Chapter 8
Designing and Prototyping Adaptive Structures—An Energy-Based Approach Beyond Lightweight Design

Gennaro Senatore

Abstract This chapter presents an overview of an original methodology to design optimum adaptive structures with minimum whole-life energy. Structural adaptation is here understood as a simultaneous change of the shape and internal load-path (i.e. internal forces). The whole-life energy of the structure comprises 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 homogenise the stresses and to keep deflections within limits by changing the shape of the structure. This method has been used to design planar and spatial reticular structures of complex layout. Simulations show that the adaptive solution can save significant amount of the whole-life energy compared to weight-optimised passive structures. A tower supported by an exo-skeleton structural system is taken as a case study showing the potential for application of this design method to architectural buildings featuring high slenderness (e.g. long span and high-rise structures). The methodology has been successfully tested on a prototype adaptive structure whose main features are described in this chapter. Experimental tests confirmed the feasibility of the design process when applied to a real structure and that up to 70% of the whole-life energy can be saved compared to equivalent passive structures.

8.1 Introduction

8.1.1 Context and Motivation

Civil structures (e.g. towers, bridges, stadia) are usually over-engineered for most of their service lives, as a result of being designed to withstand rare, worst-case loading

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scenarios. Most of the time structures experience loads significantly lower than the design load and thus this requirement not only creates significant material wastage but it also restrains structural and architectural design.

Reducing the environmental impact of structures is now a serious concern in the construction industry. In a world going through critical changes due to energy depletion and financial challenges, there is a need for technologies and design methods that will transform the way we think about buildings in a way that is fit for purpose in the 21st century—which means lean, low-carbon and smart. This fact leads to consider that buildings could be adaptive rather than relying only on passive load-bearing capacity.

Adaptive structures are defined here as structures capable of counteracting the effect of loads via controlled shape changes and redirection of the internal load-path. In this context, structural adaptation means responding to external agents (e.g. mechanical and thermal loads) to keep the system within desired boundaries maintaining optimal performances throughout its service life. The main components of an adaptive structural system comprises: (1) sensing, (2) actuation, (3) control strategy (4) load bearing capacity (Yao 1972).

Sensing enables monitoring the system to gather data regarding its state. The state is made of key parameters belonging to mechanical and thermal physical domain (e.g. stress, strain, temperature) which are mapped as a function of space and time.

Actuation can be regarded as a controlled release of energy to keep the state of the system within desired boundaries. Actuation involves the transformation of stored (e.g. chemical) or supplied (e.g. electrical, magnetic) energy into mechanical energy. This energy can be utilised for example to control the shape of the structure or to varying its stiffness.

Information gathered by sensors are processed by a suitable **control strategy** to provide input commands to the actuators. For example, a feed-forward and feedback strategy where open and closed control loop are used simultaneously. The main difference between open and closed control strategies is that in the former the response of the system is not measured (Dorf and Bishop 2011). The open-loop system uses a mathematical model of the structural behaviour to predict control actions upon detecting external loads. In the closed-loop control instead, the response of the structure (e.g. stress, displacements, accelerations) to both external events and control actions is measured so that corrections can be made to achieve the desired state. Monitoring the structural response is important to achieve stable control due to the inherent inaccuracy of the process model and the impossibility to monitor all external disturbances.

Load-bearing capacity is achieved through the network of actuators and passive structural components arranged in space to form the structure to withstand static as well as dynamic loads. The main difference from a conventional passive structure is that some of elements of the system are active (i.e. the actuators) providing controlled output energy to manipulate the internal flow of forces and the shape rather than relying only on passive resistance (i.e. geometry and material).

A classification of structures with adaptive capabilities inspired by Wada et al. (1990) is illustrated in Fig. 8.1. Kinetic structures (Zuk and Clark 1970) are integrated

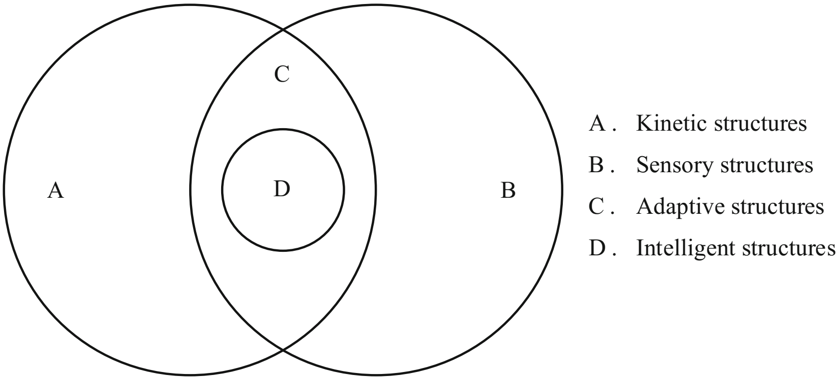

Fig. 8.1 Adaptive structures classification

with actuators to perform motion e.g. a change of shape or position. Sensory structures are integrated with sensors in order to monitor the response to loading events. The intersection of kinetic and sensory structures are adaptive structures. Modern control strategies (e.g. machine learning, adaptive control) enable structures to learn from experience (i.e. response feedback stored in memory) to improve or change control laws over time to better cope with changing environments. Adaptive structures with learning capabilities can be thought of as "intelligent" structures which can anticipate response to external changes rather than only reacting to them (Shea and Smith 1998; Domer and Smith 2005).

