September 25th - 28th, 2017
INTERFACES
architecture . engineering . science IASS 2017 hamburg

Proceedings of the IASS Annual Symposium 2017
"Interfaces: architecture.engineering.science"
25 - 28th September, 2017, Hamburg, Germany
Annette Bögle, Manfred Grohmann (eds.)

The Use of Variable Stiffness Joints in Adaptive Structures

Gennaro SENATORE[*a], Qinyu WANG[b], Henriette BIER[c], Patrick TEUFFEL[b]

[a]Applied Computing and Mechanics Laboratory (IMAC), School of Architecture, Civil and Environmental Engineering (ENAC), Swiss Federal Institute of Technology (EPFL), CH-1015 Lausanne, Switzerland
[*]gennaro.senatore@epfl.ch
[b]Chair of Innovative Structural Design (ISD) TU/e
[c]Department of Architectural Engineering + Technology, TU Delft

Abstract

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. This paper investigates the use of variable stiffness joints in adaptive structures to achieve large shape changes. Large shape changes are employed as a structural adaptation strategy to counteract the effect of the external load. The structure is designed to 'morph' into optimal shapes as the load changes. This way the stress can be homogenized avoiding peak demands that occur rarely. Numerical results show that when large shape changes are considered, material mass (and thus embodied energy) reduction is achieved with respect to both adaptive structures limited to small shape changes and optimised passive structures. Embodied energy savings become substantive when shape changes are allowed to go beyond conventional deflection limits.

However, large shape changes require significant flexibility of the joints because their fixity can affect load-path and shape control. To address this problem, a variable stiffness joint is proposed. During shape/load-path control, the joint reduces its stiffness so that required deformation patterns can be achieved with low actuation energy. After shape control the joint recovers rigidity. Experimental studies are presented to show the potential for application of joints with variable stiffness in adaptive structures.

Keywords: Adaptive structures, variable-stiffness joints, shape morphing, smart materials, actuation, structural optimisation

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) Soong et al [1, 2]. Active structural control has also been used in applications for shape control. Active tensegrity structures, structures whose stability depends on self-stress, have been used as deployable systems in aerospace (Tibert [3]) and civil engineering (Fest et al, Adam et al [4, 5]). Active compliant structures, which can be thought of as structures working as monolithic mechanisms (Hasse and Campanile [6]) have been studied for deployment of antenna reflectors and shape control of aircraft wings to improve manoeuvrability (Jenkins [7]).

The potential for using adaptation to save material has been investigated by some (Sobek et al, Teuffel, Khot, Lemaitre, Soong and Cimellaro [8, 9, 10, 11, 12]). An optimum design methodology for adaptive structures was presented in Senatore et al. [13]. 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. In Senatore et al. [14, 15] it was shown that adaptive structures designed with this method achieve energy savings as high as 70% when compared to identical optimised passive structures. The examples under consideration ranged from planar portal frames and catenary arch bridges to spatial trusses including double curved shells and exoskeleton structures. These studies confirm that adaptive structures achieve superior performance when the design is stiffness governed. For slender structures the adaptive solution outperforms the passive one not only for extreme but also for ordinary loading events and becomes competitive also in monetary terms.

This paper investigates the use of large shape changes achieved via actuation as a structural adaptation strategy to counteract the effect of external loads. An adaptive truss arch structure is presented as a case study. Large shape changes can be employed so that the structure 'morphs' into optimal shapes as the load changes. This way the load-path can be homogenized further resulting in embodied energy (i.e. material) savings compared to adaptive structures limited to small shape changes. Note that in this context, shape adaptation is achieved without relying on mechanisms having defined kinematics (e.g. pantograph mechanism). This is because the use of mechanisms based on moving parts often results in significant weight penalty due to the weight of the joints and increased complexity (Campanile [15]). The active system is integrated by replacing strategically some of the structural elements with actuators (e.g. linear motors). Controlled length changes of the actuators are used to obtain desired deformation patterns (i.e. optimal shapes).

Later the focus moves to experimental studies showing the potential for application of joints with variable stiffness in adaptive structures. Large shape changes require significant flexibility of the joints. In fact, the fixity of the joints can affect substantially load-path and shape control (Senatore [13]). To address this problem, a variable stiffness joint is proposed. During shape/load-path control, the joint reduces its stiffness so that required deformation patterns can be achieved with lower actuation energy and higher accuracy. After shape control the joint recovers rigidity.

