Proceedings of the International Association for Shell and Spatial Structures (IASS)
Symposium 2015, Amsterdam
Future Visions
17 - 20 August 2015, Amsterdam, The Netherlands

Infinite stiffness structures via active control

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Abstract

Active control has been used in civil engineering structures for a variety of purposes. Although the potential for using deflection-control adaptation to save material has been investigated by a few other authors, little attention has been given to assessing whether these material savings outweigh the energy consumed through control and actuation. Our paper seeks to address this gap, presenting experimental work on a truss with effective infinite stiffness which builds on earlier theoretical studies.

Senatore previously developed a design method that produces an optimum adaptive structure that minimizes the total energy spent throughout the whole life of the structure (embodied in the materials + operational for the control) (Senatore, et al., 2013). The method was used to design a range of structures from trusses to space frames, both determinate and indeterminate, and it was shown that it allows energy saving up to 70% compared to state of the art optimization methods.

A large scale prototype structure has now been built to validate the numerical findings and investigate the practicality of the method. This paper discusses recent experimental findings and the making of the prototype. Using the insight acquired after the making and testing of the prototype the authors will discuss potential applications of adaptive structures in selection of different scenarios, ranging from cantilever seating tiers in sports stands to lightweight roofs to slender beams with 80:1 span/depth ratio!

Keywords: adaptive structures, active control, embodied energy, operational energy, structural optimization.

1. Introduction

All structures use matter and energy to withstand loads. Passive design strategies involve putting enough matter, high embodied energy and no operational energy to resist loads (e.g. the Coliseum, Rome). Active design strategies involve using little material, low embodied energy, but continuous operational energy to resist loads (e.g. humans or animals). Active control has been used in civil engineering structures for a variety of purposes. The most wide-spread application so far has been in vibration control (Soong, 1988).

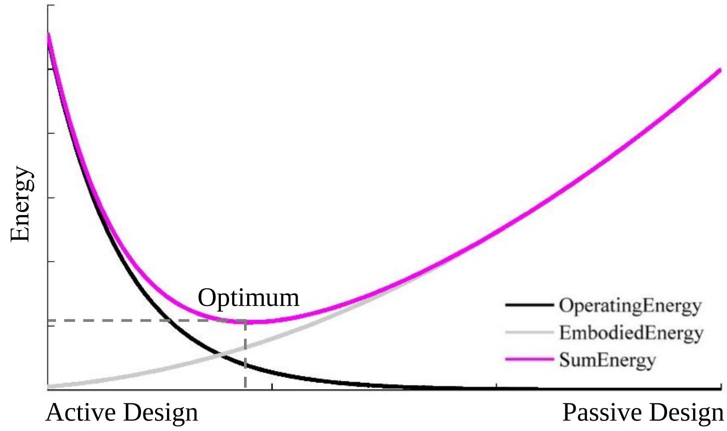

Figure 1: Whole-life energy vs. degree of adaptation

The potential of using adaptation (i.e. actuators controlling displacements) to save material has been investigated by a few (Sobek & Teuffel, 2001) but whether the energy saved by using less material makes up the energy consumed through control and actuation is a question that has so far received little attention. In his work Senatore developed a design method that produces an optimum adaptive structure that minimizes the total energy spent throughout the whole life of the structure (embodied in the materials + operational for the control) (Senatore, et al., 2013).

The process is illustrated diagrammatically in the conceptual graph shown in Fig. 1. This graph shows the total energy as a function of some notional degree of active control of the structure. The whole life energy is made of two components: operational energy and the embodied energy. For a completely passive design the embodied energy (mass of material) dominates the whole life energy: members are designed to bear 100% of the maximum expected load to meet strength and serviceability requirements. By contrast for a highly adaptive design, the embodied energy will be small but the operational energy necessary to control and actuate throughout the life of the structure will be high. The methodology developed so far obtains the minimum in whole life energy that lies between these two extremes.

The design process comprises: sizing the elements of the structure, optimizing the shape and finding the most effective topology (position) of the active elements and sensors. Strategically located active elements provide controlled output energy (actuators) in order to manipulate actively the internal flow of forces and stresses redirect them and find more efficient load-paths. In this way stresses can be homogenized and deflections kept within desired limits. The active elements (actuators) are only activated for compensation of the displacements and internal forces when the loads reach a certain threshold (the **load activation threshold** (Senatore, et al., 2011)). Therefore operational energy is only used when necessary. This dual design is used to minimize the overall energy required by the structures.

