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Adaptive Structures: Optimum Design Methodology, Case Study and Prototype

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Micro Abstract
This paper presents an overview of a new methodology to design optimum adaptive structures with minimum whole-life energy comprising an embodied part in the material and an operational part for structural adaptation. Instead of using more material to cope with the effect of rare but strong loading events, a strategically integrated actuation system redirects the internal load path to homogenize the stresses and keep deflections within limits by changing the shape of the structure.

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Introduction

Adaptive structures are capable of counteracting the effect of external loads via controlled shape changes and redirection of the internal load path. These structures are integrated with sensors (e.g. strain, vision), control intelligence and actuators. In civil engineering, active control has focused mostly on the control of vibrations for building or bridges during exceptionally high loads (i.e. strong winds, earthquakes) [1]. However, because of uncertainties regarding the long-term reliability of sensor and actuator technologies combined with building long service lives, the recent trend has been to develop active control to help satisfy serviceability requirements rather than improve on strength/safety [2].

Most design strategies for adaptive structures aim to minimize a combination of control effort and material mass of the structure. Often the structure and the actuation system are designed as separate systems - the location of actuators being decided a priori [3, 4]. However, a well-chosen actuator layout is critical to minimizing control effort. Although the potential of using adaptation to save material mass has been investigated by a few [5, 6], whether the energy saved by using less material makes up for the energy consumed through control and actuation is a question that has so far received little attention.

1 Optimum Design Methodology for Adaptive Structures

A novel design methodology for adaptive structures was presented in Senatore et al [7, 8]. This method is based on improving structural performance reducing the energy embodied in the material at the cost of a small increase in operational energy necessary for structural adaptation. The method has so far been implemented for reticular structures. The method is briefly summarised here.

1.1 Minimum Whole-Life Energy

The process comprises two nested optimization stages. The outer optimisation performs a search the optimal Material Utilisation Factor (MUT). This MUT is a ratio of the strength capacity over demand but it is defined for the structure as a whole and can be effectively thought of as a scaling factor on the allowable stresses. Figure 1 shows notionally the variation of the total energy as the MUT varies. By varying the MUT one can move from least-weight structures with small embodied but large operational energy, to stiffer structures with large embodied and smaller operational energy consumption. The active-passive system corresponding to the minimum of the sum of embodied and operational energy is the configuration of the optimum sought. The energy analysis is carried out using a material energy intensity factor to convert material mass into embodied energy [9].

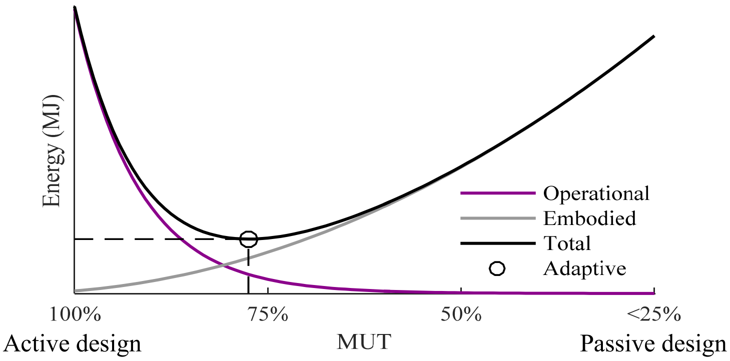

Figure 1: embodied, operational and total energy as a function of the Material Utilization Factor (MUT)

1.2 Load Path Redirection, Shape Control and Optimal Actuator Layout

The inner optimisation consists of two main routines. The first routine finds optimum load paths and corresponding material distribution ignoring compatibility and serviceability limit states, thus obtaining a lower bound in terms of material mass. When external loads are applied to the structure, the compatible forces will in general be different from the optimal forces and the resulting displacements might be beyond serviceability limits. For this reason, the second routine finds the optimal number, position and length changes of the actuators to manipulate actively the internal forces enforcing compatibility and compensate for displacements by changing the shape of the structure. A deformation vector akin to a lack of fit or *eigenstrain* [10], is defined to assign the actuator length changes. A computationally efficient routine based on *eigenstrain* assignment via the Integrated Force Method [11] is formulated to solve the actuator placement problem.

