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USING POST-TENSIONING IN LARGE SCALE ADDITIVE PARTS FOR LOAD BEARING STRUCTURES

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Abstract

One of the perennial problems with additive manufacturing (AM) is the lack of inter-laminar bond strength between the layers, also known as z-strength. This can make the use of AM fabricated parts in load bearing applications problematic. This problem can be solved in some applications with post-tensioning. The use of post-tensioning in structures can be used to ensure that layer interfaces only see compressive stresses. This method is commonly used to strengthen concrete structures since concrete is weak in tension while strong in compression. This paper explores the successful application of post-tensioning to improve z-strength of large structures made with Big Area Additive Manufacturing (BAAM) where loads are significant. Theory and examples are presented herein.

Introduction

In recent years additive manufacturing (AM) has become a viable means of fabrication of parts for a variety of applications. The design freedom allowed by AM has made it possible for designers to make things that would have previously been impossible. New geometries that could not have been manufactured with conventional techniques can now be made with relative ease. The capabilities of AM have opened many doors that previously were closed.

However, AM has its own set of limitations that must be overcome. A serious issue to overcome is anisotropic material properties. AM is a process that fabricates parts in a layer by layer fashion. This leads to a high degree of anisotropy as material properties between layers are not that same as properties within a layer. In most AM processes, the bond between layers is weak compared to the rest of the material. This causes low strength in the build direction. [1] The strength in the build direction is often called z-strength. Delamination of layers is a common failure mode in polymer AM parts.

A partnership between Oak Ridge National Laboratory (ORNL) and Cincinnati Inc. has resulted in the development of Big Area Additive Manufacturing (BAAM), which massively increases the scale of polymer additive manufacturing. [2] With BAAM, parts reaching 20ft can be printed at deposition rates approaching 100lbs/hr or higher. BAAM has opened many exciting possibilities for what can be achievable with AM. However, the z-strength in BAAM parts is severely limited, and layers may delaminate. Duty et. al. observed tensile strength in the z-direction to be only around 30% of the tensile strength in the x-direction. [3]

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Even this limited strength in the z-direction can be unreliable. The z-strength is affected by the time it takes to print a layer. With longer layer times, the part cools more before another layer of material is deposited. If the previous layer's material is too cool, adequate bonding will not occur between the previous layer and the new layer. Thus, large parts with long layer times may have very weak z-strength. Other factors can affect the z-strength as well, such as the temperature of the build environment and the geometry of the part itself. With many variables working to potentially decrease z-strength further than its already depressed value, it would be foolhardy to rely on the z-strength of BAAM printed parts in a critical application.

However, the part size capabilities of BAAM enable applications where loads on the parts are considerable. Such applications include but are not limited to: large self-supporting molds, structures, vehicles, and marine vessels. To use BAAM for such applications, the engineer must design around the z-strength weakness of the material. Therefore, design methodologies that account for the material weakness must be examined. An example of a material with a similar weakness is concrete. Concrete has good compressive strength but poor tensile strength. This is similar to AM parts, which have the tendency to delaminate when the layers are under tension, but AM parts do not fail in that fashion when under compression. Despite this weakness, concrete is widely used as a construction material in both low- and high-performance applications. By designing proper reinforcements, engineers are able to properly utilize the strength of the material. One such reinforcement strategy is to post-tension structures. This strategy can be easily adapted to BAAM and other AM parts. This paper will examine the use of post-tensioning of BAAM parts for high load applications.

Post-Tensioning BAAM Parts

Post-tensioning is a technique that is used frequently in the construction of concrete structures. Concrete is a material that performs well in compression but performs quite poorly when loaded in tension. Post-tensioning takes advantage of this fact by ensuring that all the concrete remains in compression.

A concrete structure that will undergo post-tensioning is poured in place with tubes cast into the part that run the length of the structure. After the concrete has cured, these tubes are used as channels to run steel tendons through the length of the structure. These steel tendons are fastened at either end of the structure. Then, the tendons are stretched so that they pull and compress the concrete. The tendons are placed and stretched after the pouring of the concrete hence the name post-tensioning. Strategic placement of these tendons with the appropriate force on the tendons can prevent the concrete from going into tension and increase the load capability of the structure.