8.1.2 Adaptation in Structural Applications

Active control of civil structures has focused mostly on the control of vibrations for building or bridges to improve on safety and serviceability during exceptionally high loads (e.g. strong winds, earthquakes) (Soong 1988). Active brace systems have been tested using hydraulic actuators fitted as cross-bracing elements of the structure controlling directly its deflections (Abdel-Rohman and Leipholz 1983; Reinhorn et al. 1992; Bani-Hani and Ghaboussi 1998). Deflection reduction in cable stayed bridges can be obtained via control forces provided by the stay cables working as active tendons (Rodellar et al. 2002; Xu et al. 2003). Active cable-tendons have been used to change the amount of pre-stress in reinforced concrete beams and in steel trusses to limit displacements under loading (Schnellenbach and Steiner 2013). Integration of actuators has been shown to be an effective way to suppress vibrations in high stiffness-to-weight ratio truss structures (Preumont et al. 2008).

Actuation has been used to modify the membrane stress state in thin plates and shells to help them cope with unusual loading events (Weilandt 2007). Residual stresses formed after welding, machining or formworks removal (Sobek 1987) can reduce shells load carrying capacity significantly. In the event of such disturbances, actuation in the form of induced strain distributions or induced displacements of the supports (actively controlled bearings) can be used to homogenise the stress field and in so doing minimizing the maximum stress governing the design (Neuhäuser 2014).

Active structural control has also been used in applications for shape control. Some all-weather stadia use deployable systems for expandable/retractable roofs e.g. the Singapore National Stadium (Henry et al. 2016) and the Wimbledon Centre Court (SCX 2010). Active tensegrity structures, structures whose stability depends on self-stress, have been used for deployable systems in aerospace applications (Tibert 2002) as well as for displacement control (Fest et al. 2003; Veuve et al. 2015; Adam and Smith 2008) and frequency tuning (Santos et al. 2015) in civil engineering. Active compliant structures, which can be thought of as structures working as monolithic mechanisms (Campanile 2005; Hasse and Campanile 2009), have been investigated for the deployment of antenna reflectors (Jenkins 2005), for the control of aircraft wings to improve on manoeuvrability (Previtali and Ermanni 2012) as well as for the control of direct daylight in buildings (Lienhard et al. 2011).

Because of uncertainties regarding the long-term reliability of sensor and actuator technologies combined with building long service lives and load long return periods, the recent trend has been to develop active structural control to help satisfy serviceability requirements (e.g. deflection limits) rather than contribute to strength improvement (Korkmaz 2011). If the structure relies on an active system for deflection control, its stiffness can be distributed strategically to better utilise the material.

In this context, the relevance of adaptive structures is significant. Advances in material science have mainly focused on increasing the strength of commonly used materials such as steel and concrete but not their stiffness thus leading to problems to satisfy serviceability requirements (Connor 2002). The trend to build slender, taller and longer span structures is shifting design criteria from strength to serviceability where motion control (i.e. limitations of displacements and accelerations) is one of the main issues. In addition, there has been an increase in the use of special structures for space applications, manufacturing and transport facilities that must meet strict design constraints for serviceability (Connor 2002).

8.2 Optimum Design Methodology for Adaptive Structures

In the natural world living forms and their structure are optimised around a strategic balance between material and energy resources (Vincent 1990). The metabolic cost of being adaptive to reach resources is carefully traded with the cost of energy embodied in the material. Most existing design strategies for adaptive structures are based on optimisation methods which aim at minimizing a combination of the control effort, structural response to external loads and other cost functions including the mass of the structure (Utku 1998; Teuffel 2004; Soong and Pitarresi 1987; Sobek and Teuffel 2001). However, 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.

A new optimum design methodology for adaptive structures was presented in Senatore et al. (2011, 2013). This method is based on improving building structural performances by reducing the energy embodied in the material for extraction and manufacturing at the cost of a small increase in operational energy necessary for structural adaptation and sensing. The design process comprises two main steps: (1) embodied energy optimisation and (2) operational energy computation nested within an outer optimisation minimising the whole-life energy. Whole life energy is here understood as the sum of the embodied energy in the material and the operational energy used by the active control system. Applying this methodology to a range of planar and complex spatial reticular structures, Senatore et al. (2018a) show that the adaptive solution can achieve energy savings as high as 70% when compared to identical weight-optimised passive structures. These studies confirm that adaptive structures achieve superior performance when the design is stiffness governed.

The method has so far been implemented for reticular structures with statically determinate and indeterminate topologies. Figure 8.2 shows a schematic flowchart of the design process. Each step is illustrated on a truss structure case study which is employed here as a visual aid.

8.2.1 Inputs

Inputs include the structural topology, material and type of elements, loading and deflection limits (serviceability limit state). In this case, the input layout is a catenary structure which could be thought of as a section of a truss arch bridge made of steel tubular elements. The supports are all pinned as indicated in Fig. 8.2a. The structure is subjected to a uniformly distributed dead load and two patch loads each covering half span of the bridge (e.g. vehicular traffic or train holding position). Serviceability limits are set to be a fraction of the span (e.g. span/1000 typically used for road bridges with both vehicular and pedestrian traffic (Barker et al. 2011).

Inputs include the selection of certain parts of the structure which are of critical importance to serviceability and therefore should be controlled by the active system. For example, in this case all the nodes of top chord except the supports are selected to be controlled as indicated by the circles in Fig. 8.2a. Finally, a suitable range must be chosen for the 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. The MUT varies in a range of $0\% < \text{MUT} \leq 100\%$.

