Design and control of adaptive civil structures

1 Motivation

Civil structures are usually designed to meet strength and deformation requirements to withstand rare events such as earthquakes and strong winds which in practice occur very rarely. Most structures are thus over-designed for most of their service life. Instead, structures could be adaptive to counteract the effect of external loads. The state of the structural system (e.g. displacements and internal forces) is monitored through sensors (e.g. strain gauges, optical tracking). Closed-loop control drives the actuators in order to keep the structure within required conditions.

This way it possible to redistribute the internal flow of forces so that the effect of external loading is reduced rather than relying only on passive load-bearing capacity. For example, if the structure can reduce deflections actively through controlled shape changes, its stiffness can be tuned to better utilize the material. For this reason, adaptation enables a structure to operate closer to design limits.

2 Aim and Scope

Structural adaptation has been employed to minimize the whole-life energy of load-bearing systems through optimum design of the structure and control system [1]. The whole-life energy is made of an embodied part in the material (for extraction and fabrication) and an operational part for control. The energy is minimized through a substantial reduction of the embodied energy (and thus material mass) at a small increase in operational energy that is necessary for structural adaptation during service life.

The scope of this MSc project is to extend previous work [1] by including control strategies to reduce the dynamic response of the structure within an integrated structure-control synthesis process. Numerical case studies including bridges and high-rise buildings under dynamic loading (e.g. earthquake, vehicular traffic, wind) will be considered. Some of the methods developed during this project will be tested experimentally on a large scale *prototype adaptive structure*. This is a unique opportunity to contribute to the development of a new design framework for structural engineering.

3 Objectives

O1 Investigate suitable control strategies to reduce the structure response under dynamic loading to be integrated within a structure-control optimization process:

- Induce natural frequency shift through controlled shape changes
- Active control through a hybrid system comprising active (linear actuators) and passive devices (viscous dampers).

O2 Evaluate structural performance and quantify control energy requirement during service life through numerical case studies:

- Steel bridges under earthquake and traffic loading
- High-rise structures under earthquake and wind loading

O3 Experimental testing of the methods developed in **O1** on a large scale *prototype adaptive structure*

4 Project Details

Type of project: Master project (MA3 + PDM)

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Keywords: adaptive structures, structural dynamics, minimum energy design, earthquake engineering, conceptual design, structural optimization

5 Remarks

The candidate should have a basic understanding of structural mechanics and dynamics. Familiarity with CAD software (e.g. Rhinoceros, Autocad, SolidWorks) and experience with software development (Matlab, Python, Java, C++, C#) is preferred.

The project will be carried out in English and the report must be written in English. Students will be aided via regular meetings and a close supervision. In case of a good quality contribution, co-authorship in scientific publications will be considered.

6 Background

Senatore et al formulated a new method [1, 2] to design structures that are an optimal hybrid between a passive and a fully active system. Assuming some statistical distribution for the probability of occurrence of the loads, whole-life energy is minimized by combining optimal material distribution and