1.3 Load Probability Distribution and Activation Threshold

The proposed design process can be particularly beneficial when the design is governed by large loading events having a small probability of occurrence. The load probability distribution is modelled using a lognormal distribution (figure 2 a) because it can be easily parametrised to fit different scenarios e.g. storms, earthquakes, unusual crowds but also moving loads such as trains. The mean is set to zero because the structure is expected to take permanent load passively. In other words, the probability distribution only describes the occurrence of the live load. The characteristic load (i.e. the design load) is set as the 95th percentile of the probability distribution [12]. Once the mean and the characteristic load are set, the standard deviation is fully characterized. The design life is set to 50 years.

The dotted line in figure 2 (a) represents the activation threshold (optimisation output) which demarcates two zones: on the left-hand side are the more probable low levels of load the structure will be able to withstand passively without actuation (i.e. actuators locked in position). On the right are the rarer loads with higher magnitude which the structure will only be able to resist using both passive and active load-

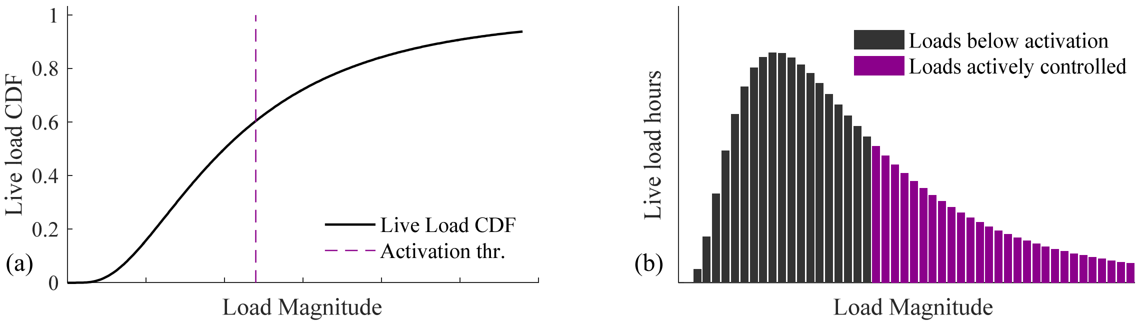

Figure 2: (a) live load cumulative distribution; (b) live load hours

bearing capacity. In other words, the load activation threshold is the load causing a state of stress violating either an ultimate (ULS) or a serviceability limit state (SLS). The two zones of the load range can also be visualised in figure 2 (b) which shows the hours of occurrence of the live load whose distribution is divided in discrete steps from zero to the design load. The introduction of the load activation threshold shows how passive and active design can be combined to reach a higher level of efficiency. The active system is only activated when the loads reach the activation threshold, therefore the operational energy is only used when necessary. Passive resistance through material and form is replaced by a small amount of operational energy.

2 Case Study

This case study is an application of the method outlined in section 1 to a complex 3D layout which is studied here as an example of tall building resisting external loads through an exoskeleton structure (i.e. no cores). Two models are considered, whose dimensions and boundary conditions are indicated in figure 3, to show how energy savings vary with the slenderness i.e. the ratio height to depth (H/D). The total building drift is set to height/500. The horizontal displacements of all the nodes but the supports are controlled. All elements have a cylindrical hollow section. To limit the optimization process complexity, the element wall thickness is set proportional (10%) to the external diameter. The mass of an actuator is assumed to be a linear function of the required force with a constant 1/10 kg/kN [13].

Five load cases are considered. L1 is self-weight + dead load which is set to 3 kN/m^2 on the floors of the building and transmitted on the nodes of the exoskeleton structure. The live load consists of four wind-type load cases arranged in two pairs with opposite directions. Figure 3 (c) shows a top view of the structure with (c) L2 (symmetrical to L4) and (d) L3 (symmetrical to L5) applied. The live load intensity varies quadratically with the height reaching a maximum of 1.5 kN/m^2.