Parts printed on BAAM are similar to concrete in that the layer boundaries will behave well under compression but will easily delaminate when placed under tensile loading. By post-tensioning BAAM parts, it is possible to increase the load bearing capacity of printed parts in a similar manner to what is conventionally done in concrete.

Load Superposition and Shifting the Stress State

In the post-tensioning process, the post-tensioned load is combined with the service load to create the net load that is applied to the structure. Through superposition, these two loads are added for the net load on the structure. By superpositioning a compressive load, one can alter the stress state in a way that eliminates tension on the structure.

Figure 1(a) shows a simply supported beam as an example. A force, F, is applied at the center of the beam. This creates bending stress in the beam. This stress is the highest at the center of the beam where the force is applied. Without any post-tensioning, the bending stress creates a normal stress in the beam with a profile as shown in Figure 1(b). [4] At the top of the beam, the normal stress is compressive (positive) and transitions linearly to a tensile normal stress (negative) at the bottom. In the center at the neutral axis, the normal stress is zero. A post-tensioned force, P, is applied on either end through use of a post-tensioning tendon shown in blue. This creates a uniform compressive normal stress across the profile of the beam. The net normal stress is the superposition of these two stresses. This yields a stress distribution at the center that varies from zero at the bottom of the beam to a higher compressive stress at the top of the beam.

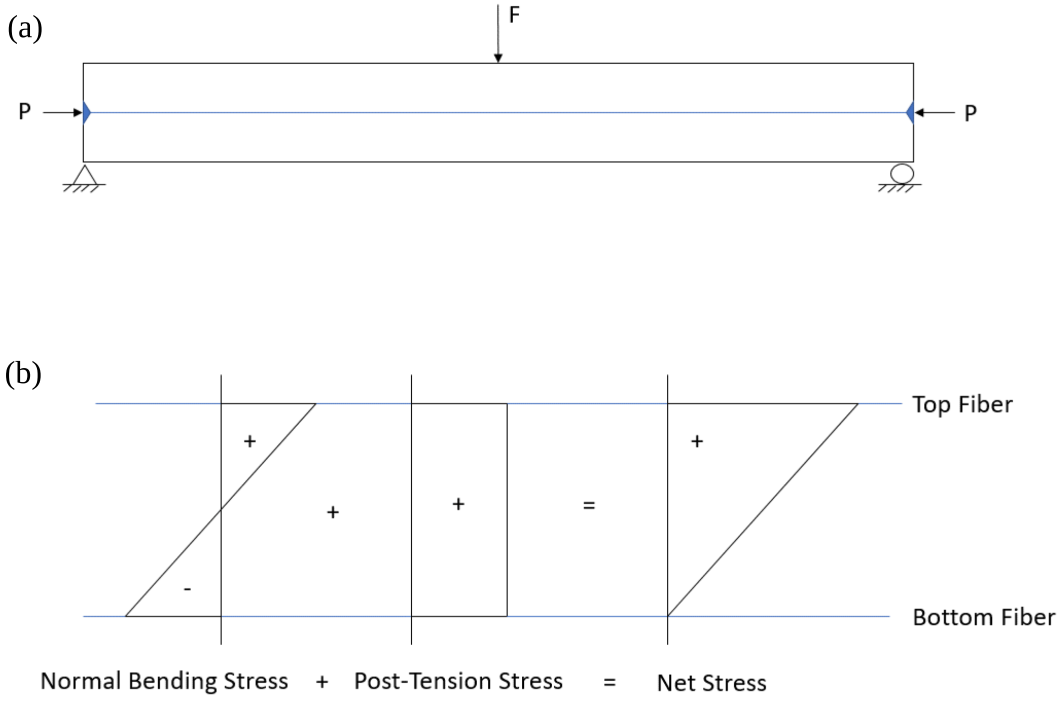

Figure 1: (a) Simply supported beam with post tensioning example. (b)Stress distribution on the beam profile

By applying the post-tension force, the stress distribution is shifted in the compressive direction causing the entire profile to be in compression. Figure 2 illustrates this. On the left is the stress distribution at a point along the beams length before applying the post-tension. The red lines designate failure in terms of yield or ultimate strength of the material. Before post-tensioning, the bottom of the beam is past failure in tension. By applying the post-tensioning force, the stress distribution is shifted in the compressive direction (to the right on the figure). This yields the stress distribution shown on the right side of this figure. Here none of the material is in failure. If an excessive post-tensioning load was applied, the stress distribution would continue to move in the compressive direction, and eventually the beam would fail in compression at the top of the beam profile.

