Wheaton Journal of

Cell Biology Research

Issue 7, Spring 2020:

"Living Architecture"

R.L. Morris, Editor. Wheaton College, Norton Massachusetts.

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The Distribution of Tensile and Compressive Forces in Articular Cartilage and the Truss Bridge

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BIO 298 / Principles of Cell Biology
Final Research Paper
27 April 2020

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Living Architecture Research Project Report
BIO 298 Principles of Cell Biology
Wheaton College, Norton, Massachusetts, USA
April 26, 2020

Rule to Build By:
"To construct self-supporting structures, balance forces of tension and compression" (Lane & Morris, n.d.).

What:
The macromolecules within the extracellular matrix of articular cartilage work in conjunction with each other to withstand tensile and compressive forces at the joints of articulating bones (James & Uhl, 2001; Fox et al., 2009).
The truss bridge maintains its upright position while bearing the weight of pedestrians and vehicles by bending and distributing tensile and compressive forces throughout the members of the bridge(Ressler, 2001, p.2; Billington et al., 2020; The Editors of Encyclopedia Britannica, 2019).

How:
Articular cartilage is found lining the bones of synovial joints (Figure 1), which are highly mobile and contain synovial fluid in the joint cavity ("Synovial Joint", 2020). The purpose of articular cartilage is to absorb impact and distribute load while minimizing friction and stress to the subchondral bones (James & Uhl, 2001; Fox et al., 2009). Articular cartilage is 2-4 mm thick and is composed of an extracellular matrix (ECM) with a small supply of chondrocytes, the only cell type within cartilage (Figure 2). The main constituents of the ECM are collagen fibrils and proteoglycans. The chondrocytes maintain the ECM and secrete the proteoglycans and collagen molecules (Fox et al., 2009; James & Uhl, 2001., 2001; Responte et al., 2007).

Of the macromolecules within the ECM, collagen is the most abundant. The basic structure of a collagen molecule consists of three polypeptide chains, woven into a triple helix (Fox et al., 2009). Collagen molecules combine, creating collagen fibrils, through the formation of crosslinks (Fox et al., 2009). Crosslinking can occur enzymatically, when in the presence of lysyl oxidase, predominantly creating pyridinoline and ketoimine crosslinks. Crosslinks can also form independent of enzymes when the amine group of a collagen molecule interacts with the sugar of another collagen molecule, creating advanced glycation end products (AGEs) (Responte et al., 2007). This linking of collagen molecules provides the tissue with extensive stability and tensile strength (Fox et al., 2009). The most common collagen molecule in articular cartilage is collagen II, accounting for 90% of the total collagen. The less abundant collagen molecules work to strengthen and create the collagenous network (Fox et al., 2009). These collagen fibrils are intertwined with proteoglycans, which further increases the structural stability of collagen (Fox et al., 2009; Responte et al., 2007).

The matrix of articular cartilage is described as having four collagenous zones: the superficial, intermediate, deep and calcified zones (Figure 3). The fibrils increase in diameter and change in orientation between each zone. The structure of the collagen network, including the zonation and fibril orientation contributes to the tensile strength of cartilage (Responte et al., 2007). The superficial zone has the most collagen, consisting of a thin, tightly cross-linked meshwork of fibrils which come in contact with the synovial fluid of the joint. Due to the stability and shear strength of cross-linked collagen fibers, this layer contributes most to the tensile strength of articular cartilage (Fox et al., 2009). The fibrils of the transitional zone are arranged obliquely, forming intertwining arches with neighboring fibers (James & Uhl, 2001; Responte et al., 2007). The intermediate zone is the first zone to contain proteoglycans, making it the first zone to resist compressive pressure (Fox et al., 2009). The deep zone contains the most proteoglycan content and has the largest fibrils, arranged perpendicular to the joint surface (James & Uhl, 2001; Fox et al., 2009). Due to the high proteoglycan content, the deep zone accounts for the most amount of compressive strength (Fox et al., 2009; James & Uhl, 2001). The fibrils of the calcified zone penetrate the subchondral bone, connecting cartilage to bone (James & Uhl, 2001).