2. Case study

The structure considered in this case study is made of planar trusses which could represent sections of a truss arch roof. Figure 1 shows one of the trusses – a 20-m span and 5 m tall arch constrained by pins as indicated in the diagram. All structural elements are assumed to be made of structural steel (S355). The energy analysis is carried out using a material energy intensity factor of 35 MJ/kg to convert the material mass of steel in the form of rods (no recycled content) into embodied energy taken from the *Inventory of Carbon and Energy (ICE)* [17].

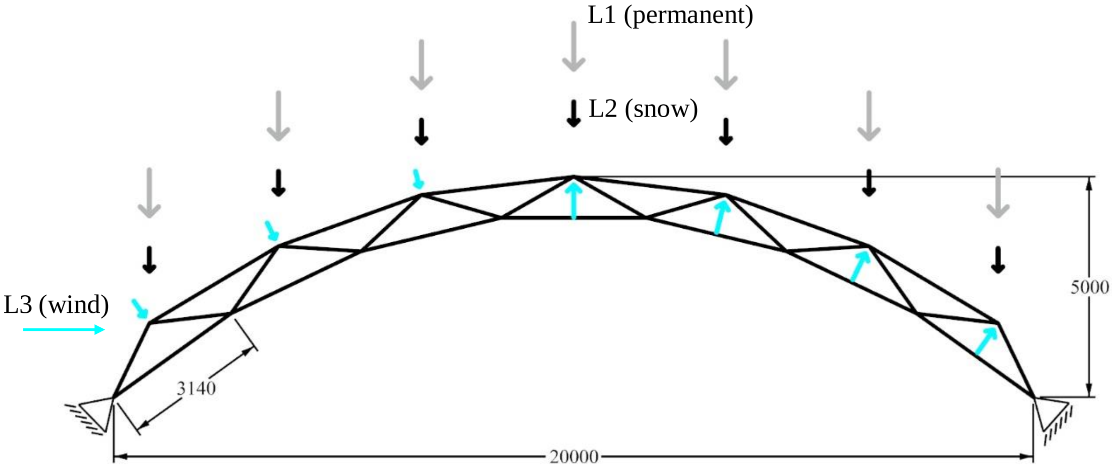


Figure 1: base layout and loads (L4 symmetrical to L3)

The dead load is set to 3 kN/m^2 on the roof panel, each truss bay supports a 5 m long (out of plane) and 20 m wide area resulting in a Uniformly Distributed Load (UDL) of 15 kN/m. Four load cases are considered: one is self-weight + dead load (L1); a vertical uniformly distributed load representing a snow-type load (L2); the other two cases are uniformly distributed loads in opposite direction representing a wind-type load (L3, L4). The live load maximum intensity is set to 1.5 kN/m^2 (live-to-the-dead-load ratio of 0.5) which is equivalent to wind maximum velocity of 50 m/s (category 2/3 hurricane). Wind or snow pressure is applied on the roof panes and tributary loads derived at the nodes as shown by the green arrows (L3) in Figure 1. Pressure coefficients for each pane are determined by the angle between wind direction and face normal as described in Eurocode 1 [18]. Four different load combinations are considered:

Table 1: catenary arch bridge – load combination cases

	Load factor	Permanent load	Load factor	Live load
LC1	1.35	L1 = dead load + self	1.5	n/a
LC2 to **LC4**	1.35	L1 = dead load + self	1.5	L2 to L4 =1.5 kN/m^2

3. Adaptive Structures Design Process

The problem formulation, based on previous work by Senatore [13] is part of on-going research at the Applied Mechanics and Computing laboratory (IMAC, EPFL). The reader is referred to (Reksowardojo et al [19]) for more details. The design process consists of two main phases:

1. Size, load-path and shape are optimised to minimise the structure embodied energy. This first phase can be thought of as a mapping between external load and shape/load path which are optimised to maximise material utilisation for each load case.
2. A suitable actuator deployment strategy (i.e. minimum actuator length changes) is searched to enforce optimal load path and shape for each load case.

The structures under consideration are pin-jointed, some of their members are able to change length thus behaving as actuators. Problem variables are section areas, internal forces (i.e. load-paths), shape changes and actuator length changes for each load case. The optimisation is subject to equilibrium constraints and ultimate limit state including member buckling. The outcome is an optimal cross section area distribution as well as an optimal shape and corresponding load path for each load case.