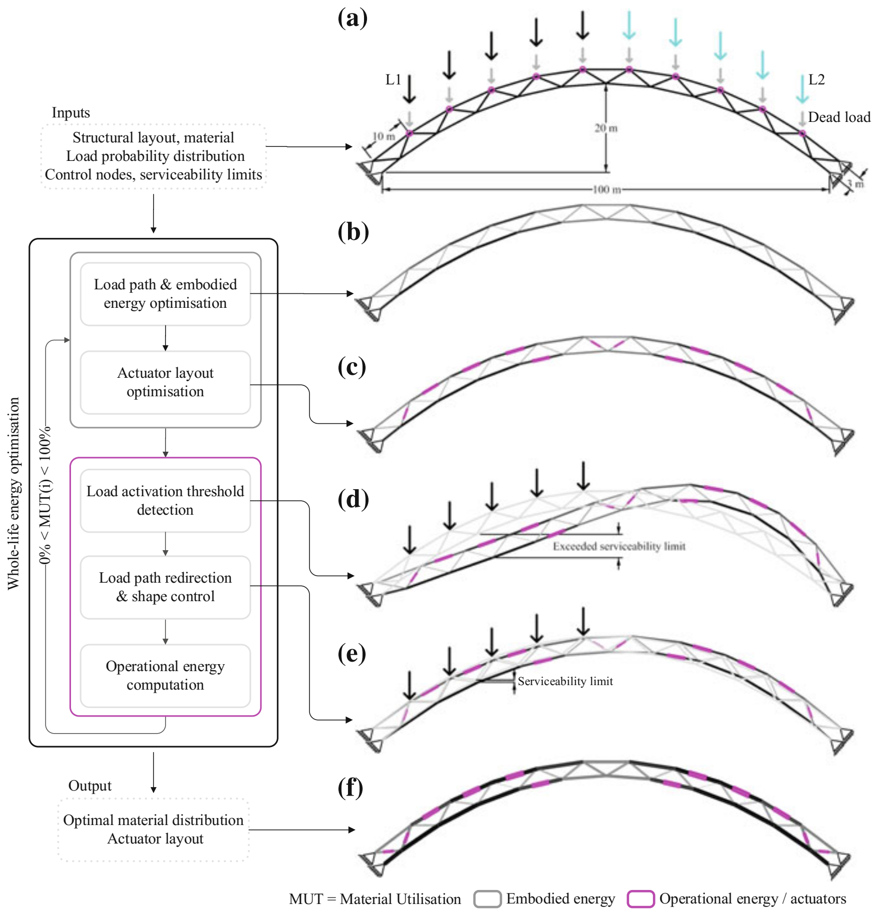

Fig. 8.2 **a** Initial layout and controlled nodes; **b** minimum embodied energy design MUT = 100%; **c** optimal actuation layout MUT = 100%; **d** deformed shape; **e** controlled shape; **f** minimum whole-life energy design MUT < 100%

8.2.2 Load-Path and Embodied Energy Optimisation

The embodied energy of the structure is minimised by optimising the internal load paths and corresponding material distribution but ignoring serviceability limit states, thus obtaining a lower bound in terms of material mass. The energy analysis is carried out using a factor to convert material mass into embodied energy (Hammond and Jones 2008). The design variables are element cross-section areas and internal forces satisfying equilibrium and "strength" constraints (admissible stress, element instability) when the structure is subjected to the design loads. This problem has been solved using sequential quadratic programming (Senatore et al. 2013).

Strength constrains (ultimate limit states, ULS) include the MUT which factors the material yield stress in tension and compression. This way, by varying the MUT one can move from least-weight structures (MUT = 100%) with small embodied but large operational energy, to stiffer structures with large embodied and smaller operational energy consumption. At this stage, the MUT is constant between 0 and 100%. Figure 8.2b shows the configuration obtained for an MUT of 100% which corresponds to the absolute minimum embodied energy structure but it might result in a high level of operational energy for structural adaptation. The MUT is the main variable of the embodied-operational energy optimization (Sect. 8.2.5) to obtain an optimum compromise between active and passive design.

The internal force vector (i.e. load-paths) is called optimal or non-compatible. This is because, at this stage, deflection constraints (serviceability limit state, SLS) as well as geometric compatibility constraints (i.e. all elements connected to a node must have the same absolute displacement) are intentionally not included. 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 next step is to design the actuation system which involves to determine the location of the actuators. The actuators are mechanical devices (e.g. linear motors) which are thought of as integrated into the structure by replacing some of its members. The actuators produce work in the form of length changes. The effect of such length changes is to manipulate the internal forces to match the optimal load-path (i.e. enforce geometric compatibility) and to reduce deflections within required serviceability limits by changing the shape of the structure.

8.2.3 Actuator Layout Optimisation

For a discretised structure (e.g. a truss) the actuator placement problem is of combinatorial nature as it involves selecting a certain number of actuator locations from a set of available sites (the structural elements). This type of problem is usually solved employing global search methods (e.g. stochastic) which can become computationally very expensive and impractical for structures made of many elements. However, in this work the actuator placement problem is formulated as a least-square constrained optimisation via a sensitivity analysis. For each element in turn, the efficacy to redirect the load-path and to correct displacements of a unitary change in length is assessed. Then the difference between the nodal displacements caused by the element length changes and the required displacement correction subject to geometric compatibility constraints is minimised.

This process produces a ranking indicating how effective each element of the structure would be if it was replaced by an active element. This way the most effective locations are selected to form the actuator layout. The minimum number of actuators to control the required displacements exactly is equal to the sum of the number of assigned controlled degrees of freedom and the static indeterminacy of the structural system. Intuitively this is the number of actuators needed to turn the structure into a controlled mechanism. One actuator can control at least one degree of freedom and for statically indeterminate structures extra actuators, as many as the number of static indeterminacy, are needed to control the internal forces. In case fewer actuators are fitted into the structure, displacements can still be compensated albeit only approximately.

8.2.4 Operational Energy Computation

8.2.4.1 Load Probability Distribution

The computation of the operational energy requires assuming some statistics on the frequency of occurrence of the loads. It is intuitively clear that the proposed design process can be particularly beneficial when the design is governed by large loading events having a small probability of occurrence such as storms, earthquakes, snow, unusual crowds etc. Probabilistic models already exist for most of these loads. For instance, earthquakes are often modelled with a Poisson distribution and wind storms with a Weibull distribution (Flori and Delpech 2010). Should this methodology be applied in a practical case, the relevant load probability distribution should be used.