The research to date has included a number of numerical design simulations, which successfully demonstrated that up to 80% reduction in structural weight and 70% of total life energy (embodied and operational) was achievable on truss like structures ranging from planar trusses (Senatore, et al., 2013) to more complex 3D configuration (Senatore, et al., 2011). More information regarding performances including monetary cost analysis can be found in (Senatore, et al., 2013).

Figure 6: adaptive truss prototype, UCL structures laboratories

2. Adaptive Truss Prototype

A large scale prototype structure has been built to validate the numerical findings, investigate the practicality of the design method and feasibility of construction. The prototype has being used to assess the mechanical behaviour of the structure and measure the power consumption of the actuators and the control hardware under loading.

2.1 The structure

The prototype is a slender 6000mm (length) x 800mm (width) x 160mm (depth) cantilevered truss structure (fig. 7) which has a span to depth ratio of 40:1 (or 80:1 for the equivalent simply supported beam). The truss is divided in 5 bays and consists of 45 elements, 20 of which are round bars and 25tubes, and it is based on a 3D Warren Truss. The sections of the elements go from 16mm to only 6mm diameter for the tie-bars and 60.33mm to 26.67mm outer diameter (average wall thickness is around 3mm). The size of the sections and the position of the actuators are obtained using the design

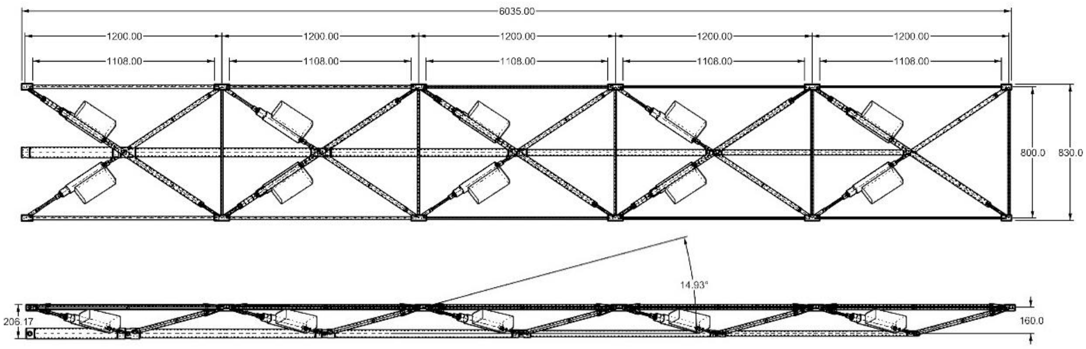

Figure 7: adaptive truss overall dimensions

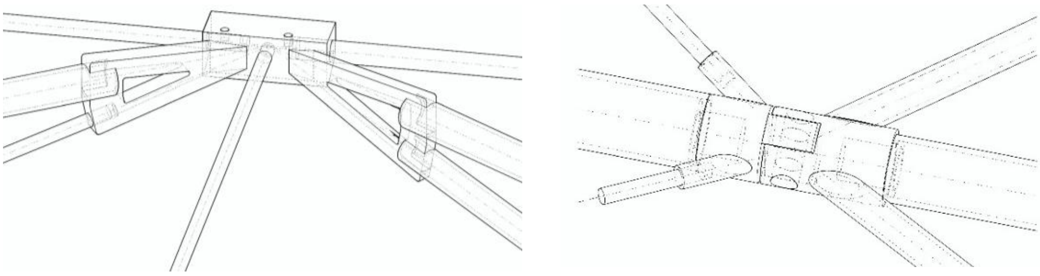

Figure 8: top cord node (left); bottom cord node (right);

method so far described. The design load is 100kg which is thought of as a person walking along its length and standing at the free end.

The optimal distribution of material (i.e. varying setions) and the pronouced slenderness of the geometry presented challenges for the making of the joints which have to house up to 7 elements of the truss meeting at one point and support the deck/façade. Figure 8 shows the typical joint for top and bottom chords. It is worth to mentioning that the only function of pin for the bottom chord node is to minimise the transfer of bending moment across the bottom chord whose members' primary function is to carry high compressive forces (up to 132 kN).