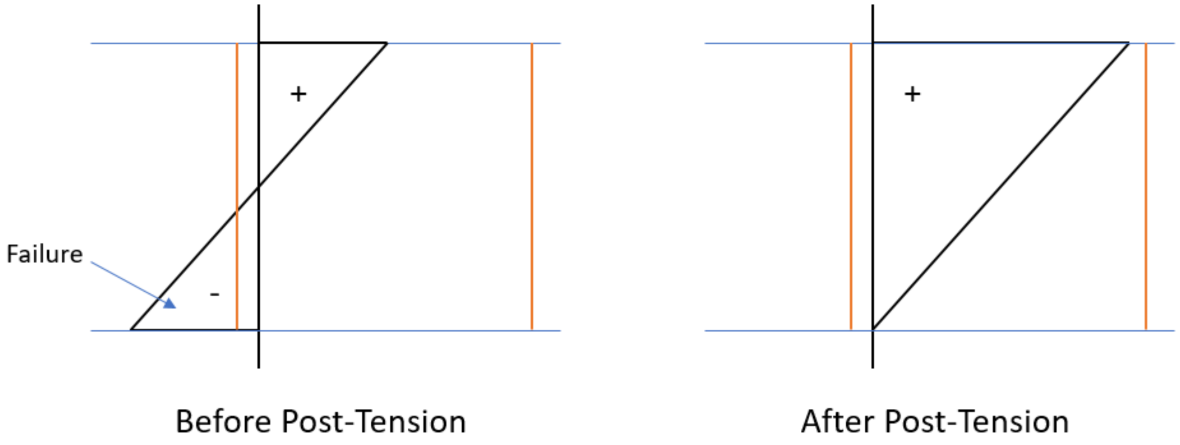

Figure 2: Stress distribution shifting to become solely compression through post-tensioning.

Designing a Beam to Prevent Tensile Stress Between Layers

Through the use of post-tensioning, large AM structures can be designed to take significant loads. The use of post-tensioning prevents tension between the layers, thus avoiding the risk of layer delamination. A beam-like structure is straightforward to design in this fashion.

In many applications for large-scale printed structures, the build direction will go down the length of the beam as shown in Figure 3. This means that normal bending stresses will be perpendicular to the layer interfaces. Therefore, the post-tensioning must be designed against the bending stresses that will pull the layers apart during service. The tendons will run down the length of the beam compressing the layers together.

Figure 3: Illustration of the build direction going down the length of the part.

Figure 4 is an example of a simply supported beam with a uniformly distributed load, w. The cross section is constant down the length of the beam. The area moment of inertia is designated as I, and the distance from the neutral axis to the outermost fiber on the tensile side is designated as c. The area of the cross section is designated as A.

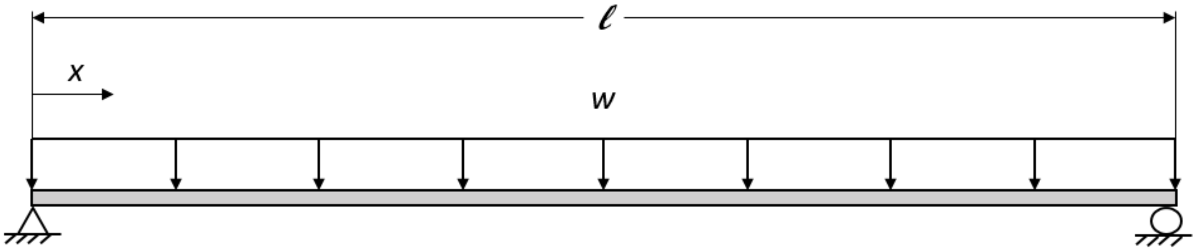

Figure 4: Supported beam with a uniformly distributed load.