Proteoglycans are the second most abundant macromolecule within the ECM of articular cartilage (Fox et al., 2009). Proteoglycans are composed of a polypeptide core with many glycosaminoglycans (GAGs) projecting along the core. These GAGs are negatively charged and repel each other, causing them to stick out, in a comb-like formation (Plopper, 2016). In addition to repelling each other, the negative charge of the GAGs attracts cations, which draws in water, causing this well hydrated tissue to resist compressive forces (Plopper, 2016; Fox et al., 2009; Responte et al., 2007). The most abundant and largest proteoglycan in articular cartilage is aggrecan, which fills the space within the collagen fibrils and acts to control the diameter of collagen fibers and the rate of their formation (Plopper, 2016). Nonaggregating proteoglycans interact with the collagen molecules and aid in the creation of fibrils (Fox et al., 2009). Proteoglycans are the fundamental component causing the compressive strength of articular cartilage (Plopper, 2016).

Articular cartilage is considered to have a biphasic nature, consisting of a fluid and solid phase. The fluid phase consists mostly of water and dissolved salt ions, the solid phase accounts for the collagen fibrils, proteoglycans and chondrocytes (Furmann et al., 2020; Fox et al., 2009; Responte et al., 2007). When a load is placed on a joint during an activity such as running or walking, the interstitial fluid increases in pressure, causing fluid to escape the ECM while transferring the load to regions of the joint under less stress(Furmann et al., 2020; Fox et al., 2009). The low permeability of articular cartilage, however, prevents the fluid from leaving the ECM fully (James & Uhl, 2001; Fox et al., 2009). With less interstitial fluid, the concentration of proteoglycans is high, as the collagen meshwork prevents the proteoglycan gel from escaping, causing osmotic pressure to increase (James & Uhl, 2001). Once the weight is lifted, the GAGs draw fluid back into the matrix, until equilibrium is reached. The movement of fluid prevents damage to the subchondral bone when that area is under impact (James & Uhl, 2001). These cartilaginous properties allow for individuals to remain upright, and engage in numerous load bearing activities, like the purpose of a bridge which faces comparable architectural obstacles.

The truss bridge is categorized as one of the six basic forms of bridges. The truss is a popular bridge, built for its economic efficiency and high strength to weight ratio (Billington et al., 2020; Ressler, 2001, p. 2). A typical truss bridge consists of two main trusses (sides), a deck, and floor beams (Figure 4) (Ressler, 2001, p. 3). A truss is formed by the arrangement of several members (load supporting structures) into repeated triangles. These series of triangles align, forming a top chord, bottom chord, and many vertical and diagonal members (Ressler, 2001, p. 2). The triangular shape of a truss is ideal in bridge composition due to the stress resistant nature of triangles, allowing these bridges to support heavy loads over long distances (The Editors of Encyclopedia Britannica, 2019). The trusses are connected by transverse members: the struts, lateral braces and floor beams. The flat surface of the bridge that supports the passage of pedestrians and vehicles is referred to as the deck. The deck absorbs the load of the vehicles and pedestrians; the weight of the deck is then supported by the floor beams which direct the weight throughout the main trusses (Ressler, 2001, p. 3-4).

The truss bridge follows the rule to build by as it supports the weight of itself, as well as additional compressive and tensile forces. The truss bridge accomplishes this by distributing these forces throughout the members of the bridge (Figure 5). The mechanism by which the bridge is able to distribute the forces of vertical loads is through the bending of the top chord (Lin & Yoda, 2017; The Editors of Encyclopedia Britannica, 2019). When the bridge bearing the weight of vertical load, the top chord is pulled down, bending slightly, causing it to compress into itself. The bottom chord is then stretched on either side in tension (Ressler, 2001, p. 8). The diagonal members of the trusses either exhibit tensile or compressive forces, depending on their arrangement and orientation (Lin & Yoda, 2017; Ressler, 2001, p.2; The Editors of Encyclopedia Britannica, 2019).

Why:

The compressive and tensile strength of cartilage protects and increases the functioning of bones without injury. These properties brought upon by the molecular components of the articular cartilage matrix provide many evolutionary advantages. The interacting macromolecules within the ECM and the biphasic nature of articular cartilage work in conjunction to produce strong compressive and tensile strength, allowing the resistance of loads (Fox et al., 2009; Responte et al., 2007). This ensures there is minimal load bearing of the subchondral bones. The tensile forces of the collagen fibrils constrain proteoglycans within the ECM. The presence of proteoglycans in the ECM ensures the cartilage is well hydrated, and able to withstand the compressive forces from various activities and movements. The presence of proteoglycans ensures the osmotic pressure will provide compressive strength throughout the joint (Plopper, 2016; Responte et al., 2007). The protection of the articular cartilage is injury preventative and increases the lifespan of the subchondral bones.