Due to the high material utilization reached with the optimized design and the challenging geometry it is important to ensure tolerances was kept as precise as possible (within ± 2mm) during the construction process. For this reason a support frame was built in order to locate precisely the position of the truss nodes. Once aligned the nodes were welded using TIG welding (fig 9).

The deck/façade of the structure consists of a series of unequal aluminium angles housing transparent acrylic panels. The choice of clear acrylic was made to allow a complete see-through in order to appreciate the compensation of displacements performed by the actuators during control. To ensure the structural role of the angles is only to transfer the load to the truss a special connection was devised that allows the independent movement of the each bay with respect to the adjacent ones (fig 9). Although the reciprocal movement of the panels is very small (in the order of 2mm at maximum load) the ability to move is essential to avoid the angles adding stiffness by contributing carrying the load. For the general case the light-weight nature of adaptive structures means that they undergo higher displacements compared to conventional structures. For this reason extra-care is needed on the design of the fittings

Figure 9: bottom chord node (right); deck angle detail (left); acrylic panel + angles (right)

2.2 Control Hardware

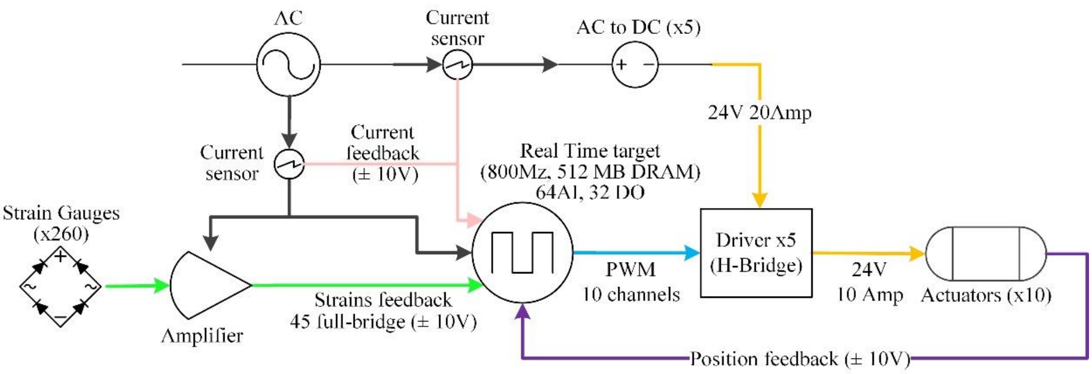

Figure 10: control hardware architecture

Fig. 10 shows the schematics for the control hardware of the prototype. It mainly consists of 10 linear actuators and their control drivers, strain sensors and their amplifiers and a main controller for acquisition and processing. The architecture for the control hardware is designed setting as primary aim that of achieving on-line identification of the structural system for it to be able to be control itself without user intervention nor predetermined knowledge of the loads (position, direction or magnitude) that hit the structure. Given any structural system in order for it to be identified the state of strains/stresses or a measure of its displacements have to be known. Since the structure under consideration can be thought of as statically determinate (even though due to the transfer of flexural and torsional it is not) it is possible to reconstruct the displacements knowing only the state of strains/stresses. For statically indeterminate structures direct measurement of the displacements is needed. For this reason each element of the structure has embedded strain gauge sensors that are utilized to obtain the internal load path and reconstruct the nodes spatial positions in real-time. The strain gauges are installed using two or four 90 degree rosettes each having a gauge that measures the strain along the principal direction (axis of the element) and the other in the transversal direction. The latter acts as Poisson gauge for

