ADAPTIVE STRUCTURES FOR WHOLE-LIFE ENERGY SAVINGS

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ABSTRACT

The design methodology described in this paper takes a substantial shift from conventional methods. Traditionally sizing is based on the worst expected load scenario. By contrast to this conventional passive approach the method presented here replaces passive member strategically with active elements (actuators) which are only activated when the loads reach a certain threshold. The structure can withstand low level of loads passively. Above the threshold, actuation comes in to allow the structure to cope with high but rare loading scenarios. Active control introduces operational energy consumption in addition to the energy embodied in a passive design. In this paper we use this dual design to minimize the overall energy required by the structures.
This methodology has been used on a simple truss structure and it was showed that it allows significant weight saving compared to conventional passive design. We extend the application of the methodology to a more complex 3D structure. It is confirmed that an optimum activation threshold exists that leads to design that minimises the total energy of the structure. Compared to an optimised passive design we show that the total energy saving is 10-fold.

Keywords: *adaptive structures, whole life energy, multi-objective optimization, actuators*

1. INTRODUCTION

Designing and building structures with minimal environmental impact is now a common concern in the construction sector. Conventional structural design practice usually involves ensuring that the strength and deformation of the structure meet the required limits to cope with the worst load cases. When the design is governed by loads whose magnitude varies very little (such as self-weight) then there is little scope for improvement. However the design is often governed by unpredictable events such as strong wind storms or earthquakes. Then the structure is effectively overdesigned for most of its working life.

In a previous paper (1) a simple pin-jointed truss was considered. Active load-bearing capacity was provided by actuators that replace some of the elements and whose controlled length change allows the pattern of internal forces to be modified, "load path management" (2). In so doing stresses can be minimized and homogenized while displacements are kept within desired limits. The design process consists in determining the cross-sectional areas of the passive elements as well as the optimal number and position of the actuators to minimise the total energy. This total energy includes the embodied energy of the material used in the structure as well as the operating energy necessary to operate the active elements.

This paper explores the potential of adaptive structures for a more complex class of 3D spatial structures and investigates to which extent and under which conditions the conclusions reached in the previous study hold.

1.1 Conceptual Framework

The objective of the design process is to find an optimum adaptive structure that minimises the total energy. This optimum will be situated between two extreme cases: at one end, the bulky passive design that has lots of embodied energy but requires no operating energy; at the other end, a highly adaptive structure with little embodied energy but high operating consumption. To investigate systematically the performance of intermediate structures between these two extremes, the load threshold at which the actuators start working is varied. This is illustrated diagrammatically in the conceptual graph shown fig.1. This graph shows the embodied energy (mass) increasing linearly as the structure is more and more passive and the operating energy (actuators work) expressed as function of a parameter which can be considered as a percentage of the maximum expected load. The minimum of the sum of the functions corresponds to a solution that is the optimum sought.
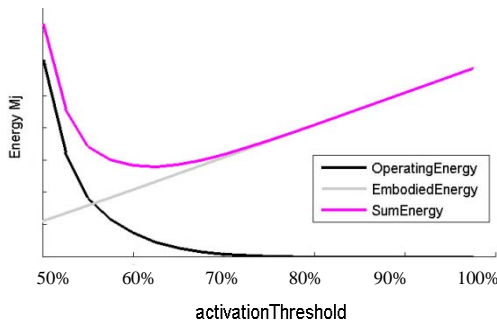

Figure 1. Embodied-Operating Energy

Fig. 2 shows the cumulative frequencies of occurrence for a generic stochastic load. The dotted line represents the activation threshold which traces the difference between two zones of the load-history.
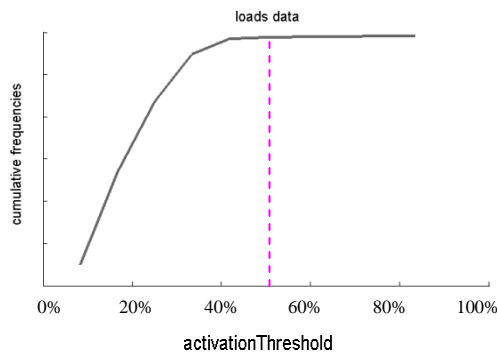

Figure 2. Load Activation Threshold

On the left there all loads and corresponding frequencies with which the active elements will not deal directly and that passive load-bearing capacity of the structure will be able to withstand. On the right there are the loads with higher magnitude but less probability of occurrence which the adaptive structure will be able to withstand using both passive and active (actuators length change) load-bearing capacity.