3.1. Size, Load-Path and Shape Optimisation

Figure 2 shows the optimal cross section area distribution and the optimal shapes obtained using the design process outlined in section 3. Note that both element diameters and node positions are represented to scale 1:150. Regarding the optimal shapes, the structure reduces the depth from end to mid span under permanent load (figure 2 a) while under LC1 (permanent + snow) the depth increases slightly from the ends to mid span (figure 2 b). Under LC3 (permanent + wind) the change of depth becomes prominent on the windward side of the structure reducing on the downwind side as shown in figure 2 (c). The optimal shape for LC4 mirrors that under LC3.

To benchmark the adaptive solution in terms of embodied energy, it is compared with an adaptive structure designed using size and load-path optimisation without considering shape changes and a passive structure designed using an optimisation routine that outperforms the Modified Fully Utilised Design Method (Patnaik et al [20]). Both these methods are given in Senatore et al [13, 14]. The adaptive structure limited to small shape changes achieves energy savings of 5% with respect to the passive one. Employing large shape changes results in 8% energy savings when adaptation is limited within deflection limits of span/500 and 21% when the shape change bounds are extended to ±200 mm. Note that the energy assessment is carried out without taking into account the weight of the actuators.

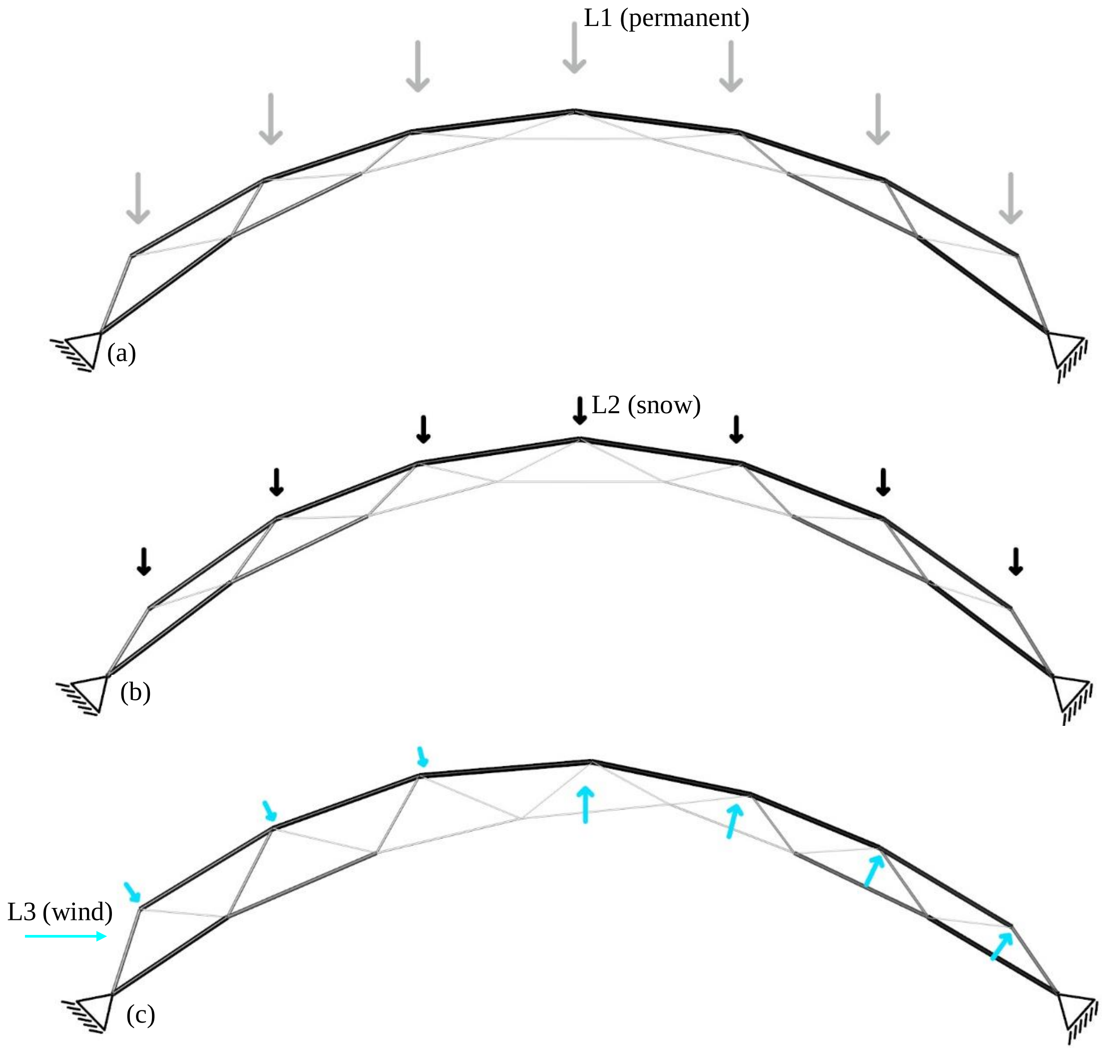


Figure 2: optimal shapes S1, S2, S3 (symmetrical to S4). Scale 1:160.