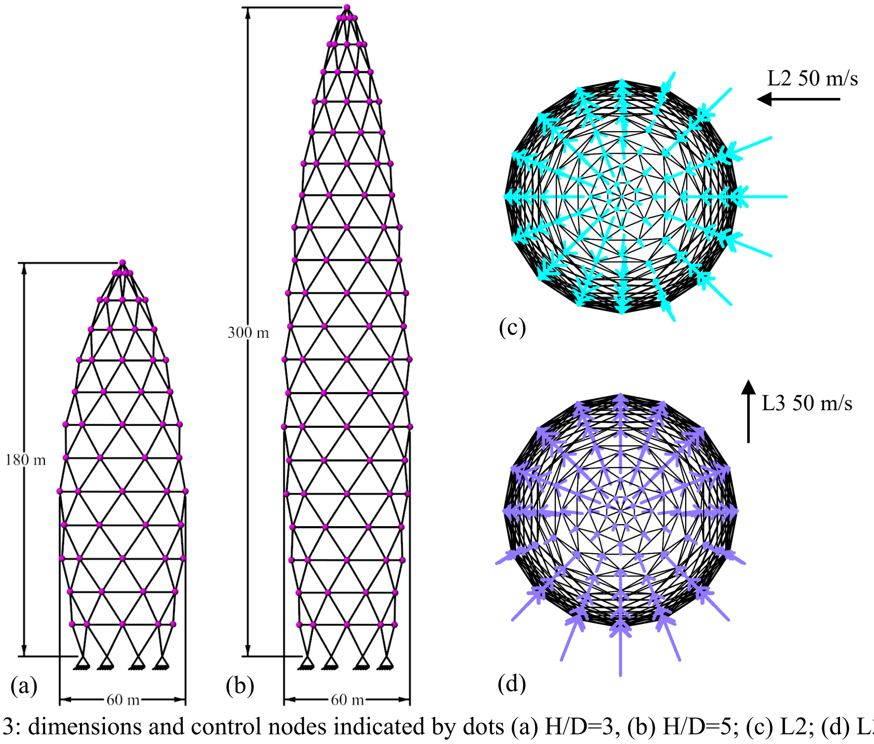

Figure 3: dimensions and control nodes indicated by dots (a) H/D=3, (b) H/D=5; (c) L2; (d) L3

All live load cases have identical probability distribution (see section 1.3). The activation thresholds are found at 1.0 kN/m^2 and 0.7 kN/m^2 when the H/D ratio is 3 and 5 respectively. In terms of wind velocity, the activation thresholds correspond to approximately 40 m/s and 34 m/s and the total time during which actuation is required to compensate for deflections is 1.25 and 3 years.

Figure 4 (a) shows the embodied, operational and total energy as the material utilization factor (MUT) varies for both cases. Total energy savings compared to a passive structure with identical layout designed using state of the art optimization methods [14] are 8% for H/D=3 and 31% for H/D=5 as shown in figure 4 (b). The optimal adaptive structure is found for an MUT of 51% for the former and 43% for the latter. This is because for a higher H/D, displacement compensation takes more operational energy and therefore it must be minimized by decreasing the MUT.

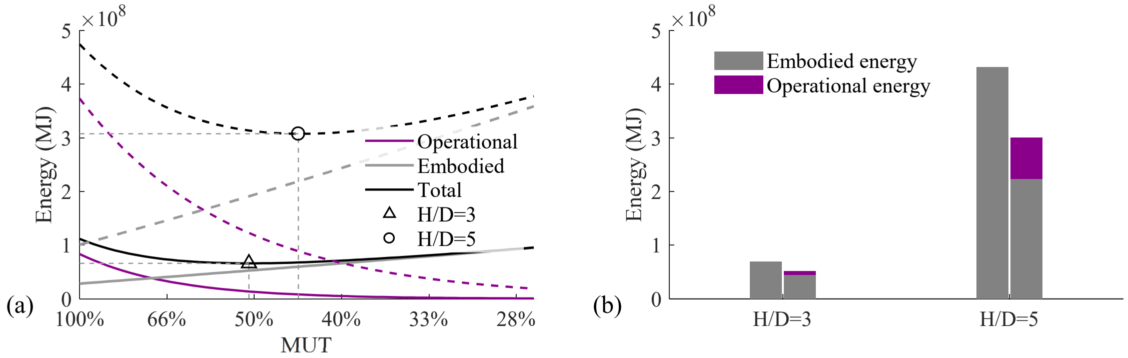

Figure 4: (a) embodied, operational and total energy vs MUT; (b) passive vs adaptive total energy