1.2 Case Study | The Setting

In this paper we explore the potential of adaptive structures for 3-D free-form truss structures in order to validate and test the range of applicability of the methodology presented in (1). Fig. 3 & 4 show a catenary dome whose shape is obtained using Day's dynamic relaxation algorithm (3) starting from a flat mesh and pin-constraining the four corner points.
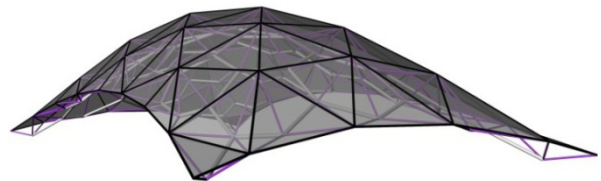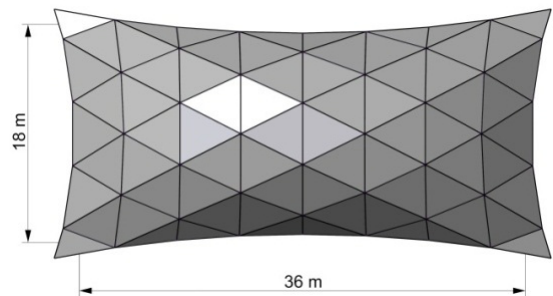

Figure 3. Catenary Dome, Perspective

Figure 4. Top View

The 3-dimensional truss (fig 5(a)) is composed by 3 layers:

- The triangulated pattern represented in fig 5 (a) which is the external cladding layer;
- The pattern in fig 5(b) formed by lines starting from the vertices of the triangles and meeting at specified height along the normal from their centers (the depth of the truss);

- The hexagonal pattern in fig 5(c) obtained by joining the points along the normal of the triangles in which the members of the 2nd layer meet;

The reason for having such truss topology (degree of indeterminacy=69) is for testing potential energy savings for indeterminate structures because of the bigger number of actuators required respect to determinate structures. The number of required active elements is equal to the indeterminacy of the system plus the number of desired controlled DOFs (2)
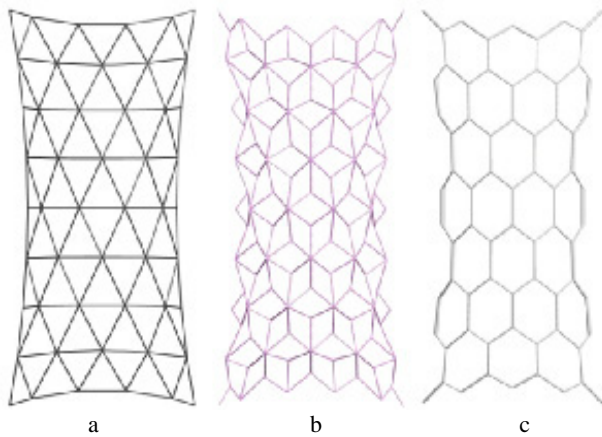

a   b   c

Figure 5. *Truss topology made by 3 overlapping layers*

1.3 Load Cases

As far as load cases go, wind is often the main cause of concern for this typology of structures and is taken here as example of time-varying load as done in (1). Wind velocities for prevailing wind directions (fig. 6) and with their frequencies (hours) of occurrence are retrieved from the weather file for London Heathrow station. Fig. 6 (right) represents the wind velocity landscape for the entire year where the x axis is weeks, y is hours within a day and the z axis is speed (km/h). The values of wind velocities are factored as indicated by the Euro Code 1 (4) considering a height above sea level of 10 m and probability of storm occurrence of 1 in 50 years. Pressure coefficients for each triangle pane are determined by the angle between wind direction and normal to the pane (4) such that:

$$F = \frac{vel^2}{2} \times \rho_{air} \times cpe \times Area \qquad (1)$$

where F is the force for each pane that is transferred to the nodes (fig. 7) and *Area* measures the planar extension of each pane. The max expected wind velocity generates the load distribution that the active and passive load bearing capacity of the structure will be designed to withstand.
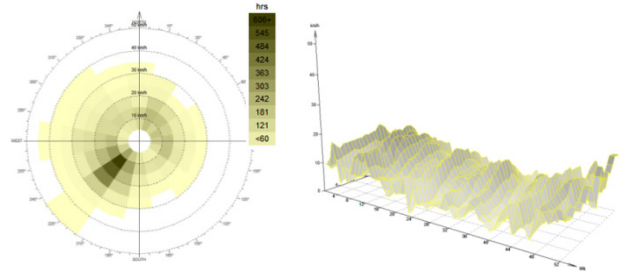

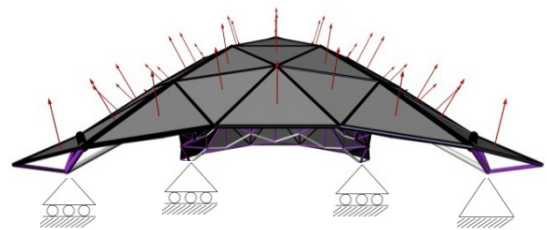**Figure 6.** *Wind Velocities and Frequency*

Figure 7. *Wind Forces*

2. DESIGN PROCESS

2.1 Linear Programming

Following Teuffel (2) the design process starts with finding the optimal distribution of section areas A_i and axial forces N_i that minimise the volume (mass) of the structure:

$$min \ V = \sum_{i=1}^{ne} A_i * l_i \qquad (2)$$

where V is the total volume, A_i the cross-sectional area of each element and l_i their length. This function is subjected to a set of equality (force equilibrium at node) and inequality (strength limit) constrains given by:

$$C \cdot N_k - P_k = 0 \qquad (3)$$

$$\frac{N_{ik}}{A_i} \leq \frac{\sigma_T}{\gamma}; \quad -\frac{N_{ik}}{A_i} \leq \frac{\sigma_C}{\gamma} \qquad (4)$$

where C is the matrix of cosines directions of the elements and constrained degree of freedom; N_k and N_{ik} are the vector of axial forces for each load case P_k, and the force in the i_{th} member respectively. Admissible stress limits in tension and compression

are σ_T and σ_C which can be factored with the parameter γ eq. (4). The optimization routine, called Linear Programming (5), does not take into account at this stage compatibility conditions. Fig. 8 & 9 show the optimal (yet non-compatible) distribution of axial forces and cross sectional areas for the structure taken into exam.
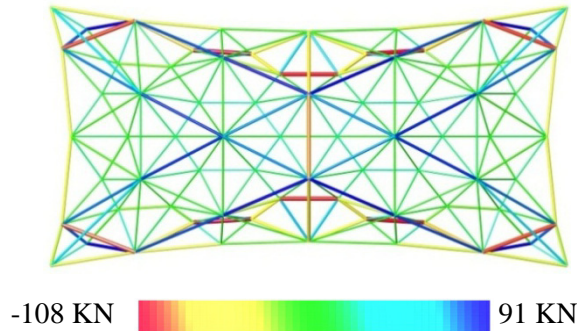

-108 KN 91 KN

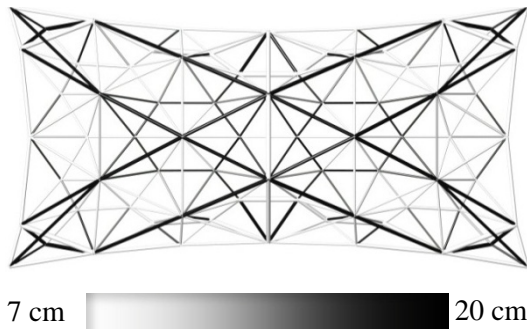*Figure 8. Optimal Force Distribution*

7 cm 20 cm

Figure 9.Optimal Section Radius

2.2 Controlled Displacements

Next step is to evaluate the so obtained configuration with an FEM analysis in order to determine compatible forces and displacements. Fig. 10 shows the difference (ΔN) between the "optimal Forces" (not compatible) and the compatible axial forces. Fig. 11 plots the deformed shape (max vertical deflection 15 cm) that this configuration would have using the optimal sections.