3.2. Shape and Load Path Control

The shape obtained for LC1 is selected as the base shape, i.e. the structure is assumed to be built using shape S1. This is because S1 shape (and corresponding load-path) is optimal under permanent load. When the live loads hit the structure, the actuation system must provide corrective actions in the form of length changes to match the corresponding optimal shape as close as possible. This step requires an

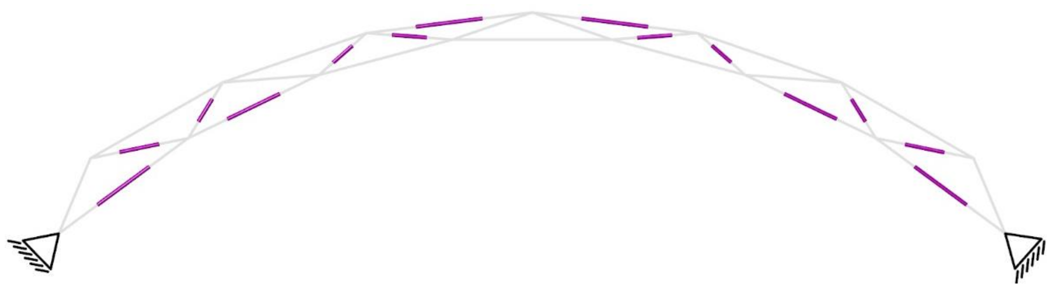


Figure 3: optimal shape S1 and actuator layout (actuator represented in purple)

actuator layout (i.e. position of the actuators) to be known. Because the problem formulation considers geometric-non linearity, a search must be carried out to find the most effective actuator layout that minimises the structure whole-life energy (embodied in the material and operational for structural adaptation). However, in this study, the actuator layout is predetermined by choosing 14 elements whose positions are indicated in Figure 3.

The problem is formulated as a minimization of the error norm between optimal shapes and shapes achieved via actuation using sequential quadratic programming. The actuator length changes are the problem variables. Dynamic relaxation (Day, Barnes, Senatore and Piker [21, 22, 23]) is employed to simulate the actuator length changes. Figure 4 shows the shapes and load-paths mapped onto the truss geometry achieved after actuator deployment. The shapes achieved via actuation are not identical to the optimal shapes (shown greyed out in the background) nor the load paths are to the optimal ones. Note that during shape optimisation all nodes but the supports were allowed to change position. A closer match towards optimal shapes and load-paths would be possible if all elements were able to change length or if a lower number of nodes were selected to change position during shape optimisation. In addition, a more efficient actuator layout found via search methods would deliver a closer shape/load path match. Having said that, both shapes and load path obtained using the predetermined actuator layout shown in figure 3 are close to the optimal ones and ULS is respected for all load cases.