Cartilage with tensile and compressive strength allows individuals to lead active lives without causing damage to their bones. Activities resulting in impact to our joints include but are not limited to jumping, running, throwing, even walking (James & Uhl, 2001). These activities promote our overall health. It would not be possible to take part in high intensity training and many sports if it were not for the protection and shock absorption of the cartilage in our joints. Evolutionary speaking, if we were incapable of doing a simple task, such as running, without it resulting in an injury to our bones, it would have been very difficult to outrun and defend oneself from predators. Furthermore, a lack of cartilage with tensile and compressive strength can result in serious joint pain, swelling and immobility. Articular cartilage is necessary to prevent the early onset of many joint related injuries or challenges such as arthritis ("Arthritis", 2020).

The purpose of a bridge is to allow the passage of individuals or vehicles above from one side of an obstacle to the other with limited vertical support (Lin & Yoda, 2017 p.1; Bridge Masters, 2017). The bridge must follow the rule to build by, balancing the forces of their own weight in conjunction with additional vertical, compressive and tensile forces in order to stand upright and properly function (Ressler, 2001, p.2; The Editors of Encyclopedia Britannica, 2019). By bending under the weight of vertical loads, the truss bridge is able to distribute compressive and vertical forces throughout its members, allowing it to remain stable while supporting the weight of heavy vehicles for long distances (Ressler, 2001, p.2,6,8,9; Billington et al., 2020).

Figures:

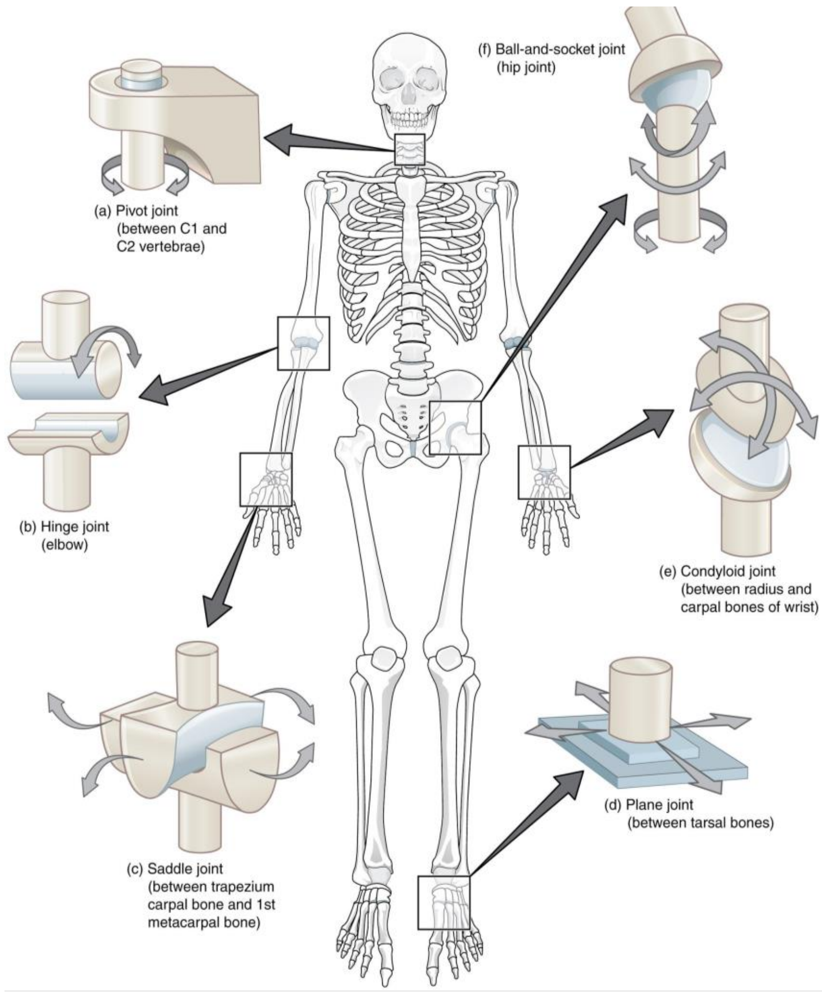

Figure 1: **Examples and Locations of the Six Synovial Joints.** This image displays the six types of synovial joints, their actions, and specific locations of these joints. Articular cartilage can be found lining the bones of each of these joints with the purpose of decreasing impact to that region ("Synovial Joint", 2020). (Figure from OpenStax., 2013.)

