide a more sustainable solution.

The opportunities and applications for the IsoTruss geometry are seemingly limitless, particularly as industries continue to move toward sustainability and full lifecycle considerations.