The first step is to find the maximum tensile stress from bending present in the beam. This can be found from shear and moment diagrams or from beam tables. Since this is a simple load case, a beam table can be used. Tables from *Shigley's Mechanical Engineering Design* [4] give the moment as:

$$M = \frac{wx}{2}(\ell - x)$$

The maximum moment is found in the center:

$$M = \frac{wx\ell}{4}$$

This is where the maximum tensile bending stress is found. The bending stress is given as:

$$\sigma_{max} = \frac{-Mc}{I} = \frac{-wx\ell c}{4I}$$

This tensile stress must be canceled out by a compressive stress from the post-tensioning. Thus, the post-tensioning stress is given by:

$$\sigma_{post} = -\sigma_{max}$$

In many cases it is easiest to assume the post-tensioning force is uniformly distributed over the whole cross section. Thus, the total post-tension force, P, can be found by:

$$P = \sigma_{post}A$$

This example used a simply supported beam of constant cross section with a simple load case. More complex beams can be analyzed with similar methods. Standard beam techniques can be used to find the maximum tensile normal stress from the bending. Then a post-tension load is found, which cancels out the tensile bending stress. After doing this, the beam must be checked to ensure that none of the beam will fail under compression with the addition of the post-tension load.

Stiffness and Load Paths

The above discussion of post-tensioning assumes that the externally applied load will only travel through the printed beam and not through the post-tensioned tendons. The only load on the post-tension tendons should be the designed post-tensioning force. If the load path for the externally applied load travels partially or entirely through the tendons, then the structure will not perform as expected. This could cause failure of the tendons if the post-tensioning stress is close to the yield stress of the tendon.

To ensure the load paths are as expected, the relative stiffness of the tendons and the printed structure must be carefully designed. Loads will follow the stiffest path available. If the tendons are much lower in stiffness (>10x) than the printed structure, the amount of load that travels through the tendons will be negligible, and the structure will behave as expected. To achieve this low stiffness of the tendons, it may be required to put springs in series with each tendon. These springs can also be compressed to generate the post-tensioning force in the tendon.

Tendon Placement

Placement of the post-tensioning tendons is also important. The above calculations assumed that the post tensioning force was uniformly applied across the surface area. To ensure this, tendons should be evenly spaced across the cross section.

More complex tendon placement designs are possible but will not be examined here. In such designs, the post-tensioning force will not have an even distribution. Instead, the post-tensioning force will vary across the cross section, so the post-tensioning stresses are applied closer to where the are required, rather than across the whole cross section. These designs can have tendons that bend and change position as they travel down the length of the structure.

The Additive Manufacturing Integrated Energy (AMIE) Project

ORNL has demonstrated the use of post-tensioning on several large AM structures. Two will be examined below. The first example is the Additive Manufactured Integrated Energy (AMIE) 3D printed house shown in Figure 5. [5] This project was completed by ORNL in collaboration with other ORNL researchers and industry partners in 2015.

Figure 5: Project AMIE 3D Printed House

The shell of the house was printed on the BAAM system in multiple profile sections. Figure 6 shows assembly of the sections. The total length of the house is 38 ft. The house had to support its own weight as well as loads during transportation. To join the sections together and prevent layer separation, threaded rods were run through the length of the house. These rods function as post-tensioning tendons. Belville washers were place on the end of the rods to act as springs. Nuts were tightened against the washers to generate the post-tensioning force in the rods. In total, four rods were used to provide a total of 8,000 lbs of post-tensioning force.

Figure 6: Sections of the Project AMIE House During Assembly.

Alliance MG Boat Hull Mold

A second example of using post-tensioning on AM parts is the fabrication of a boat hull mold for Alliance MG, LLC. [6] This mold was 35 ft long, and it is now used to manufacture hulls of catamaran boats using a vacuum assisted resin transfer (VARTM) process. The mold was printed in 12 sections on the BAAM system and then machined and assembled.

The mold was designed to be self-supporting, which means it does not require an external support structure. The design load for the mold was 6,000 lbs evenly distributed over the structure. This included the weight of the mold itself as well as the hull being molded. The mold was designed to be supported on a set of casters near the front and back of the mold. Figure 7 shows the caster and support arrangement. It was found that this arrangement created a moment in the center of 52 kip-in and a moment of -51 kip-in at the supports. The section depth, area moment of inertia, and cross-sectional area were calculated at both the center and the supports of the mold using the CAD model. Those values were then used to calculate the required post-tension load at the center and support locations. The greater of these calculated post-tension loads was found to be 6,300 lb., and this value occurred at the supports. A factor of safety was then added on top of this. A total of 10 post-tension rods were used; each rod was tensioned to 1,500 lb. for a total post-tensioned load of 15,000 lb.