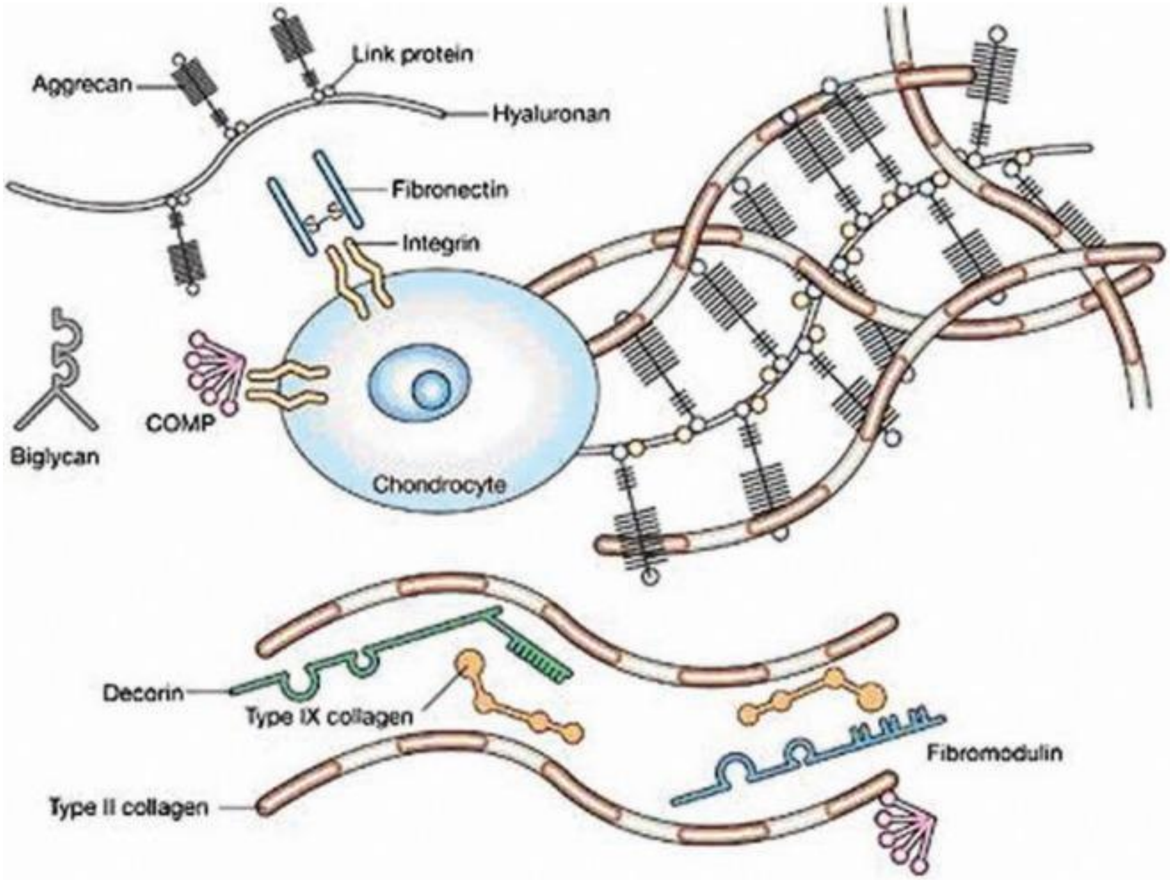

Figure 2: The components of the articular cartilage matrix. A chondrocyte can be seen secreting collagen II fibers in the center. The collagen II molecule can be seen interacting with collagen IX at the bottom of the image. The proteoglycan, aggrecan, is in the top left corner of the image, consisting of the protein core, hyaluronan, with sugar chains attached via link proteins (Fox et al., 2009). This image features additional noncollagenous proteins and smaller proteoglycan components of the extracellular matrix, including biglycan, fibromodulin, decarin, COMP, integrin, and fibronectin. (Figure from Fox et al., 2009.)