The design process involves the selection of nodes whose displacements will be kept within desired limits. For a consistent control of this structure, the vertical displacement of all the nodes of the top layer are selected as controlled DOFs and constrained at being at most 3.6 cm (span/1000). This gives a Δu between the compatible and desired displacements. The work (forces time length change) provided by the active elements will

compensate ΔN and Δu in order to satisfy both compatibility conditions and desired controlled displacements.

-24 KN 23 KN

Figure 10. ΔN

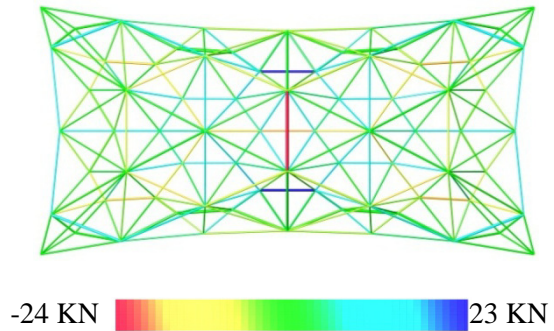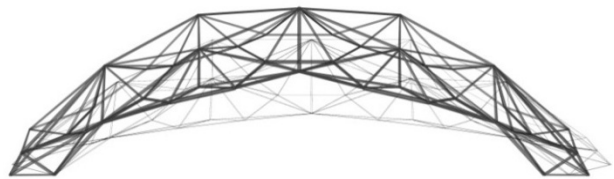*Figure 11. Compatible Displacements*

2.3 Sensitivity Analysis

The minimum number of actuators is, given as the indeterminacy of the system plus the number of controlled DOFs (6), is in this case 41+32=73. This is the minimum number of actuators to turn this hyper static structure into a controlled mechanism. The most efficient positions for the actuators are those where the active elements have the largest effect on both axial forces and controlled displacements. This problem can be formulated as a least square optimization routine starting with the computation of the sensitivity matrices S_U and S_N for displacements and axial forces. These matrices store the effect of a unit length change for each element on nodal displacements (S_U) and axial forces (S_N) of the other elements. Using the principle of virtual works, each element length is increased by one unit length and a FEM analysis derives the vectors ΔN_{ij} and ΔU_{ij}. These are the resulting axial forces in all the other elements and nodal displacements i caused by element j. Once the sensitivity matrices are computed it is possible to find the active elements length change ΔL that satisfies the desired controlled DOFs (Δu) eq.(5) and compatibility conditions eq.(6):

$$min\|S_U \cdot \Delta L_{all} - \Delta u\|^2 \qquad (5)$$

$$S_N \cdot \Delta L_{all} = \Delta N \qquad (6)$$

At this stage ΔL_{all} is obtained considering all elements being active. In order to derive the set of most efficient elements we compute the efficiency (7) of each member as:

$$e_{ik} = \frac{S_N \cdot \Delta \widetilde{L_{ik}}}{\Delta N_k} \quad (7)$$

$$E_i = \frac{\sum_{k=1}^{nLCases} \sum_{i=1}^{ne} e_{ik}}{\sum_{i=1}^{ne} \sum_{k=1}^{nLCases} \sum_{i=1}^{ne} e_{ik}} \quad (8)$$

where $\Delta \widetilde{L_{ik}}$ is the vector composed of the length change of element i for the load case k having all the others components set to 0. The global efficiency E_i of each member is obtained with eq. (8) Fig. 12 & 13 show the position of the most efficient actuators for the truss structure taken into exam.
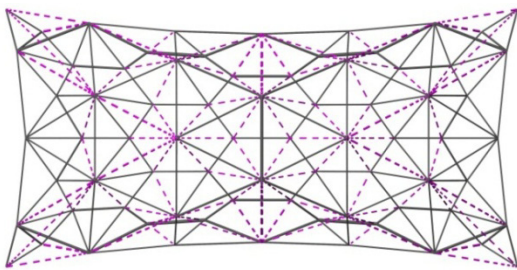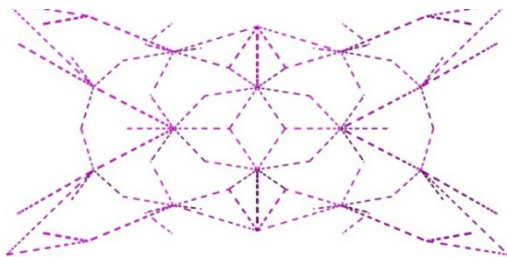

