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Exploring the application domain of adaptive structures

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A R T I C L E I N F O

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A B S T R A C T

Using a previously developed design methodology it was shown that optimal material distribution in combination with strategic integration of the actuation system lead to significant whole-life energy savings when the design is governed by rare but strong loading events. The whole-life energy of the structure is made of an embodied part in the material and an operational part for structural adaptation. Instead of using more material to cope with the effect of loads, the actuation system redirects the internal load-path to homogenise the stresses and change the shape of the structure to keep deflections within limits.

This paper presents a systematic exploration of the domain in which adaptive two-dimensional pin-jointed structures are beneficial in terms of whole-life energy and monetary costs savings. Two case studies are considered: a vertical cantilever truss representative of a multi-storey building supported by an exoskeleton structure and a simply supported truss beam which is part of a roof system. This exploration takes five directions studying the influence of: (1) the structural topology (2) the characteristics of the load probability distribution (3) the ratio of live load over dead load (4) the aspect ratio of the structure (e.g. height-to-depth) (5) the material energy intensity factor. Results from the main five strands are combined with those from the monetary cost analysis to identify an optimal region where adaptive structures are most effective in terms of both energy and monetary savings. It was found that the optimal region is broadly that of stiffness-governed structures. For the cantilever case, the optimal region covers most of the application domain and it is not very sensitive to either live-to-dead-load or height-to-depth ratios thus showing a wide range of applicability, including ordinary loading scenarios and relatively deep structures.

1. Introduction

Adaptive structures are defined here as structures capable of counteracting actively 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 focussed mostly on the control of vibrations for building or bridges to improve safety and serviceability during exceptionally high loads (i.e. strong winds, earthquakes) [1,2]. Active brace systems have been tested using hydraulic actuators fitted as cross-bracing elements of the structure, controlling directly its response using actively controlled forces [3–5]. Cable stayed bridges have been controlled using the stay cables as active tendons to reduce displacements [6,7]. Active cable-tendons have also been used to change the amount of pre-stress in reinforced concrete beams and in steel trusses to limit displacements under loading [8]. The integration of actuators has been shown to be an effective way to suppress vibrations in high stiffness/weight ratio truss structures [9].

Actuation has been used to modify the membrane stress state in shell structures which are usually designed via shape optimisation methods achieving ideal geometry under permanent load. To deal with rarely occurring loading conditions different to the permanent load, additional material is distributed locally which is, therefore, only utilised during peak demands. In addition, in the event of cuttings or residual stress formed after formworks removal [10], the load carrying capacity is reduced significantly. In the event of such disturbances, actuation in the form of induced strain distributions or induced support displacements (actively controlled bearings) has been used to homogenise the stress field and in so doing minimising the maximum stress governing the design [11,12].

Active structural control has also been used in applications for shape control. Some all-weather stadia use deployable systems [13] for expandable/retractable roofs e.g. the Singapore National Stadium [14].

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Tensegrity structures consist of a set of compression and tension members whose stability relies on self-stress [15–17]. Tensegrity structures have been used for deployable systems in aerospace applications [18] and they have been investigated for force/displacement control [19–21] and frequency tuning [22] in civil engineering. Compliant structures can be thought of as structures which act like monolithic mechanisms. Compliance can be discrete or continuous. In the former, motion is allowed using flexural hinges (i.e. hinges that allows motion by bending) [23] while in the latter it is achieved through the flexibility of the constituent elements of the structure [24]. Active compliant structures have been used for the deployment of antenna reflectors [25], for the control of aircraft wings to improve on manoeuvrability [26] as well as for the control of direct daylight in buildings [27].

Adaptive structures have a good potential for mitigating strong hazard events and control of displacements and vibrations in deflection-sensitive structures [28]. Because of uncertainties regarding the long-term reliability of sensor and actuator technologies combined with long service lives of buildings and long return periods of loads, the recent trend has been to develop active structural control to help satisfying serviceability requirements rather than contributing to strength and safety improvement [29].