For the purpose of describing the design methodology in this chapter, it is more convenient to work with a generic distribution which can be easily parametrised to fit different loading scenarios. The load probability distribution is modelled here using a Log-Normal distribution because it is closely related to the Normal probability distribution, hence it is general, only taking positive real values and thus providing the desired bias toward the lower values of the random variable. For simplicity, the mean of the underlying normal distribution is set to zero. Following the limit-state design methodology, the characteristic load (i.e. the design load) is set as the 95th percentile of the probability distribution (Nowak and Collins 2012). Once the mean and the characteristic load are set, the standard deviation is fully determined. The design life is usually set to 50 years. The effect of the assumptions made here regarding the load probability distribution are tested systematically in (Senatore et al. 2018b).

8.2.4.2 Load Activation Threshold

The hybrid passive-active structural system is designed so that in normal loading conditions it can take the load using only its passive capacity with the actuators locked in position. The actuators are only activated when the loads reach an activation threshold which is the load causing a state of stress violating either an ultimate (ULS) or a serviceability limit state (SLS). This means that only the rarer loads with higher magnitude but less probability of occurrence need both passive and active load-bearing capacity and therefore the operational energy will be only used when necessary. The introduction of the load activation threshold shows how passive and active design can be combined to reach a higher level of efficiency. Passive resistance through material and form is replaced by a small amount of operational energy.

8.2.4.3 Load Path Redirection, Shape Control and Actuator Work

For any load above the load activation threshold the active system must redirect the internal load-path and control the shape of the structure. For instance, Fig. 8.2d shows that the nodal displacements caused by the design load exceed serviceability limits. Figure 8.2e shows the shape controlled via actuation whereby all controlled displacements are reduced to the required limits.

To compute the operational energy, further assumptions have to be made regarding the mechanical efficiency and the working frequency of the actuators. The mechanical efficiency depends on the actuation technology. For instance, hydraulic actuators have a mechanical efficiency in a range 90–98% (Huber et al. 1997). To be conservative, it is assumed that actuation is hydraulic with a mechanical efficiency of 80%. The mass of an actuator is assumed to be a linear function of the required force with a constant of 0.1 kg/kN (ENERPAC 2016).

It is assumed that the actuators always work at the first natural frequency of the structure which is likely to dominate the response of most structures excited by dynamic loads relevant to civil engineering. This assumption is conservative because it implies that even if the loads only vary very slowly in time, the actuators work at the first natural frequency of the structure. It is also assumed that non-active means are employed to control vibrations (e.g. tuned mass dampers) if required.

During structural adaptation, each actuator does work to change length under resisting forces. The sum of all actuators work divided by the mechanical efficiency and multiplied by the working frequency times the hours of occurrence of a load, is the energy spent for a particular load occurrence above the activation threshold. Summing over all loads above the activation threshold gives the energy needed for structural adaptation throughout the structure service life.

8.2.5 Minimum Whole-Life Energy Design

The outer optimisation performs a search for the optimal Material Utilisation Factor (MUT). For each MUT, the embodied energy and internal load-paths are optimised (Sect. 8.2.2), subsequently the optimal actuator layout is obtained (Sect. 8.2.3) and the operational energy is computed (Sect. 8.2.4). Figure 8.3 shows notionally the variation of the embodied and operational energy as well as their sum (i.e. total or whole-life energy) as the MUT varies. The active-passive system corresponding to the minimum of whole-life energy is the configuration of the optimum sought. Figure 8.2f shows the minimum whole-life energy design for the case study defined in Sect. 8.2.1. Although this structure has a higher embodied energy than that obtained for an MUT of 100% shown in Fig. 8.2c, its whole-life energy is lower because it requires a much lower operational energy for structural adaptation.

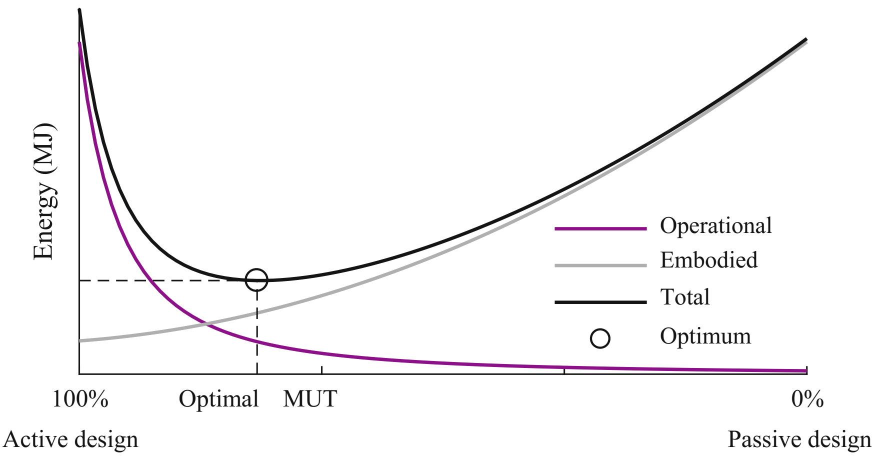

Fig. 8.3 Embodied, operational and total energy as a function of the material utilisation factor (MUT) © IOP Publishing. Reproduced with permission. All rights reserved (Senatore et al. 2018c)

The comparison between Fig. 8.2c and f shows that the embodied energy optimisation (Sect. 8.2.2) and the actuator layout optimisation (Sect. 8.2.3) are very much interdependent. This is because the actuators, by changing the shape of the structure to meet deflection requirements, allow it to be much leaner with lower embodied energy. Conversely, the actuator optimal layout is dependent on the structure within which the actuators are to be fitted. The efficacy of an actuator regarding force and displacement control depends, aside from its location in the structure and the position of the controlled nodes, from the contribution of the passive load-bearing capacity. When varying the MUT, the resulting material distribution changes thus requiring a different internal load-path redirection and displacement compensation. For this reason, the actuator optimal layout changes for different values of the MUT.