Figure 12. *Most Efficient Actuators Pattern*

Figure 13. *Active Elements Isolated from the Structure*

2.4 Adaptive Structure

After finding the actuators position, it is possible to compute the length change on only the most efficient actuators that satisfy controlled DOFs eq.(10) and compatibility conditions eq.(11):

$$min\|S_{Ured} \cdot \Delta L - \Delta u\|^2 \quad (9)$$

$$S_{Nred} \cdot \Delta L = \Delta N \quad (10)$$

where S_{Nred} and S_{Ured} are reduced by taking only the

columns corresponding to chosen active elements. Finally, a FEM analysis in performed on the structure imposing these length changes (ΔL_i for each actuator using principle of virtual works) verifying that the displacements of the controlled DOFs are within the desired limits. Fig. 14 shows the final deformed shape with actuators in deployed state.
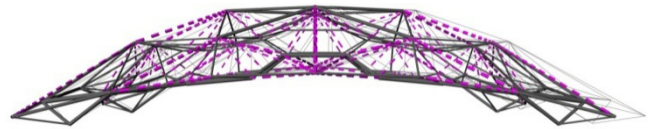

Figure 14. *Deformed Shape with Actuators in Deployed*

Comparison between the adaptive solution and a passive optimised structure obtained using FUD (Fully Utilised Design) (8) reveals significant weight savings (fig. 13&14). The mass of the former is 10 times lower than that of the latter. Fig 15&16 plot the stresses for adaptive and passive configuration respectively. In the adaptive configuration material is used much more efficiently.
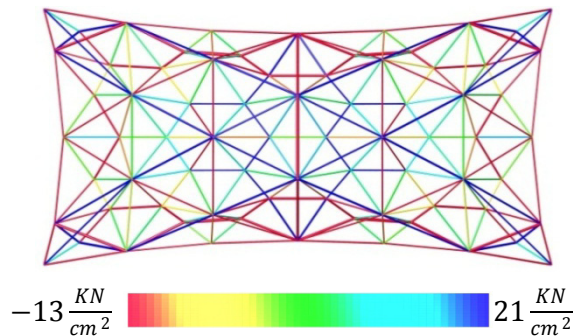

$$-13 \frac{KN}{cm^2} \qquad 21 \frac{KN}{cm^2}$$

Figure 15. *Stresses and Sections Adaptive Structure*

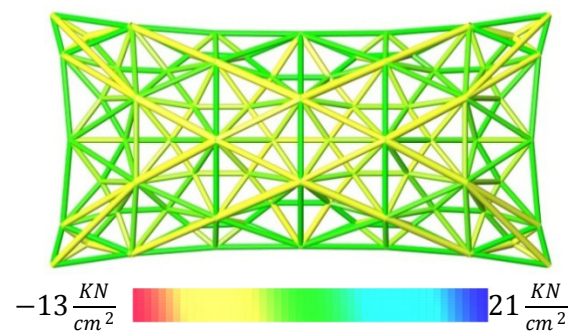$$-13 \frac{KN}{cm^2} \qquad 21 \frac{KN}{cm^2}$$

Figure 16. *Stresses and Sections, Passive Structure*

3. COUPLED OPTIMIZATION EMBODIED-OPERATING ENERGY

3.1 Energy Assessment

Initial assumptions about the operating frequency of the actuators and the time of occurrence of the load cases (i.e. wind velocity) have to be made for computing the operating energy of the system. It is sensible to assume that a transient load such as wind is able to excite structures up to 5 Hz at worst (high velocity and vortex shedding). The work done by an active element in order to satisfy compatibility conditions and desired control displacements can be formulated as:

$$W_{ik} = \frac{N_{ik} * \Delta L_{ik} * freq. * time_k}{actuatorEfficiency} \qquad (11)$$

In eq. (11) it is assumed that an actuator exerts a force N_{ik} and performs a length change ΔL_{ik} with a frequency being kept constant for all the time of occurrence $time_k$ of each load case P_k (hours of occurrence of wind velocities). Working frequency and working efficiency of the actuators are set as 2.5 Hz and 50% respectively as preliminary conservative assumptions. In addition, wind velocities and frequencies are assumed to stay the same as those retrieved from the weather file for the entire life-cycle of the structure (here taken as 50 years).