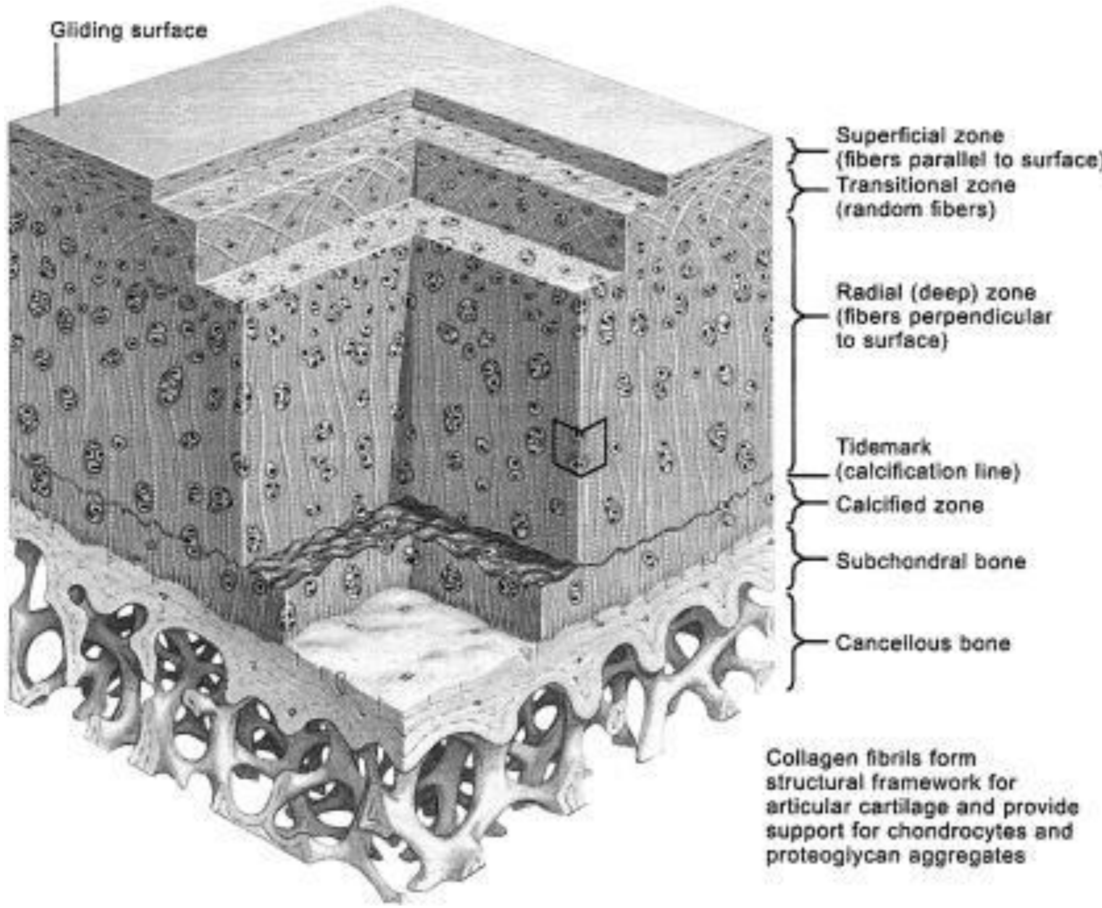

Figure 3: The Zonation Within the Extracellular Matrix of Articular Cartilage. The artist features the zoning of the articular cartilage matrix and provides labels to the right of the image, indicating each zone and its distinctive characteristics. The round bodies dispersed throughout the matrix are chondrocytes, which are oriented similar to the collagen fibrils within their respective zone. The lighter shaded lines indicate the collagen fibril positioning. Note the increase in diameter of the collagen fibrils and their change in orientation between each zone (James & Uhl, 2001). (Figure from James & Uhl, 2001.)