8.2.6 Structural Adaptation Simulation

Structural adaptation is here understood as a controlled change of the shape and internal forces of the structure. Simulating a controlled shape change is not a trivial task. For truss systems such as those described in Sects. 8.2 and 8.3, a shape change is the result of simultaneous expansion or contraction of the actuators that are fitted into the structure. Even for a truss system (which is made of elements that can only be either in tension or compression) most of commercially available simulation tools do not offer a way to assign directly an extension or contraction of one or more elements in the structure.

A convenient method to compute internal forces and displacements resulting from element length changes is the Integrated Force Method (IFM) (Patnaik 1973). The IFM was originally formulated to allow a geometric imperfection, caused by a lack of fit or thermal strains for instance, to be dealt with in a compact way and without the need to choose any specific member as redundant. This is because in statically indeterminate structures, internal stresses can be caused by geometrical imperfections and therefore should be taken into account in structural design. In the design method outlined in Sect. 8.2, a deformation vector akin to a lack of fit is defined to assign the actuator length changes. The length change of an actuator is thought of as a non-elastic strain which is referred as eigenstrain (Ziegler 2005). Shape control and internal load path redirection simulation (see Sect. 8.4.3) is handled by a computationally efficient routine based on eigenstrain assignment via the Integrated Force Method. This routine is described comprehensively in Senatore (2016).

An alternative way to simulate controlled shape changes via actuation is given in Senatore and Piker (2015) which presented a formulation combining the principle aspects of the Dynamic Relaxation method (Day 1965; Barnes 1977; Williams 2000) and the co-rotational formulation for the Finite Element Method (Crisfield 1990; Felippa and Haugen 2005). In this formulation, elements forces, moments and inertia are appropriately lumped at nodes. Position, velocity and acceleration of each node are computed iteratively. A co-rotational approach is employed to compute the resultant field of displacements in global coordinates including the effect of large deformations (i.e. geometric non-linearity). The system converges to an equilibrium position around which it oscillates and eventually settles when the out of balance forces and moments residuals are below a set tolerance. This formulation was implemented into a cross-platform software called "PushMePullMe" (Senatore 2017a) written in Java and later as the game "Make A Scape" (Senatore 2017b) running on the mobile operating system iOS.

Since convergence to equilibrium is iterative, it is possible to change interactively the length of an element (often referred as "rest-length" in this context) to simulate its expansion or contraction. In addition, because computation of displacements and forces relies only on the local element stiffness matrix (i.e. there is no need to assemble a global stiffness matrix), changing the length of an element does not take substantial computational resources. For illustration purposes, Fig. 8.4 shows (a) an hypothetical roof truss structure whose top chord elements are replaced by actuators (indicated in purple) and (b) the shape change obtained by reducing the length of all the actuators by 10% the initial length.

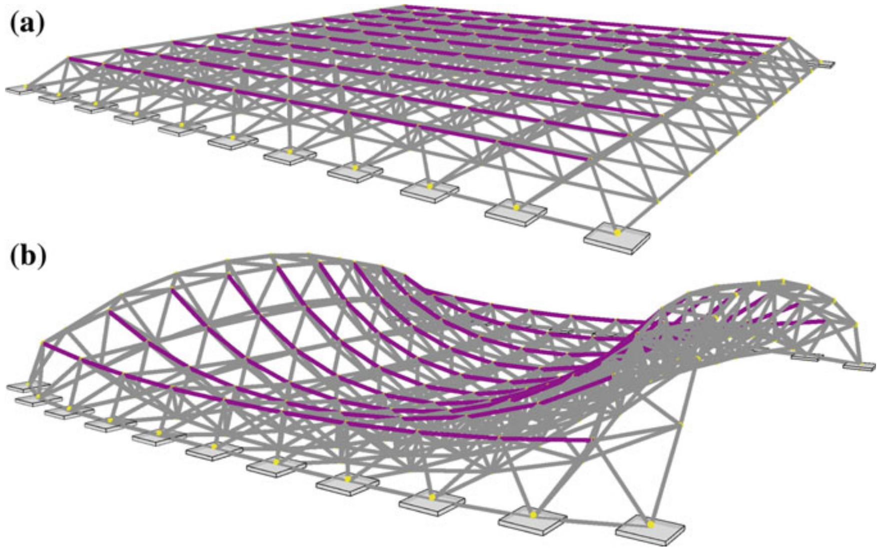

Fig. 8.4 Adaptive roof structure: **a** initial geometry; **b** shape change after 10% actuator length reduction

8.3 Case Study

The structure considered in this case study is a simplified model of a tower building known as 30 St Mary Axe or informally the "Gherkin", a tall building in the City of London. This case is part of a parametric study that has been carried out to investigate how adaptive structure performances in terms of mass and energy savings as well as monetary costs vary when the design process is applied to complex spatial configurations (Senatore et al. 2018a). The model is loosely related to the original geometry which is studied here as an example of a tall building resisting external loads through an exoskeleton structure. This means that the example studied here has no structural core (although the real 'Gherkin' does). As cores reduce significantly commercially usable floor space, systems that can do away with them free up the floor layouts and are therefore of structural, architectural and commercial interest.

Two models are considered to show how energy savings vary with the slenderness i.e. the ratio height to depth (H/D). Main dimensions and boundary conditions are indicated in Fig. 8.5. All elements are assumed to have a cylindrical hollow section. To limit the complexity of the optimisation process, the element wall thickness is set to 10% of the external diameter. Limit to the total building drift is set to height/500. The horizontal displacements of all the nodes except the supports are controlled.