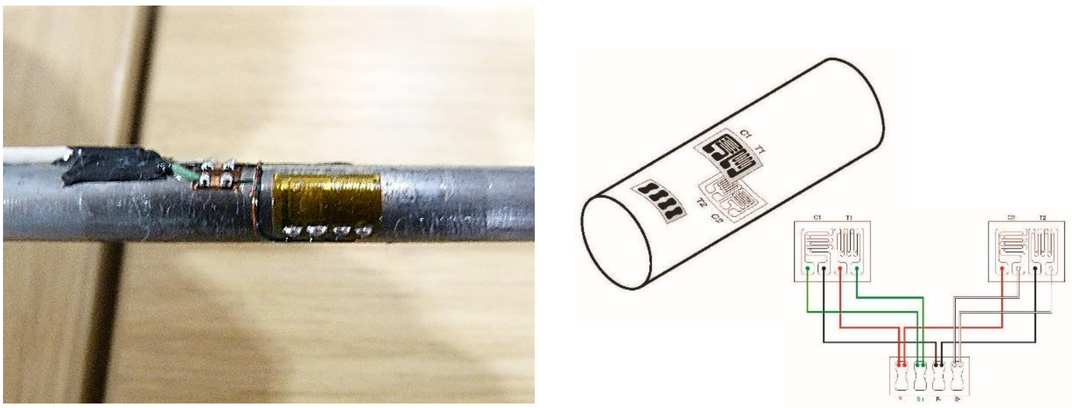

Figure 11: full bridge strain gauge sensor

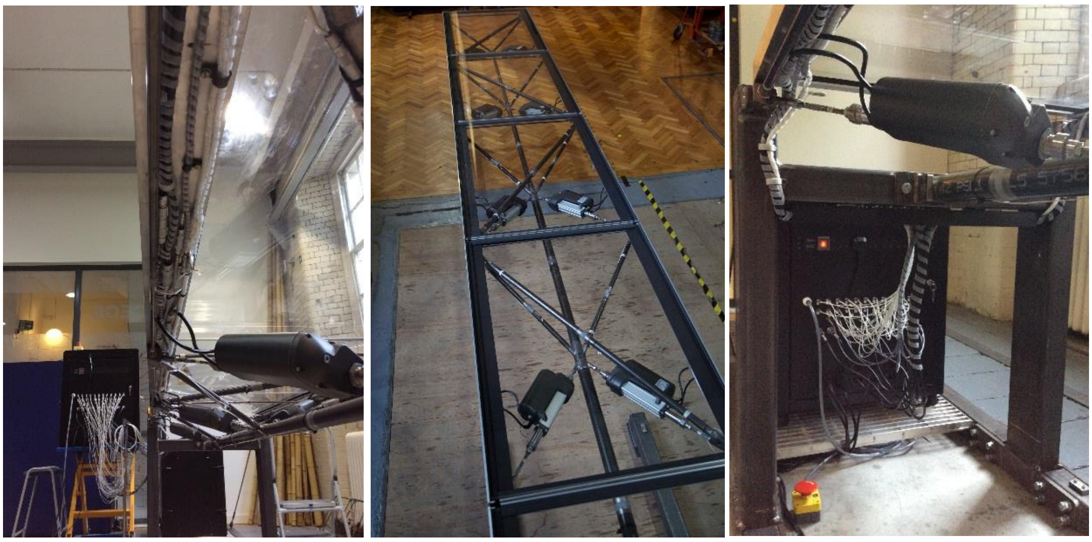

Figure 12: signal cables (left); actuators integrated (middle); actuator close up (left)

compensation of the transversal strains. The control algorithm is based on the axial value of the strains as the structure was a truss with ideal pins. However, due the welded nodes and their morphology, bending and torsion are still transferred to the elements. For this reason, some of the elements mount an 8-gauge bridge (4 rosettes, 2 opposite facing pairs arranged at 90 degree with respect to the axis of the rod or tube) which rejects bending strains more effectively. The 8-gauge sensors are installed on the truss's elements that experience comparatively higher torsional and bending strains. The orientation of the plane of the sensors is optimised to maximise bending and torsional strains rejection for both 4 and 8-gauge bridges. There are a total of 260 strain gauges grouped into 45 bridges whose power and signal cables run bundled and clipped onto the bottom face of the aluminium angles on both the top chords (fig. 12).

The linear actuators are integrated into the structure using couplers, positioned within the tension diagonal members (fig.12). The motors have maximum velocity of 11mm/s at no load and 7mm/s at max load which is 10kN both in traction and compression. Each actuator has a built-in potentiometer that provides absolute position feedback. The position feedback is not only necessary to control their length change but also, together with the strain values, to calculate the spatial position of the nodes.