Figure 7:Caster arrangement on boat hull mold.

Aluminum plates were used on both ends of the mold to apply the post-tensioning force. Figure 8 illustrates how the post-tensioning was done showing only one of the 10 rods. The rods run the length of the mold. On one end, a nut was placed to secure the rod. On the other end, a spring was put around the rod, and a nut and washer were used to tighten down on the spring. The amount of deflection in the spring is proportional to the load in the rod. This provides a way to measure the amount of post-tensioning. The spring also reduces the composite stiffness of the post-tensioning element as discussed above.

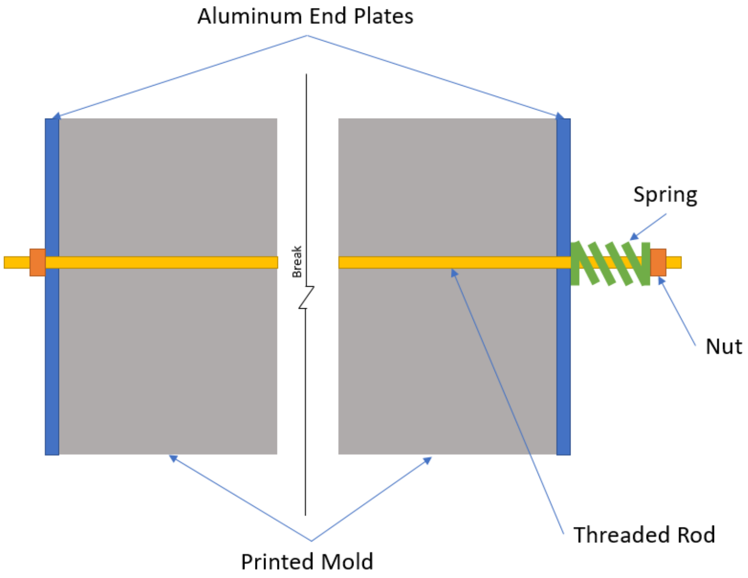

Figure 8: Illustration of the assembly of the mold sections using post tensioning.

Figure 9 shows the actual aluminum plate with the post-tensioning rods and springs.

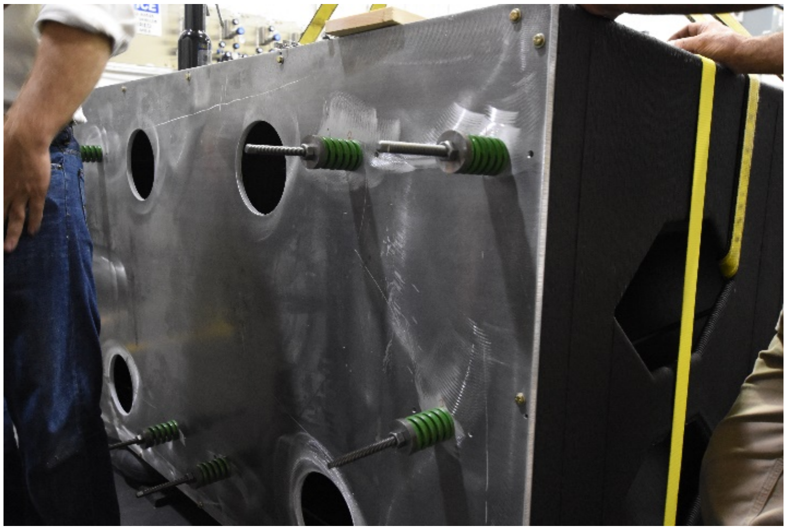

Figure 9: Post-tensioned mold using rods, springs, and an aluminum plate.

To ensure the load was applied approximately evenly across the profile, FEA was performed on the aluminum plates. Contact stress between the aluminum plate and the mold was computed as well as plate deflection. This simulation was used to inform the rod placement and plate design to help ensure relatively uniform compression on the mold. Results from the final FEA are shown in Figure 10.