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 8.5c shows a top view of the structure with (c) L2 (symmetrical to L4) and (d) L3 (symmetrical to L5) applied. The live load intensity

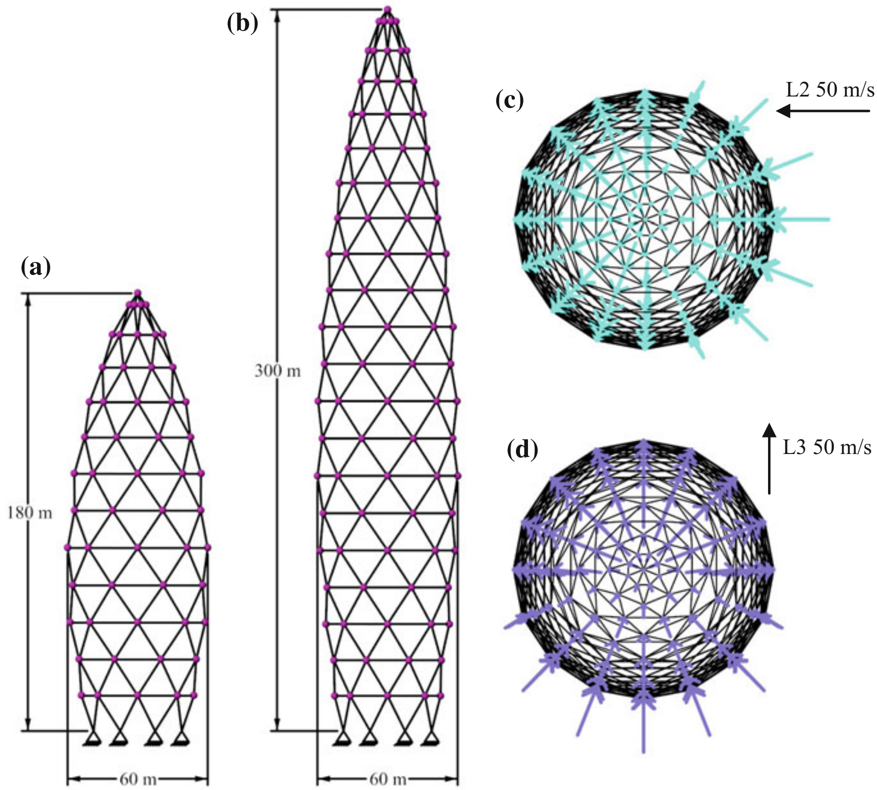

Fig. 8.5 Dimensions and control nodes indicated by dots **a** H/D = 3. **b** H/D = 5; **c** L2; **d** L3. Reproduced with permission from ASCE (Senatore et al. 2018a)

varies quadratically with the height reaching a maximum of 1.5 kN/m^2 which is equivalent to a wind velocity of 50 m/s (category 2/3 hurricane). All live load cases have identical probability distribution (see Sect. 8.4.1).

The activation thresholds are 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 and 34 m/s and the total time during which actuation is required to compensate for deflections is 1.25 and 3 years. Mass and total energy savings compared to a passive structure of identical layout designed using a state of the art optimisation method (Patnaik et al. 1998) are 25 and 8% for H/D = 3 and 48 and 31% for H/D = 5. The optimal adaptive structure is obtained for an MUT of 51% for H/D = 3 and 43% for H/D = 5. This is because for a higher H/D (i.e. a more slender structure), displacement compensation takes more operational energy and thus the MUT decreases.

Figure 8.6 compares the passive structure (a) with the adaptive structure (b) for the case H/D = 5. As expected the actuator layout (represented in purple) is denser towards the bottom of the structure because it is the most effective location for

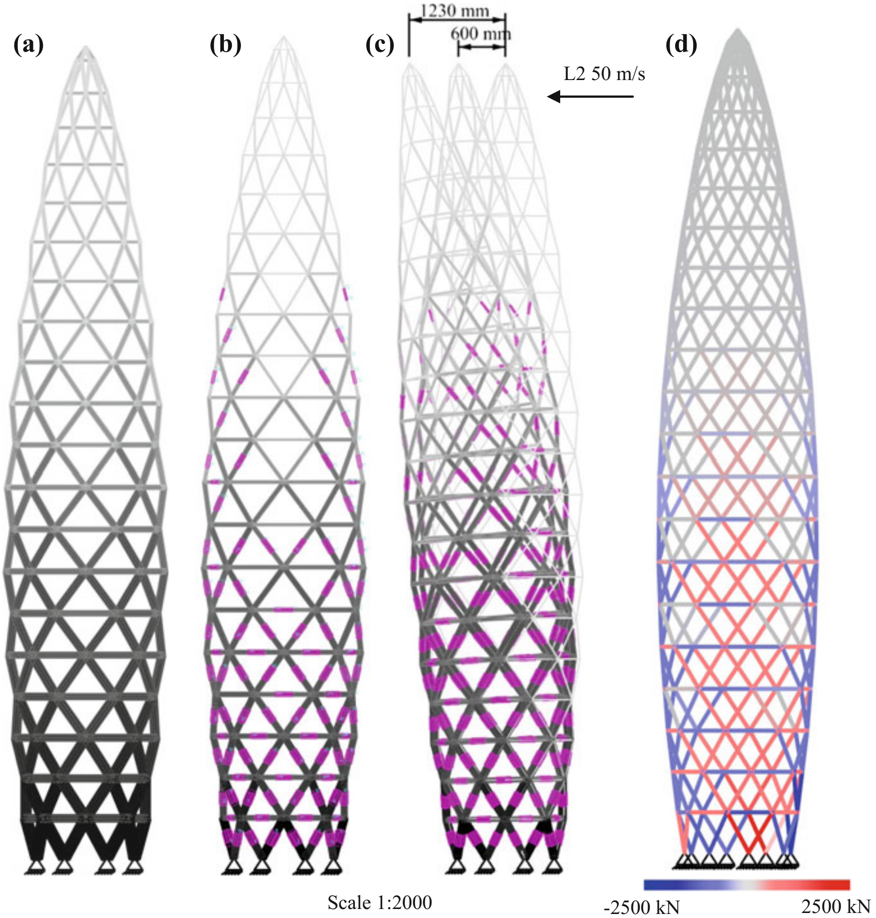

Fig. 8.6 **a** Passive, **b** adaptive, **c** controlled & deformed shape (mag. 50 ×), **d** load path redirection Reproduced with permission from ASCE (Senatore et al. 2018a)