The control unit contains two amplifiers for a total of 45 channels in order to amplify the signal of the strain gauge sensors, 5 power supplies each feeding a pair of actuators, 5 control drivers for the actuators and the main controller. The main controller is low power (800MHz, 512 MB DRAM) embedded real-time target machine and acquisition system (FPGA). Furthermore current sensors are installed in order to monitor the power being consumed by the actuators and the rest of the control hardware.

2.3 Control Software

Senatore developed and implemented a control algorithm that is based on the design method referenced in section 2 and the integrated force method (Patnaik, et al., 1991) (the mathematical formulation and

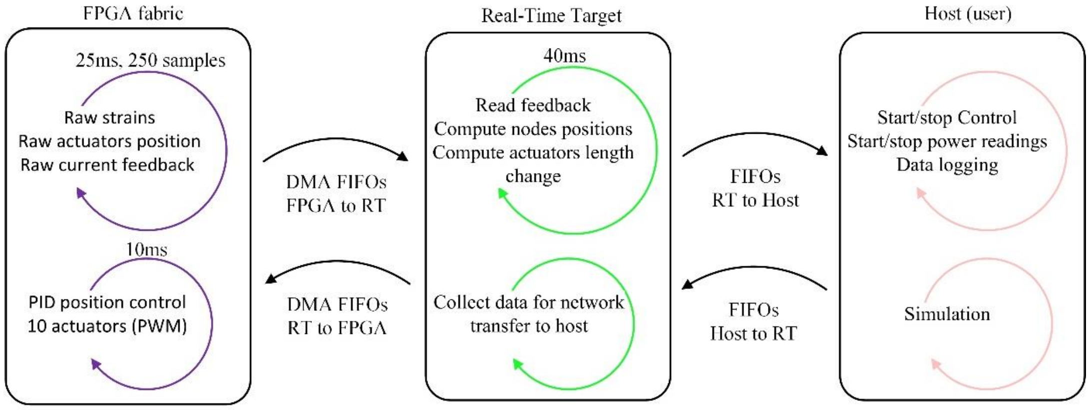

Figure 13: control software architecture

details of the software architecture will be published elsewhere). The control software can be divided in 3 main parts: (acquisition, processing and visualization. The acquisition and actuators position control are implemented using the FPGA fabric of the controller. The real-time target runs the main control routine which takes as inputs the strains and the actuators feedback position. These are used to first reconstruct the nodes spatial position and successively to compute the most efficient length changes of the actuators to bring the structure to the desired shape (in this case flat within ±2mm accuracy end to end) displacements. Data visualization, data logging and control simulation for comparison with theoretical predictions are implemented on the host computer (laptop or desktop machine). Fig 13 illustrate the architecture of the control software.

An efficient implementation was needed to keep one full cycle within 40ms with very little jitter (within 2ms). It is important to achieve deterministic control (small or null jitter) and as fast as possible in order to avoid the actuators are driven with delay with respect to the state of displacements of structure. For this reason fixed-point arithmetic was used where possible and DMA (direct memory access) data buffer were utilised for the transferring data between the FPGA and RT. In addition network communication between the RT and the host was implemented to run independently from the main control loop in order not to affect determinism.

3. Experimental Results

3.1 Displacements control – infinite stiffness structure

One of the main objective of this experimental setting is to test the feasibility of controlling the cantilever truss structure in real time to maintain serviceability requirement (limit on displacement) without any assumption on the direction, position and magnitude of the load. In other words the aim is to enable the structure to be responsive to the environment without predetermination of any kind effectively achieving an infinite stiffness (virtually 0 displacements under loading).

Extensive loads tests ranging from weights from 10kg to 140kg placed several positions (including asymmetric configurations that induce torsion) on the deck show that the structure is able to control itself within ± 2mm tolerance from end to end. Similar results in terms of displacements compensation

Figure 14: control person walking (left); 100kg no control (top right); 100kg controlled (bottom right)

are recorded when a person walks on the deck (fig. 14). During the walk the actuators move subtly to continuously compensate for the moving load achieving a very stable control. Interestingly during control the movement of the structure are almost not perceivable to the observer and they become more noticeable when a load (weights or person trying to push the structure) is applied suddenly.