Figure 5 compares the passive structure (a) with the adaptive structure (b) for the case H/D=5. The actuator layout (represented in magenta) is denser towards the bottom of the structure where it is most effective to reduce the top nodes large displacements. Without active displacement compensation, the maximum deflection is 1230 mm which is beyond serviceability limit (height/500 = 600 mm) as shown in figure 5 (c). The load path redirection (difference between optimal and compatible forces) for L2 is illustrated in figure 5 (d). Matching the optimal load path requires adding compressive forces on the side the wind load hits the structure and on the opposite side which is subjected to negative pressure. Tensile forces are required in the orthogonal direction to the lateral load.

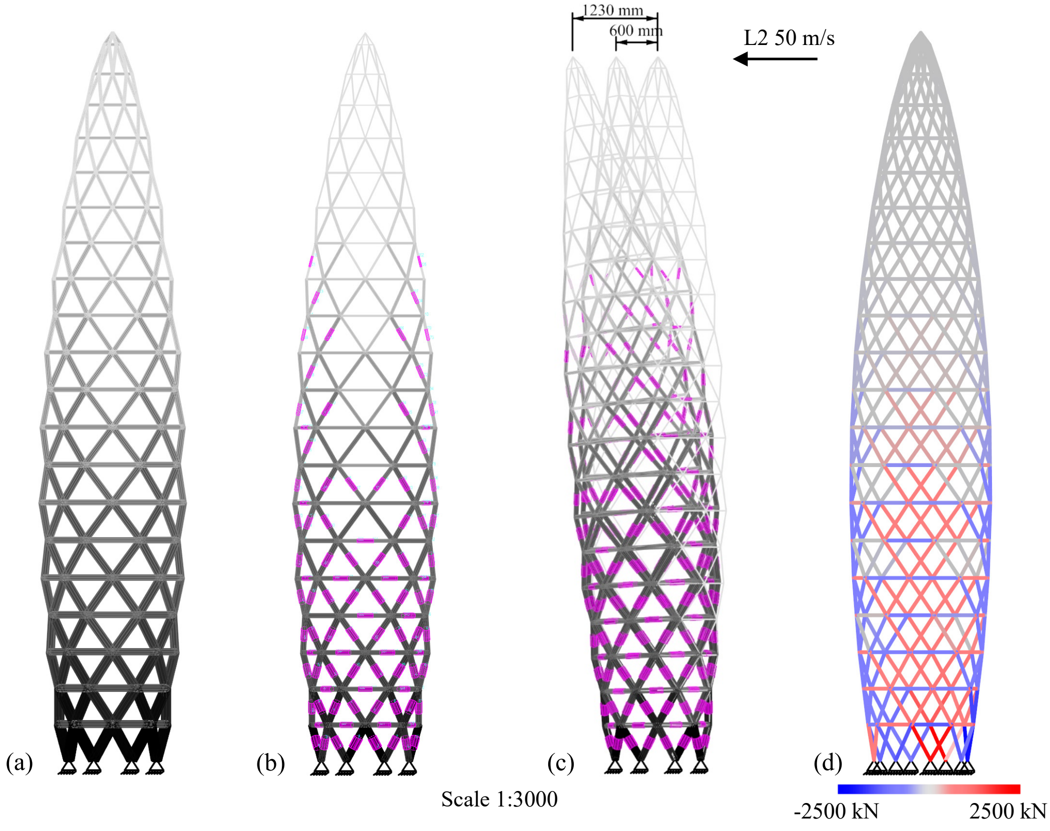

Figure 5: (a) passive; (b) adaptive; (c) controlled & deformed shape (50× mag.); (d) load path redirection

3 Experimental Prototype

A large scale prototype, designed using the method outlined in section 1, was built at the University College London Structures Laboratory. The prototype is a 6 m cantilever spatial truss with a 37.5:1 span-to-depth ratio consisting of 45 passive steel members and 10 electric linear actuators strategically