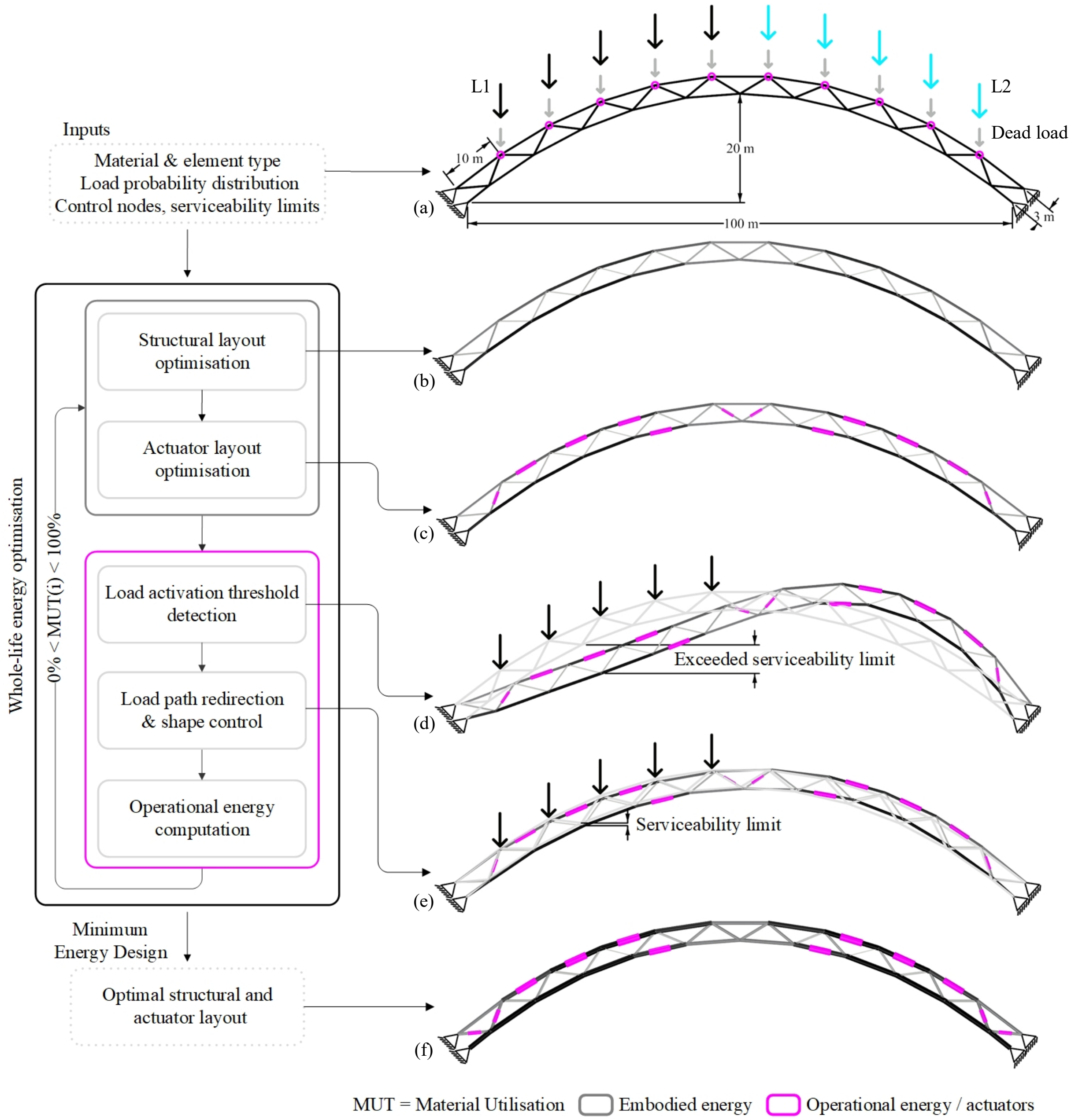

Figure 1: a) initial layout and controlled nodes ; b) minimum embodied energy design MUT=100% ; c) optimal actuation layout MUT=100%; d) deformed shape; e) controlled shape; f) minimum whole-life energy design.

strategic integration of the actuation system, which is only used when loading events exceed a certain threshold. Instead of using more material to cope with the effect of the loads, the active elements change the shape of the structure in order to homogenize the stresses and keep deflections within limits. Figure 1 shows a schematic flowchart of the design process.

Extensive numerical simulations, which compare optimized passive structures with the equivalent adaptive solutions, show the whole-life total energy could be reduced by up to 70% for slender structures [3]. When the critical limit state is governed by stiffness, (e.g. slender structures and structures requiring severe deflection limits), the adaptive solution becomes competitive also in monetary cost terms [4]. A large-scale prototype, designed using this methodology was successfully tested demonstrating the feasibility and applicability [5].

7 References

[1] G. Senatore, P. Duffour and P. Winslow, "Synthesis of Minimum Energy Adaptive Structures," *Structural and Multidisciplinary Optimization,* vol. 60, no. 3, pp. 849-877, 2019.

[2] G. Senatore, P. Duffour, S. Hanna, F. Labbe and P. Winslow, "Adaptive Structures for Whole Life Energy Savings," *International Association for Shell and Spatial Structures (IASS),* vol. 52, no. 4 December n. 170, pp. 233 - 240, 2011.

[3] G. Senatore, P. Duffour and P. Winslow, "Energy and Cost Analysis of Adaptive Structures: Case Studies," *Journal of Structural Engineering (ASCE),* vol. 144, no. 8, p. 04018107, 2018.

[4] G. Senatore, P. Duffour and P. Winslow, "Exploring the Application Domain of Adaptive Structures," *Engineering Structures,* vol. 167, pp. 608-628, 2018.

[5] G. Senatore, P. Duffour, P. Winslow and C. Wise, "Shape Control and Whole-Life Energy Assessment of an "Infinitely Stiff" Prototype Adaptive Structure," *Smart Materials and Structures,* vol. 27, no. 1, p. 015022, 2018.