The control routine descried in section 2.3 was able to control the structure within a 10% of the max displacement (for a 100mm displacement would reduce to around 10mm rather than 1-2mm). As expected for some of the elements there was a non-negligible difference between the value of the theoretical strains and the real ones due to flexural and torsional contribution, stiffness of nodes and actuators themselves etc. In addition the uneven floor and the deformation of the support frame adds disturbance to the control. In order to mitigate such disturbances the direct measurement of the displacements under several loads was recorded and used for calibration based on non-linear regression (a technique borrowed from machine learning was integrated within the control algorithm to give prediction on the correction).

3.2 Power consumption – whole life energy assessment

The other main objective of this experiment is to confirm the claim that adaptive structures allow savings on the total energy of the structure, which consists of an embodied and an operational part. In reality, the designer cannot know the number and magnitude of live loads applied on a structure until it is actually built. Although for some types of load there is generic statistical data (e.g. for wind gusts in EN1991-4), for this adaptive truss and this paper a load distribution graph was generated for illustrative purposes, see fig.15 (left). This skew Gaussian distribution is effectively a reference curve to measure the total power consumption under loading. This skew Gaussian distribution is effectively a reference curve to measure the total power consumption under loading. This curve is intended to loosely represent common loading scenarios for building structures. These are in fact are normally subjected to live loads whose magnitude is lower than dead load but they still have to be designed to deal with rare loads. Fig. 15(left) shows the activation threshold for the adaptive truss prototype being at 0.27 kN (27 kg). This means that for all the loads below 27kg the end deflection will be within the allowed limit which in this case is 33mm (approx. 600/180).

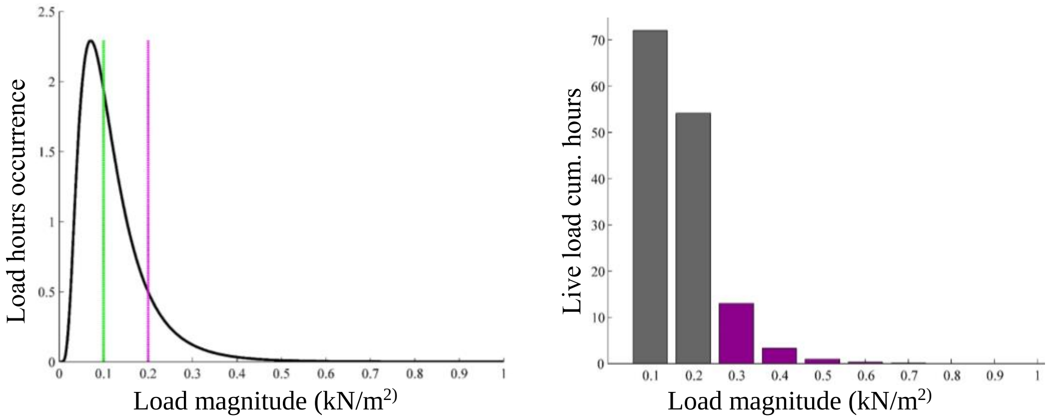

Figure 15: live load distribution (150 years)

Fig. 15(right) shows a discretization of the yearly load history which is divided into 10 steps (from 10kg to 100kg), i.e. the load is thought of as acting in discrete steps. In so doing, it is possible to apply loads such as weights and measure the power consumption to compensate for displacements. The power being monitored is for all the electronic devices including the actuators and their AC to DC power supply converter. Each load case (10 to 100kg) is dropped/removed on/from the truss with a cable lift stacker. The truss immediately adapts to it. For practical reasons the truss is programmed to stay completely flat (rather than moving to span/180 deflection) which means that the power measured is higher than it could/should be (i.e. a conservative approach).

Fig. 16 shows the power curves for 100kg load cycle (left) and for all the load cases tested. The curves are consistent and repeatable even if the cable lift stacked is manually operated. An interesting point is that the energy needed to keep the structure flat during loading is much less that that needed when unloading because in this last case the actuators have only to control the release of tension necessary to adapt.