In order to take into account the minimization of the operating energy, the design process described above step (2.0 to 2.4) is repeated iteratively within an outer loop. The main variable of the outer loop is the parameter γ that is used to derive the maximum allowable stress utilised in the inequality constraints eq. (4). By varying this factor, it is possible to obtain least-weight structures with large operating energy (γ=1) to structures with bigger sections and smaller operating energy consumption (γ higher). For each γ it is possible to obtain a corresponding value for the activation threshold that is the load above which the actuators must be activated to satisfy imposed displacement constraints.

The design process can be subdivided in the following steps:

- Define a range of γ;
- For each $γ_i$ repeat steps 2.0 to 2.4 (sections, actuators position and their length change);
- Analyse (FEM) each solution without active elements as many times as there are load cases in order to find the threshold (activation threshold) below which the structure works adequately (ULS, SLS and controlled DOF displacements respected) even without actuation;

- Compute the operating energy eq. (11) and the embodied energy for each $γ_i$. The embodied energy is computed using conversion coefficient for the energy intensity of steel in form of bar-rod taken from the Inventory of carbon and energy - Bath University (9);

- Find the $γ_{optimal}$, minimum of the function given by the sum of embodied and operating energy (fig. 17), and repeat optimization (steps 2.0 to 2.4) to obtain the optimal configuration and corresponding activation threshold (fig 19);

Fig 18 shows the comparison between the embodied energy of an optimised passive structure with identical topology (using FUD (8)) and the sum of embodied and operating energy for the equivalent adaptive structure configuration. The balance is 5-fold in favor of the adaptive structure.
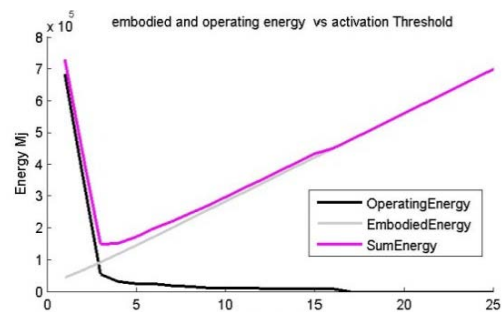

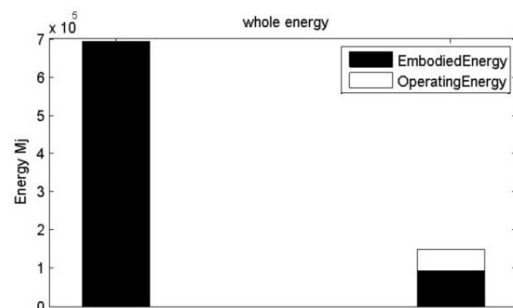***Figure 17.*** *Embodied-Operational Energy vs γ*

Figure 18. *Passive/Adaptive total energy (50 years)*

Fig. 20 shows the actuators position for the optimal configuration and fig. 23 the rendered view of the structure. Note that the size of the sections is larger

