Adaptive Truss Prototype to save material

IStructE Research Award Final Report

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The aim of the project was to build a large-scale prototype that demonstrates that fitting a truss with active elements strategically located and controlled can save large amounts of energy over the structure's whole life. Most structures are designed to withstand a worst case loading that will only occur rarely (earthquake, storm). In these cases, the structure is effectively overdesigned for most of its life. Extensive numerical testing on trusses of various topologies has shown that this methodology can save up 80% in the structure whole life energy.

The IStructE Research Grant allowed a prototype to be completed successfully. This prototype structure was built to validate the numerical findings, investigate the practicality of the design method and the feasibility of construction.

1 Description of the prototype

1.1 The structure

The prototype is a slender 6000mm (length) x 800mm (width) x 160mm (depth) cantilevered trussed platform (fig. 1) which has a span to depth ratio of 40:1. The truss is divided in 5 bays and consists of 45 elements: 20 round solid bars and 25 hollow tubes. The sections of the elements go from 16mm to only 6mm diameter for the bars and 60.33mm to 26.67mm outer diameter for the tubes (average

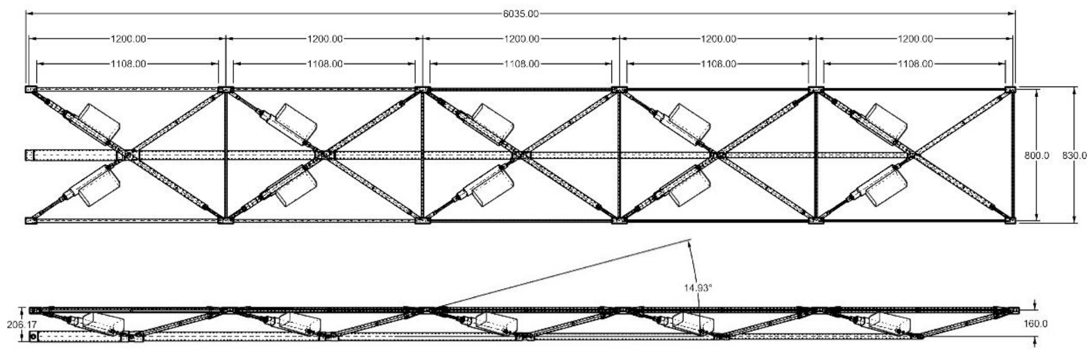

Figure 1: Adaptive truss plan and elevation with overall dimensions (mm)

wall thickness 3mm). The size of the sections and the position of the actuators are obtained using the design method developed earlier in the project. The structure was designed to support a 1KN load at its tip so that a person could walk safely along the platform. Plan and elevation views of the truss are shown in Figure 1.

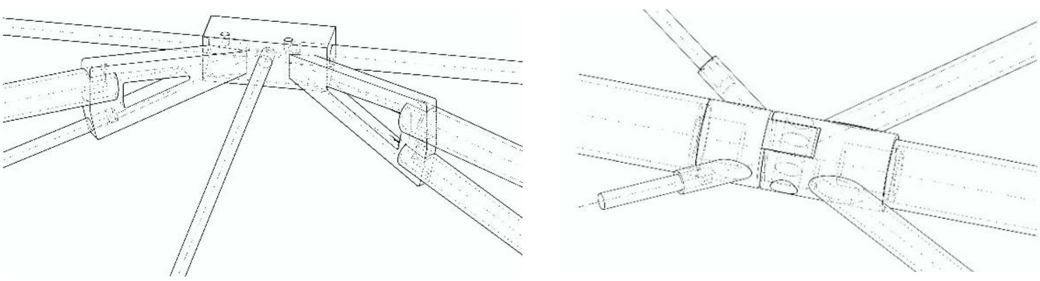

Figure 2: top cord joint (left); bottom cord joint (right);

The optimal distribution of material (i.e. varying setions) and the remarkable slenderness of the geometry presented challenges for the manufacturing of the joints which have to connect up to 7 elements of the truss at one point and also support the deck. Figure 2 shows two examples of joints for top and bottom chords. During construction, the truss was held in position using a purpose-built temporary propping structure. Once the members and joints were aligned they were welded using TIG welding. A of pin was inserted in the bottom chord to minimise the transfer of bending moment across this chord as these members carry a fairly high compressive forces (up to 132 kN).

1.2 Control Hardware

The control hardware used in the prototype consists of 10 linear actuators (GIVE ACTUAL REFERENCE HERE) and their control drivers, strain sensors and their amplifiers and a main controller for acquisition and processing. The linear actuators (fig.3) are integrated into the structure using couplers, positioned within the tension diagonal members. The motors have maximum velocity of 11mm/s at no load and 7mm/s at max load which is 1kN both in traction and compression. Each actuator has a built-in potentiometer that provides absolute position feedback.

Ignoring the stiffness of the joints, the structure can be considered statically determinate so it is possible to reconstruct the nodal displacements knowing the state of strains/stresses. For this reason each element of the structure has embedded strain gauge sensors that measure the internal forces and allow the nodes' spatial positions to be inferred in real-time. There are a total of 260 strain gauges grouped into 45 bridge.

Figure 3: Loaded adaptive truss with zero deflection (left); actuators integrated (rig).

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.

1.3 Control Software

The control software can be divided into 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 to successively 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). Data visualization, data logging and control simulation for comparison with theoretical predictions are implemented on the host computer (laptop or desktop machine).

2. Experimental Results

2.1 Displacements control – infinite stiffness structure

The main purpose of this prototype was to test the feasibility of controlling a structure in real time so as to respect serviceability requirements on deflection for arbitrary load positions and magnitudes (within some specified ranges).