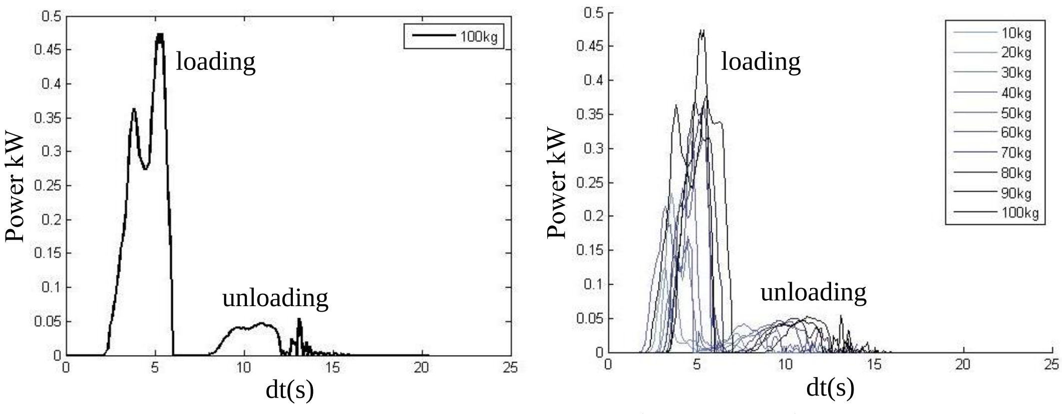

Figure 16: power measurement (current sensor)

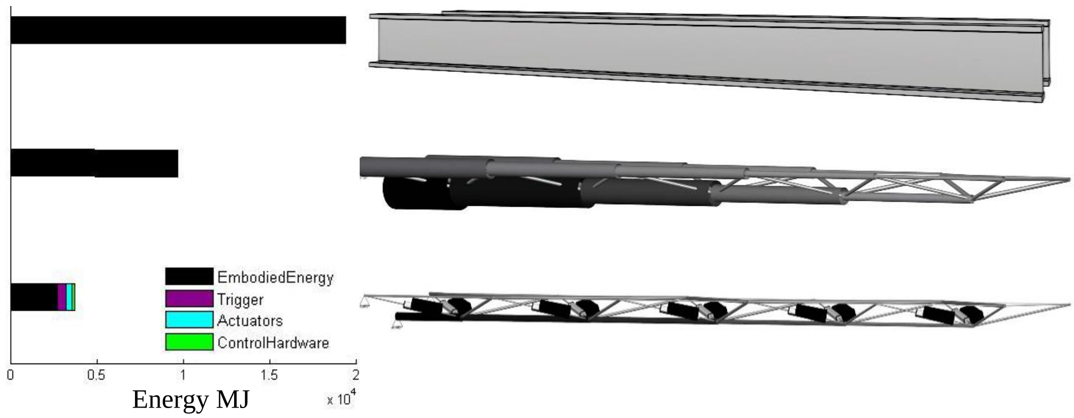

Figure 17: energy comparison (a) I-beams (b) optimised passive truss (c) adaptive truss

Fig. 17 shows the energy comparison between an equivalent structure made of two steel I-beams (depth 356mm, weight 500kg, which would only stay within span/180 deflections), an equivalent truss sized using a state of the art optimization routine (SQP) (Spillers & MacBain, 2009) and the adaptive truss. The adaptive truss's operational energy is broken down in 3 terms): (1) the operational energy for the actuators, (2) the operational energy for the control hardware, (3) the operational energy for the "trigger". The trigger is another sensor whose function is to detect anomalous movement and engage the contactor to give power to the control hardware. This must have low power requirement because it is the only piece of equipment that must stay on for the entire life of the structure. For the case of this prototype an LVDT would be adequate (average consumption is 0.16W)) (LVDT, n.d.). For large scale structures other methods would be considered including GPS and close-range photogrammetry.

The adaptive truss was designed for a live to dead = 0.8. For large projects the actual value for the live to dead is typically around 0.5 - 0.8. In addition, even when including the energy spent for controlling all the live load cases below the activation threshold the energy comparison stays in favour of the adaptive. These results and their interpretation are very promising and encouraging, the load distribution used to compute the overall power consumption needs further attention and sensitivity studies. The full interpretation of the results and the energy assessment with other type of loading distribution curves is being published elsewhere.

4. Adaptive Structures Applications

4.1 A new design philosophy

Adaptive structures present a new design philosophy for structural engineers. Fundamentally, design engineers no longer need to use large quanities of materials to meet non-safety critical requirements:

1) Conventional materials e.g. steel tubes/bars in this prototype, still provide strength and safety (ultimate limit state requirements) as well as deflections under day-to-day loads

2) Actuators control/prevent excessive movements and deflections (serviceability limit state) which in practice occur very infrequently.