The potential of using adaptation to save material has been investigated by some [30–33] 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. A novel design methodology for adaptive structures was presented in Senatore et al. [34]. This method is based on improving structural performance through the reduction in the energy embodied in the material at the cost of a small increase in operational energy necessary for structural adaptation and sensing. In [35] it was shown that adaptive structures designed with this method can achieve up to 70% energy savings when compared to identical passive structures designed using state art optimisation methods. The examples studied so far range from planar portal frames and catenary arch bridges to spatial configurations of complex layout including doubly curved grid-shells and exoskeleton structures. A large scale prototype designed using this methodology was successfully tested validating key assumptions and numerical predictions [36].

These conclusions are based on a set of assumptions including the structural layout, the live load probability distribution and the material energy intensity. The purpose of this paper is to investigate how energy and monetary costs vary are as these inputs are changed via a parametric study.

2. Background: adaptive structures design methodology

In conventional design situations, members are capacity designed and the highest demand is dictated by a worst load case. However, generally building structures experience loading significantly lower than the design load, meaning that they are effectively overdesigned for most of their working life.

If the structure relies on an active system for deflection control, its stiffness can be distributed strategically such that the passive-active configuration achieves higher efficiency in terms of whole-life energy. The whole-life energy (also referred as total energy) is here understood as the sum of the embodied energy in the material and the operational energy used by the active control system. Senatore et al. [34] proposed a new design method whereby the active system is only used when necessary to ensure that the whole-life energy of the structure is kept to a minimum. The method is briefly summarised here, the reader is referred to [37] for a detailed presentation. The method has so far been implemented for reticular structures and this paper only deals with such structures. The process comprises two nested optimisation stages as shown by the flowchart in Fig. 1.

The outer optimisation stage identifies a structure with minimal overall energy (embodied + operational) for a given load probability distribution. This is done by varying the Material Utilisation Factor (MUT) which can be thought of as a scaling factor on the cross-sections. Varying the MUT changes the design from a least-weight structure with small embodied but large operational energy, to a stiffer structure with large embodied and smaller operational energy. This is shown diagrammatically in Fig. 2 which describes the notional variation of the total energy with the MUT.

The inner optimisation itself consists of two main steps. The first step finds the optimum load path and corresponding material distribution ignoring geometric compatibility and serviceability limit states thus yielding a design that represents a lower bound in terms of material mass. The optimisation is subject to equilibrium and ultimate limit state constraints including member buckling. The members of the structure are sized so that they have the capacity to meet the worst expected 'demand' from all load cases for strength only. Under external loads however, the compatible forces are in general different from the optimal forces and the resulting displacements might be beyond serviceability limits. For this reason, the second step finds the optimal actuator layout to manipulate the internal forces by changing the shape of the structure. The actuators are devices which can either reduce or increase their length and are integrated in the structure by replacing part of their elements. Via controlled actuator length changes, geometric compatibility is satisfied and at the same time deflections are controlled. For indeterminate structures, it is possible to control both the internal load-path and shape. Instead, if the structure is determinate, the active system can only control the shape because there is no self-stress state.

Once the actuator layout is known, a control strategy is determined. If a change in the loads causes a state of stress that violates a serviceability limits state (SLS), the load path is redirected and displacements are controlled by the active system. In case of a power outage or actuation system failure and concurrent occurrence of a strong event, the structure might not be serviceable but load carrying capacity is not compromised (i.e. fail-safe). In other words, the structure is designed not to collapse under the worst load case even without the contribution of the active system.

The structure is designed to take permanent loads as well as randomly fluctuating live loads. The methodology is based on the probability of occurrence of the live loads. In a real design situation, this probability should be based on empirical data or commonly used statistical models for the load considered. For illustrative purposes an example of one such probability distribution function is shown in Fig. 3(a) and (b). The method identifies the load activation threshold (the dashed line in Fig. 3a) above which actuation is needed for compensation of internal forces and displacements. Fig. 3(b) plots the hours of occurrence for each level of the load obtained by discretising the probability density distribution scaled by the total number of hours of service. The introduction of the load activation threshold shows how passive and active design can be combined to reach a higher level of efficiency.

3. Parametric exploration

3.1. Scope

The parametric study carried out in this paper has five main objectives:

1. Compare statically indeterminate against determinate structures to appreciate the influence of the load-path redirection on operational energy consumption;
2. Appreciate the sensitivity of the energy savings to features of the probability of occurrence of external loads;
3. Appreciate the sensitivity of the energy savings to the live load to dead load (L/D) ratio;
4. Study the importance of the slenderness of the structure by varying