Extensive loads tests using static weights ranging from 100N to 1kN placed at several positions on the deck (including asymmetric configurations that induce torsion) showed that the structure is able to control itself within ± 2mm tolerance from end to end. Similar results in terms of displacements compensation are recorded when a person walks on the deck (fig. 2). During the walk the actuators move subtly to continuously compensate for the moving load achieving a very stable control.

2.2 Power consumption – whole life energy assessment

The other main objective of this experiment was to test the claim that adaptive structures allow savings on the total energy of the structure. At the design stages, engineers cannot know in detail the magnitude and number of occurrence of live loads applied on a structure. Although for some types of loads there are generic statistical data (e.g. for wind gusts in EN1991-4), for this adaptive truss a generic skewed Gaussian load distribution was used for illustrative purposes. This allowed the total power consumption under loading to be estimated. As part of the design methodology, an optimum load activation threshold is determined below which the actuators are not used. For the adaptive truss prototype this threshold is at 0.27 kN. For any load below 0.27kN the end deflection will be within the allowed limit of 33mm (~ 600/180).

Static loads within the design range were applied in turns and the total power consumption (actuators and ancillary equipment) needed to compensate for displacements was measure. Fig. 4 shows the power curves for a 1kN load cycle (left) and for all the load cases tested. The curves are consistent and repeatable. Note that the energy needed to keep the structure flat during loading is much less that that needed during unloading because in the latter case the actuators only have to control the release of tension necessary to adapt.

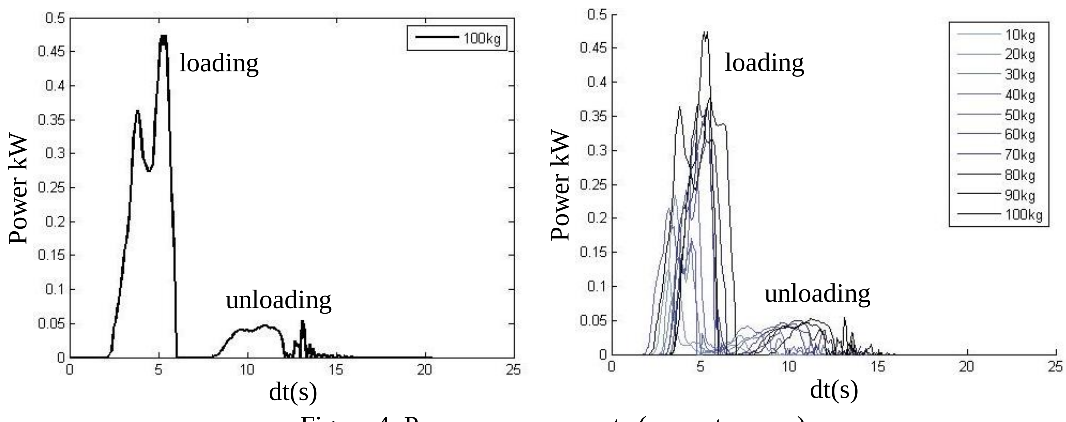

Figure 4: Power measurements (current sensor)

Combined with the assumed probability of occurrence of each load, these discreet measurements allowed the total power consumption to be estimated. Fig. 5 shows the energy comparison between an equivalent structure made of two steel I-beams (depth 356mm, weight 500kg, which would keep the tip deflection within span/180), an equivalent truss sized using a state of the art optimization routine (Spillers & MacBain, 2009) and the adaptive truss. The adaptive truss's operational energy is broken down into 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 movements 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)). For large scale structures other methods would be considered including GPS and close-range photogrammetry.

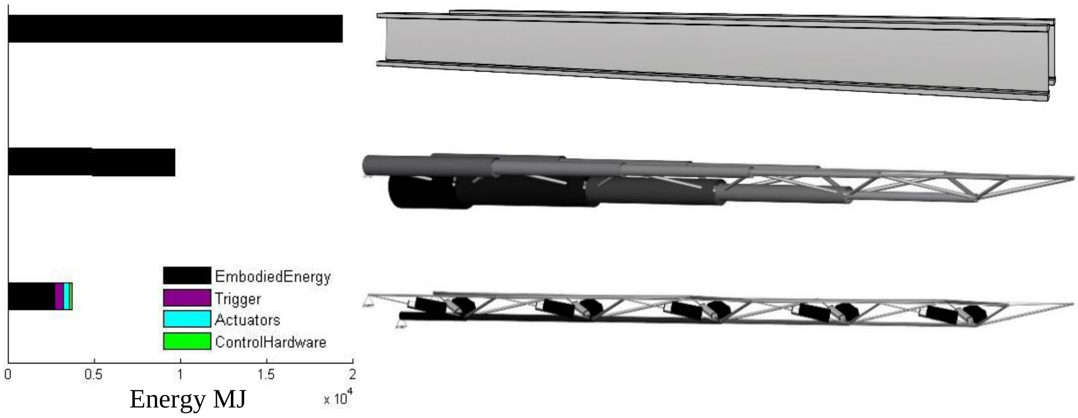

Figure 5: energy comparison (a) I-beams (b) optimised passive truss (c) adaptive truss

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.

3. Adaptive Structures Applications – A new design philosophy

Adaptive structures present a new design philosophy for structural engineers. Structural engineers no longer need to use large quantities of materials to meet non-safety critical requirements. 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. 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 significantly 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. Due the fail-safe nature of linear electric actuators use here, if the power is cut then the actuators simply stop moving and the load carrying capacity is not compromised.

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