the actuator length changes to reduce the top nodes displacements. Without active displacement compensation, the maximum deflection is beyond serviceability limit (height/500 = 600 mm) as shown in Fig. 8.6c. The load path redirection (difference between optimal and compatible forces) for L2 is illustrated in Fig. 8.6d. 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. The maximum length changes are about 40 mm expansion made by the bottommost actuators located on the opposite side the load is applied which must deploy under the highest compressive forces (35,000 kN). The highest tensile forces are approximately 18,000 kN applied by the actuators placed on the horizontal elements (it can be thought of as the action of tightening "rings" on a basket-like structure).

8.4 Experimental Prototype

A large scale prototype (here named "adaptive truss"), designed using the method outlined in Sect. 8.2, was built at 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 fitted within the tension diagonal members. The adaptive truss main dimensions are shown in Fig. 8.7.

The truss is 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 is thought of as a person walking along the deck. This is modelled as three load cases representing the worst scenarios when the person stands at the free end with their weight distributed equally between the two end nodes or when their entire weight is concentrated on either one of them. The magnitude of the live load is set to 1 kN (100 kg). Deflection limits are set to 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 deck/façade of the structure consists of a series of aluminium angle profiles which house transparent acrylic panels Fig. 8.8a. Clear acrylic has been chosen to allow the actuator length changes to be seen during control. The aluminium angles also provide housing to power and signal cables which are bundled and clipped to their bottom face as shown in Fig. 8.8b.

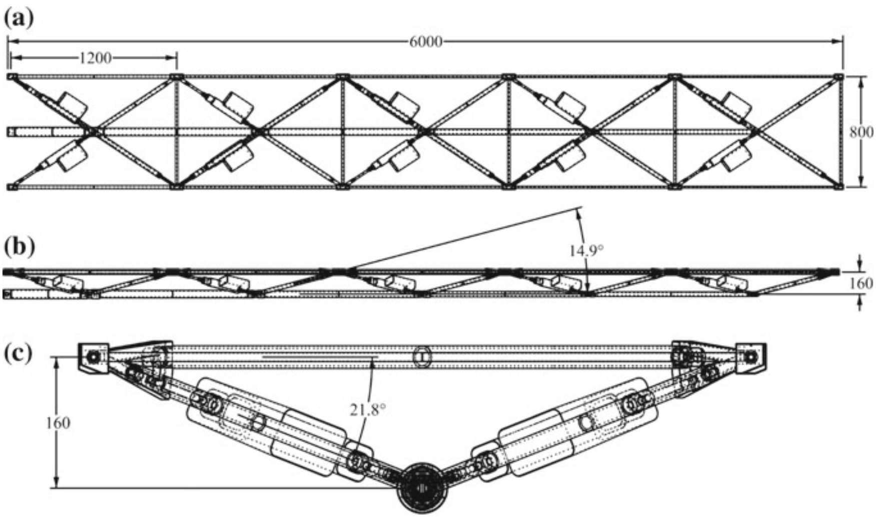

Fig. 8.7 Adaptive truss dimensions, **a** plan view, **b** elevation, **c** side view © IOP Publishing. Reproduced with permission. All rights reserved (Senatore et al. 2018c)

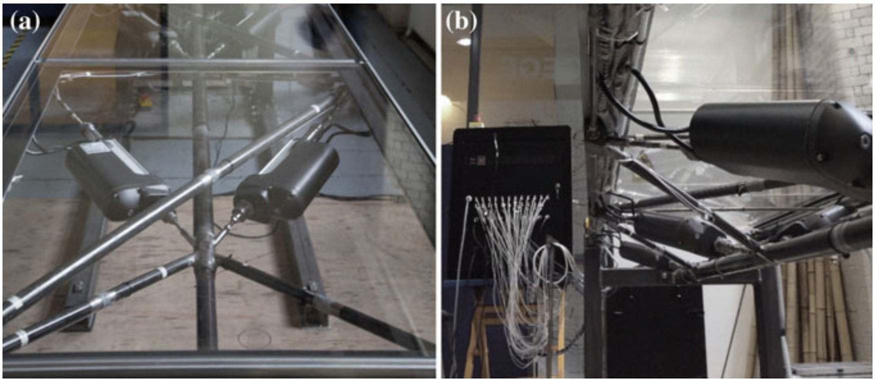

Fig. 8.8 **a** Deck/façade; **b** signal and power cables clipped underneath the aluminium angles © IOP Publishing. Reproduced with permission. All rights reserved (Senatore et al. 2018c)

The control system architecture has been designed with the primary aim to achieve identification of the response to loading in terms of internal forces and displacements for the structure to be able to be control itself without user intervention. The control system comprises ten linear actuators, a control driver board for each pair of actuators, 45 strain gauge based sensors, two amplifiers for signal conditioning and a main controller for acquisition and processing. The deformation of each element together with the actuator stroke position feedback are fed into the main controller. These inputs are processed to reconstruct the node spatial positions to assess whether their displacements exceed the required serviceability limit. In this case, the actuators vary their stroke length to change the shape of the structure so that controlled node displacements are reduced within required limits. To keep power consumption to a minimum, a switch on/off command is sent to the actuator driver to cut off power supply as soon as the target position is reached. The reader is referred to (Senatore et al. 2018c) for a detailed presentation of the prototype including the control algorithm.