The implications of this philosophy are that adaptive structures are particularly suited to stiffness-governed situations – which is the case for a great many engineering structures. More specifically, when compared to conventional structural designs, adaptive structures can use siginficantly less material, be much more slender, and/or have an infinite effective stiffness (zero deflection). In the case of this prototype, a combination of all three benefits are in fact achieved, as discussed in earlier chapters. Due the the failsafe nature of linear electric actuators, if the power is cut then actuators simply stop moving and load carrying capacity i.e. requirement (1) above, is not compromised.

4.2 Performance advantages and design scenarios

Applying the above new design philosophy, scenarios where adaptive building structures could bring significant benefits include:

- Scenarios where the end use has very stringent / high performance requirements for deflection, therefore the infinite effective stiffness capability of adaptive structures can clearly outperform conventional structures. For example, laboratory buildings, gantry crane runway beams, bespoke facades etc. see Fig. 18 (right).
- Situations when the structural design is governed by high but rare loads, such as earthquakes and wind storms. Consider also a football stand which is crowded for just 90 minutes once per week! An adaptive structure optimised to remain serviceable under rare high loads (as opposed to solely optimised for minimum slenderness or infinite effective stiffness) can give 80% material weight savings compared to conventional passive structures;
- Adaptive structures are technically well suited to architectural buildings where very high slenderness / shallow structural depths are needed. This could be either a pure aesthetic driver, limited floor-ceiling heights in a new building, or limited space for new structure in a complex refurbishment. Regardless of the situation, this prototype has shown that adaptive structures can achieve 80:1 span/depth for simply supported beams which is simply not possible with conventional structural solutions (c.f. ~12:1 conventional trusses and 20:1 for conventional steel beams.)
- Long span / high rise structures are typically stiffness governed and so tall buildings, bridges, and roofs could all see benefit from adaptive technology. These types of structures would likely take a combination of all three characteristics (stiffer, lower weight, more slender). For example, an architectural footbridge could be very slender and at the same time lighter than normal, in order to install over a railway in a single crane lift. Tall buildings could have a much smaller stability core and smaller footprint, see Fig 18(left).
- Using fast-acting actuators would allow adaptive structures to fully control dynamics/vibrations as well as deflections. The actuators used in this prototype were readily available from the automotive industry (at relatively low cost) and move at 11mm/s, nevertheless they are still able to increase effective damping in the truss from 0.5% to 3%. The drawback of course is that controlling vibrations expends much more operational energy therefore passive solutions such as tuned mass dampers are still likely to be preferred.

The case studies examined so far are for plane or space trusses/frames but the methodology can be extended to other types of structure. Future work could explore how to achieve this in practice, and develop design solutions for specific contexts/projects e.g. different number/position of actuators, alternative types of sensors and control system optimized for different types of loadings.

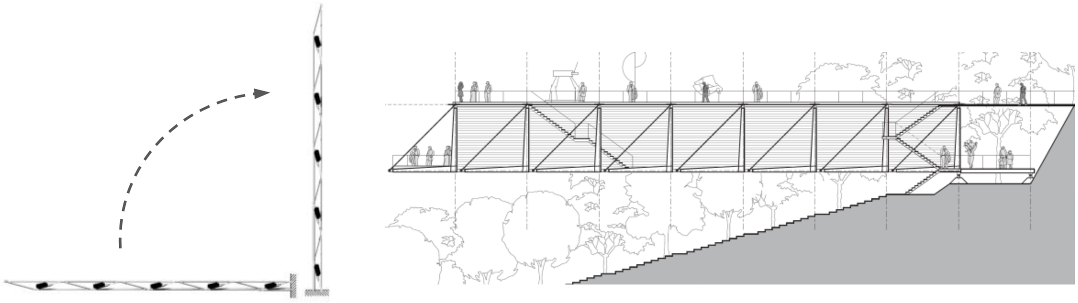

Fig 18: High-rise buildings no longer governed by stiffness (left); concept art gallery (RHSP) with very strict deflection and movement requirements (right)

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