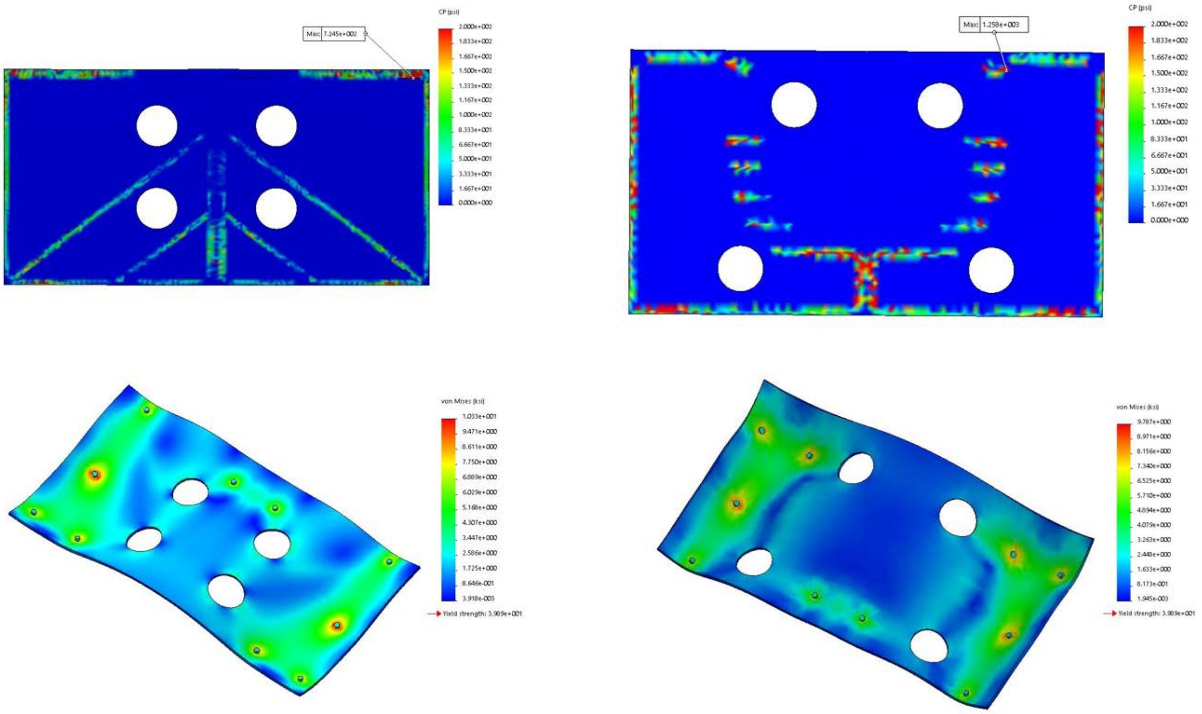

Figure 10: Endplate FEA Results.

Figure 11 shows the mold during assembly. The figure shows the stern section as it about to be joined to the rest of the mold. The tension rods can be seen hanging out of the mold before they are threaded through the stern section.

Figure 11: Assembly of mold sections with tensioning rods.

After assembly was complete and all the post-tension rods were loaded, the mold was successfully able to support itself. The mold has been successfully in production. The final assembled mold is shown in Figure 12.

Figure 12: Final Mold.

Continuing Work

Since the AMIE house and the Alliance MG boat mold, other post-tensioned printed structures have been made. The methods presented in this paper are currently being refined and expanded in these projects. Some of this work has included improved design of post-tensioning methods. Work is also being done to experimentally validate the post-tensioning methods. This will include the design and fabrication of canonical beams that will be printed and post-tensioned. These beams will then be tested in a load frame to failure. The continuing work in this area will allow for the fabrication of larger and more ambitious structures while increasing confidence in the integrity of the structures.

Conclusion

Post-tensioning has historically been effective for use in concrete structures to improve the strength of the structures. Large-scale AM has some of the same weaknesses as concrete, and post-tensioning helps improve strength in this application as well.

The success of post-tensioning for printed, load-bearing structures has been demonstrated in several real-world projects, including the development of the theoretical foundation. The success of these projects is significant because it expands the horizons of what is possible with large-scale additive manufacturing. It is now possible with the BAAM system to rapidly fabricate large, load-bearing structures that do not require external support structures. Future applications that can be enabled with the post tensioning design methodology could include vehicles, infrastructure, military use, and many other applications.

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