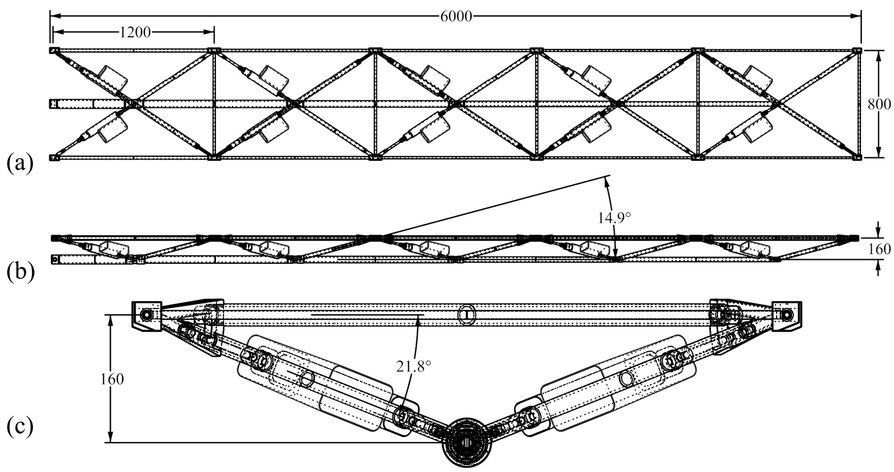

Figure 6: adaptive truss dimensions (a) plan view, (b) elevation, (c) side view

fitted within the tension diagonal members. The truss was designed to support its own weight which consists of 52 kg for the steel structure, 50 kg for the actuators (5 kg each) and 70 kg for the acrylic deck panels and housing. The live load was thought of as a person walking along the deck – the worst case being a load of 1kN (100 kg) at the tip of the cantilever. Deflection limits were set span/500 (12 mm) because due to its pronounced slenderness, this truss can be regarded as the scaled super structure of a tall tower subjected to wind load. The members of the structure are sized to meet the worst expected 'demand' from all load cases to be fully compliant to Eurocode 3 in terms of ultimate limit state but ignoring deflection requirements.

The frame is fully instrumented to monitor the stress in the passive members, the deflected shape, and the operational energy consumed by the active elements. Extensive loads tests showed that the displacements could be practically reduced to zero with no prior knowledge of the direction, position and magnitude (within limits) of the external load thus achieving an "infinite" stiffness structure (i.e. zero deflection under loading). Figure 9 shows an example of the difference between uncontrolled/deformed shape (transparent) and the controlled shape.

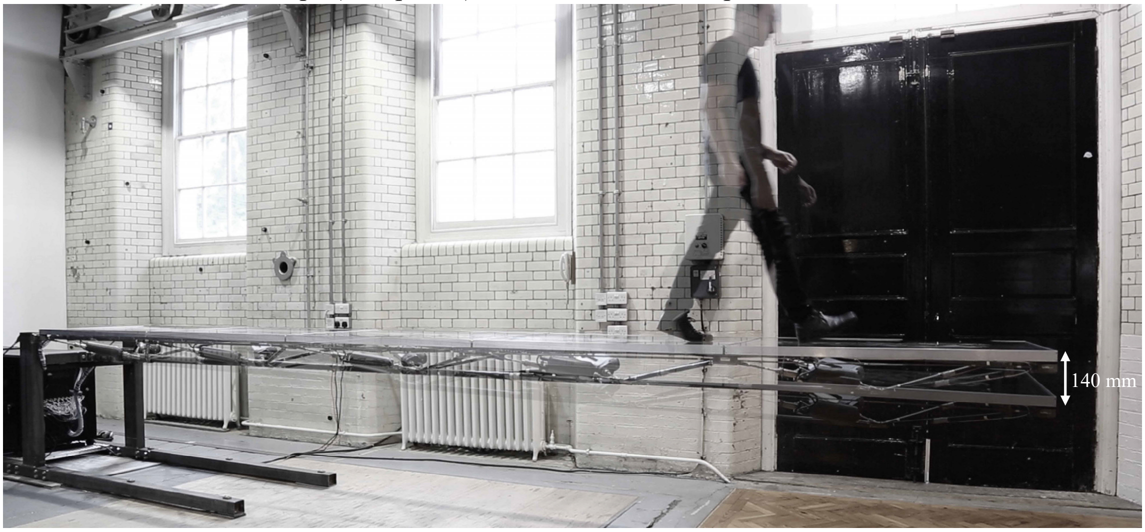

Figure 7: person walking (70 kg), comparison deformed (transparent) and controlled shape