Extensive loads tests has shown that the displacements are practically reduced to zero with no prior knowledge of direction, position and magnitude (within limits) of the external load thus achieving an "infinite" stiffness structure (i.e. zero deflection under loading). When a person walks on the deck, the actuators change length continuously to compensate for displacements as the load changes position. Figure 8.9 shows an example of the difference between the deformed (i.e. without control) and controlled shape. Demonstration movies are available online (Senatore 2017c).

Current sensors were installed at the mains supply to monitor the power used for shape control. Energy 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 live load probability distribution (Sect. 8.4.1) was divided in 10 steps from 10 to 100 kg. Each load (in the form of weights) was placed on the deck between the end nodes. The total operational energy

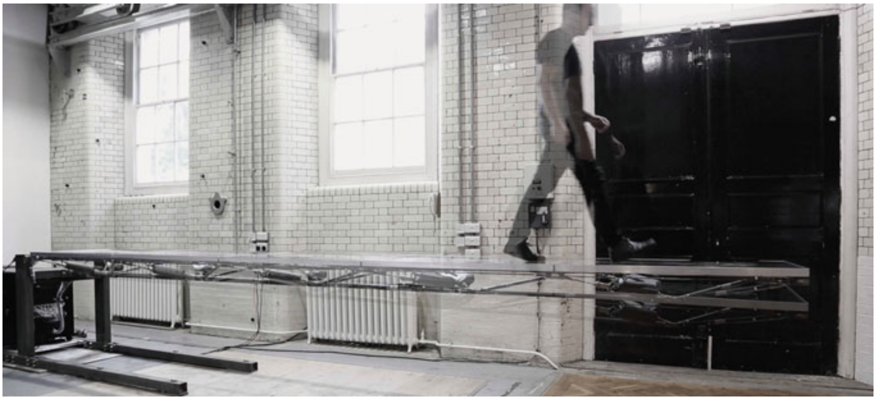

Fig. 8.9 Person walking (70 kg), comparison between deformed (transparent) and controlled shape (Senatore et al. 2018c)

was computed by multiplying the energy consumption needed for shape control by the live load hourly distribution for all loads above the activation threshold (a weight of 14 kg at the free end). The adaptive truss prototype has been benchmarked against two passive structures designed to cope with identical loads and deflection limits. The first structure is made of two steel I-beams while the second is an equivalent truss designed using a state-of-the-art optimisation method (Patnaik et al. 1998). Measurements has shown that the adaptive truss achieves 70% energy savings compared to the I-beams and 40% compared to the optimised passive truss.

Using fast-acting actuators would allow full control of 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 11 mm/s. Nevertheless, they are still able to increase effective damping in the truss from 0.5% to 3%. However, actively controlling vibrations expends much more operational energy therefore hybrid solutions using actuation to compensate for large displacements and passive means (e.g. tuned mass dampers) to control vibrations are still likely to be preferred.

This prototype was also built as a demonstration piece to show in a practical and interactive way the potential of the underlying design methodology to professionals in the field—structural engineers, architects, fabricators. The structure was exhibited at various key institutions amongst with University College London and during the International Association for Shell and Spatial Structures symposium (IASS) held in Amsterdam in 2015. A month solo exhibition took place in August 2016 at a well-known building technology gallery space called "The Building Centre" situated in central London (Senatore 2017d).

8.5 Discussion

Adaptive structures offer an emerging design paradigm that deals with providing stiffness in a completely different way to traditional engineering. Using adaptation as a strategy to counteract the effect of the external load allows large quantities of materials to be saved while meeting safety critical requirements:

(1) Conventional materials e.g. steel tubes or rods as shown in the prototype presented in this chapter, still provide for strength and safety (ultimate limit state requirements) as well as for deflections under day-to-day loads;
(2) The actuation system controls excessive movements and deflections (serviceability limit state) which in practice occur very infrequently;
(3) In case of a power outage the actuators simply stop moving (i.e. fail-safe) but load carrying capacity is not compromised because of point 1.

The design method proposed in this work produces structures that combine three objectives which are usually mutually exclusive: (1) the structure has a low overall environmental impact (minimum whole-life energy design); (2) the displacements can be controlled within very tight limits; (3) the structure is extremely slender. Being able to combine these three objectives is unique in structural engineering and architecture. In the case of the prototype structure described in Sect. 8.4 a combination of all three benefits has been in fact achieved.

Applying this design philosophy, scenarios where adaptive structures could bring significant benefits include:

- When the end use has very stringent/high performance requirements for deflection, therefore the "infinite stiffness" capability of adaptive structures can clearly outperform conventional structures. For example, laboratory buildings, gantry crane runway beams, bespoke facades etc.
- When the structural design is governed by high but rare loads, such as earthquakes and wind storms. The same applies to structures that are in service for only a few hours per week (e.g. stadium stands). An adaptive structure optimised to remain serviceable under rare high loads 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.
- Long span/high rise structures are typically stiffness governed and so tall buildings, bridges, and roofs could all see benefit from adaptive design. 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.

8.6 Conclusions

This chapter outlines an optimum methodology to design adaptive structures. Structural adaptation is employed 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 feasibility and applicability of the design method and that for slender configurations adaptive structures achieve substantive total energy savings compared to passive structures.

The method proposed here works within the assumption of small displacements and was implemented for statically determinate and indeterminate reticular structures. Ongoing work (Reksowardojo et al. 2017; Senatore et al. 2017) is exploring large shape changes (i.e. finite displacements) to allow for a full utilisation of the shape adjustable properties of adaptive structures for the purpose of saving energy. Future work could extend this design method to other structural systems (e.g. beams, shells) and investigate structural adaptation using material with non-linear behaviour (e.g. concrete).

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