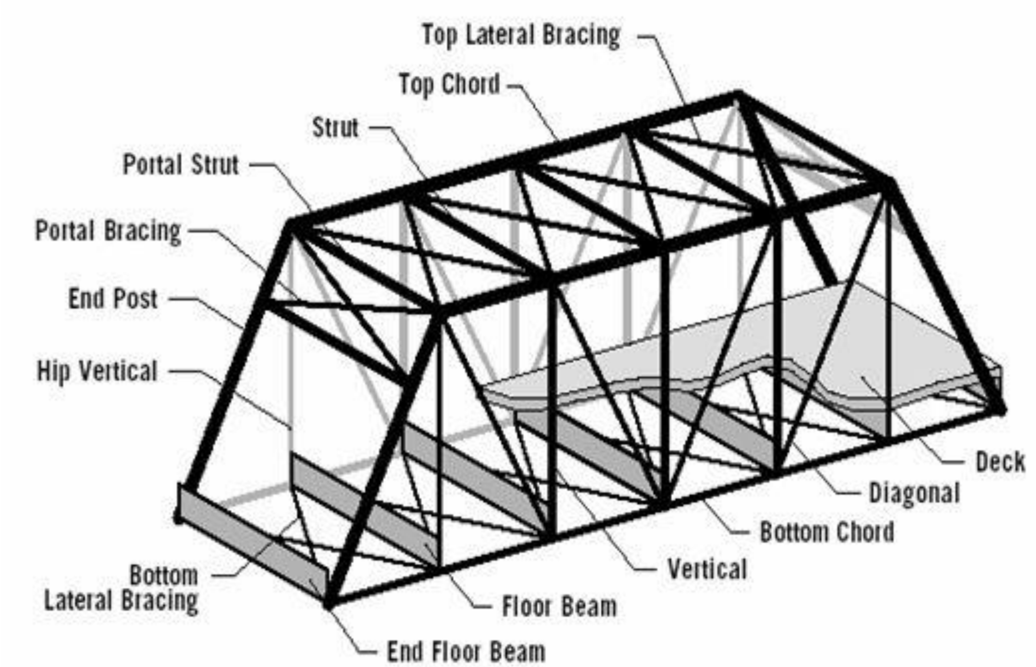

Figure 4: Isometric view of a basic truss bridge plan. This image features the major structural components of a truss bridge, all of which are labeled. Note the repeated triangles formed by the members of either truss. (Figure from Ressler, 2001, p. 3.)

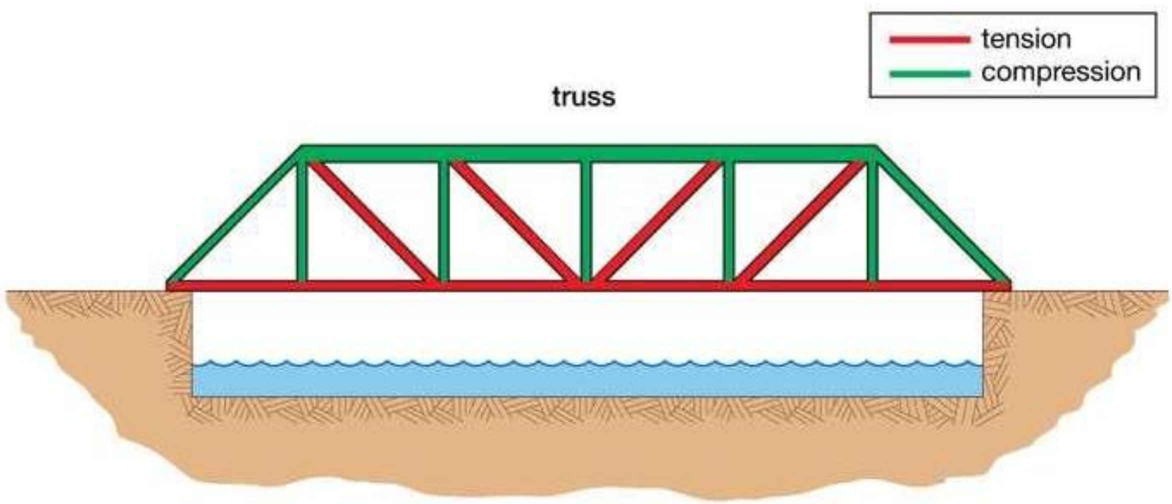

Figure 5: **Distribution of Tensile and Compressive Forces in the average truss bridge**. This image depicts the tensile and compressive forces distributed throughout the truss bridge. As shown above, the members compose a series of triangles which connect along the top and bottom of the bridge, forming the chords. The top chord, colored green, bends slightly compressed under the weight of a vertical load, causing it to push inward and down, which then forces the bottom chord to go into tension and press outward. As shown, the members of the bridge engage in either tension or compression, depending on orientation (Ressler, 2001, p. 3). (Figure from Billington et al., 2020.)

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