Power consumption was recorded during displacement compensation under quasi-static loading for all electronic devices including the actuation system, signal conditioning and main control processor. The external load was modelled as described in section 1.3. The total energy of the adaptive truss prototype was benchmarked against two passive structures designed to cope with identical loads and deflection limits. The first structure is made of two steel I-beams. The second is an equivalent truss designed using state-of-the-art optimization methods [14]. Measurements showed that the adaptive truss achieves 70% energy savings compared to the I-beams and 40% compared to the optimised passive truss.

Conclusions

This paper outlines a new methodology to design adaptive structures. Structural adaptation is employed as a strategy to counteract the effect of loads. The novelty of this work lies in the development of a methodology that produces, given any stochastic occurrence distribution of the external load, an optimum design of the structure for minimum whole-life energy comprising an embodied part in the material and an operational part for adaptation. The case study showed that even for complex structures, significant energy savings can be achieved, the more so the more stiffness-governed the structure is. Experimental tests confirmed the reliability of the design method and that for slender configurations adaptive structures achieve substantive total energy savings compared to passive structures.

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References

[1] T. T. Soong, “State of the art review: active structural control in civil engineering,” Engineering Structures, vol. 10, pp. 74-84, 1988.

[2] S. Korkmaz, “A review of active structural control: challenges for engineering informatics,” Computers and Structures, no. 89, pp. 2113-2132, 2011.

[3] N. Khot, “Multicriteria Optimization for Design of Structures with Active Control,” Journal of Aerospace Engineering, vol. 11, pp. 45-51, 1998.

[4] T. Soong and G. Cimellaro, “Future directions in structural control,” Structural Control and Health Monitoring, vol. 16, pp. 7-16, 2009.

[5] W. Sobek and P. Teuffel, “Adaptive Systems in Architecture and Structural Engineering,” in Smart Structures and Materials 2001: Smart Systems for Bridges, Structures, and Highways,S. C. Liu, Editor, Proceedings of SPIE, 2001.

[6] P. Teuffel, “Entwerfen Adaptiver Strukturen,” (Doctoral dissertation), University of Stuttgart - ILEK, Struttgart, 2004.

[7] G. Senatore, P. Duffour, S. Hanna, F. Labbe and P. Winslow, “Large Scale Adaptive Structures for Whole Life Energy Savings,” International Association for Shell and Spatial Structures (IASS), vol. 52, no. No. 4 December n. 170, 2011.

[8] G. Senatore, “Adaptive Building Structures,” (Doctoral Dissertation) University College London, London, 2016.

[9] G. Hammond and C. Jones, “Inventory of Carbon & Energy (ICE),” (Technical Report), University of Bath, Bath, 2008.

[10] H. Irschik and F. Ziegler, “Eigenstrain Without Stress and Static Shape Control of Structures,” The American Institute of Aeronautics and Astronautics (AIAA) Journal, vol. 39, no. 10, pp. 1985-1990, 2001.

[11] S. Patnaik, “An Integrated Force Method for Discrete Analysis,” International Journal for Numerical Methods in Engineering, vol. 6, pp. 237-251, 1973.

[12] A. S. Nowak and K. R. Collins, Reliability of Structures, 2nd ed., Taylor & Francis, 2012.

[13] ENERPAC, “E328e Industrial Tools - Europe,” 2016. [Online]. Available: http://www.enerpac.com/en-us/downloads. [Accessed 12 07 2017].

[14] S. Patnaik, A. Gendy, S. Berke and D. Hopkins, “Modified Fully Utilized Design (MFUD) Method for Stress and Displacement Constraints,” International Journal for Numerical Methods in Engineering, vol. 41, pp. 1171-1194, 1998.