(bigger γ) respect to those shown in fig. 9) since here the optimization process takes into account both embodied and operating energy.
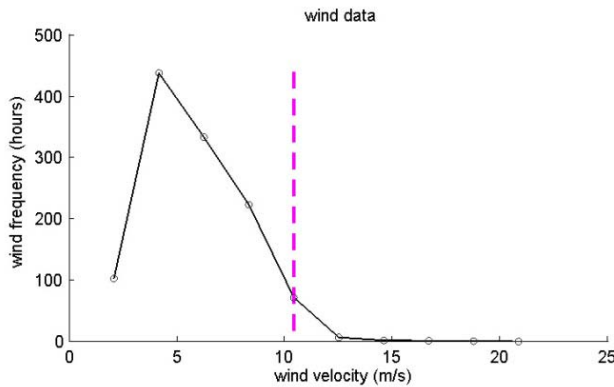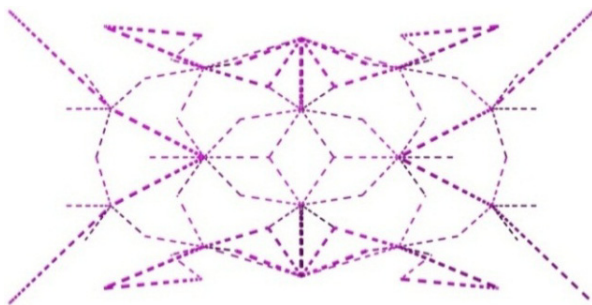

Figure 19. *Activation Threshold Optimal*

Figure 20. *Actuators Position Optimal*

3.2 Comparison with previous case study

Comparison with a 2-dimensional truss structure of similar span subjected to the same time-varying load (1) shows that total energy savings have been further increased. Fig. 20 plots the embodied-operating energy function of the 2-dimensional truss. In this case the weight of the operating energy is substantially lower than that for the 3-D case. For this reason, the activation threshold is found to be lower since the 2-D structure relies more on its passive load-bearing capacity.

The main reason for such outcome is that in the 3D truss structure it is much more difficult to keep deflections within desired limits so that the actuators need to come in more often and for lower value of the imposed load. However, since the design process is based on the coupled optimization of both embodied and operating energy a new trade-off can be found that minimise both (fig 17).   A comparison (fig. 21) of the total energy for the adaptive structures (2D-3D) with their corresponding passive optimized version (FUD)

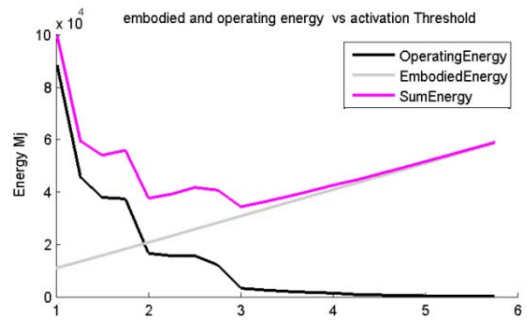show that total energy savings are doubled for the 3d truss structure.

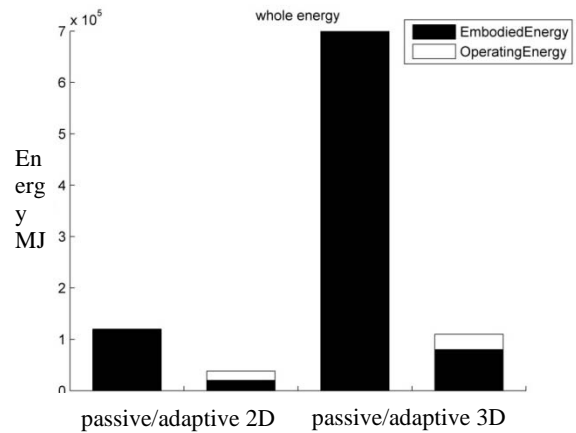

Figure21. *Embodied-Operational 2D case*

Figure 22. *Comparison Total Energy 2D-3D case*

CONCLUSIONS

This paper explores the potential of adaptive structures to save whole life energy. Whole life energy savings can be achieved by using actuation to cope with large but rarely occurring loads. The methodology proposed allows a fairly complex 3D truss dome structure to be optimized (1) first to place actuators in the most efficient location within the structure (2) to minimise the size of the remaining passive members and (3) to determine the optimal activation threshold above which the structure becomes active. This study confirms that such optimum activation threshold exists. For such an optimally designed active structure, it is shown that the whole life energy saving are 5 fold compared to an optimised but completely passive structure of the same geometry. Comparison with the results from the previous study suggests that the conclusions reached on a simple design are confirmed and strengthened for a more complex structure.

239

Figure 23. *Perspective, Rendered view*

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