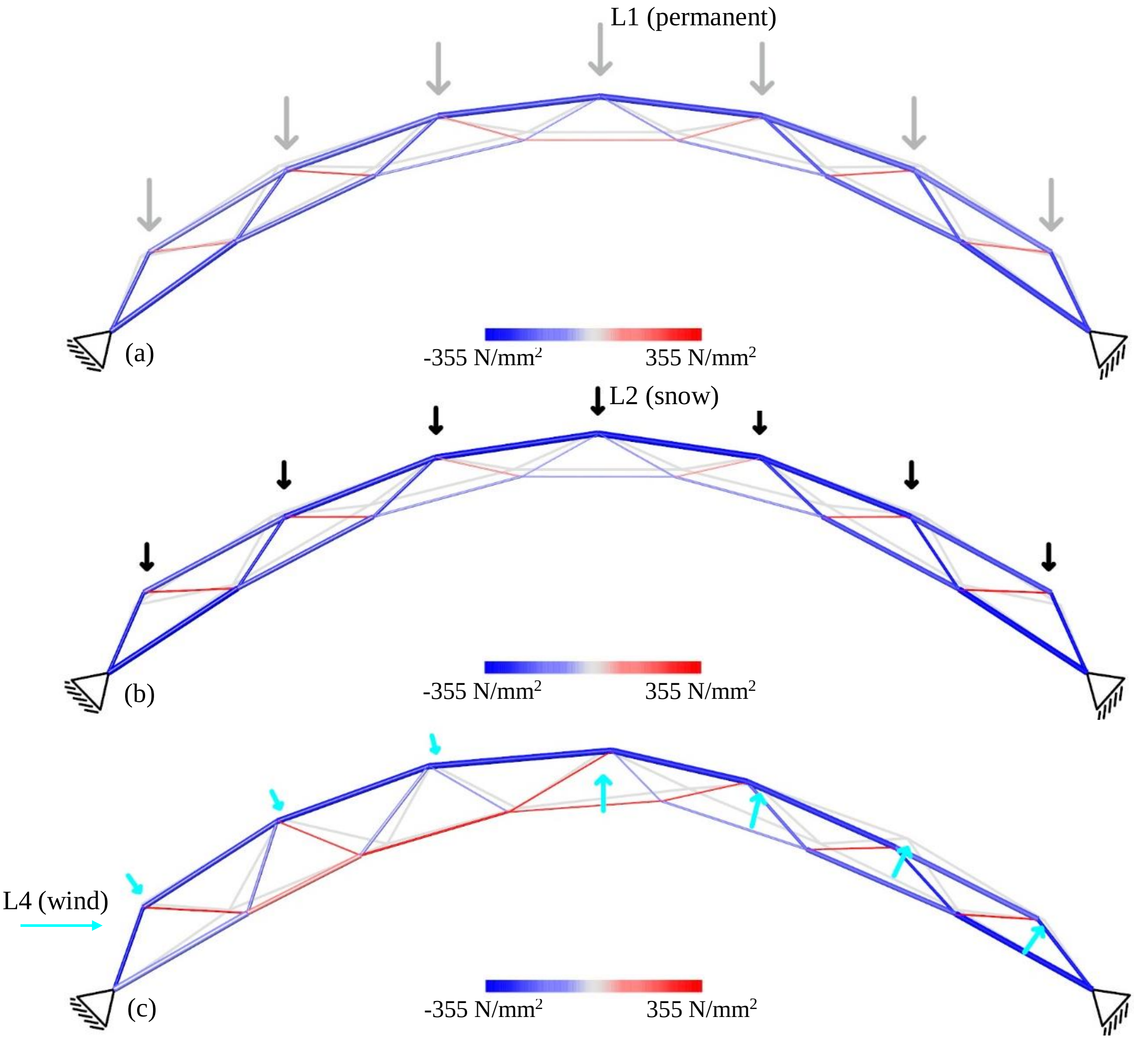


Figure 4: shapes achieved after actuator deployment and element stress

4. Variable Stiffness Joint

4.1. Joint States

A joint with variable stiffness is proposed to have at least two states: a 'locked' and a 'released' state. In a lock state the joint retains its fixity transferring moments between the elements that connect to it. In a 'released' state, the joint soften thus allowing connecting elements some degree of movement. The joints should change state when a shape change is required with the aim to minimise actuation energy and ease shape and load-path control accuracy.

4.2. Material selection

A recent survey of materials with enhanced transduction properties (i.e. so called 'smart materials') is given in Bogue [24]. Amongst those commercially available, shape memory alloys (SMAs) and shape memory polymers found application in aerospace engineering primarily for shape control of aircraft wings, Barbarino *et al.* [25]. Experimental work by Markopoulou [26] test shape memory polymer (SMP) for shape control of a small-scale frame structure arranged in triangular modules based on an origami pattern. The SMP joints are laser-cut and placed at the intersection between adjacent modules. A heat source triggers the phase change in the joints which soften thus allowing the structure to be easily deformed via external actuation.

A review of SMP mechanical properties was made by Meng and Hu [27]. SMPs can strain up to 400% featuring a large variation of stiffness between a glassy and a rubbery state which makes them potential candidates for application in shape control of adaptive structures. Above the transition temperature (Tg) the elastic modulus is 3 orders of magnitude lower than that of the glassy state. The SMP chosen in this experimental study is called MM-5520, its Mechanical properties are reported in Table 2. The transition temperature Tg is 55°C, the glass phase is at Tg -20°C while the rubber phase is at Tg +20°C.

Table 2: Shape memory polymer MM-5520 mechanical property

	Hardness (H_DD)	100% modulus (MPa)	Tensile strength (MPa)	Elongation (%)	Bending modulus (MPa)	Bending strength (MPa)	Special gravity	Tg (°C)
Glass	77	-	48	30-50	2150	80	1.25	55
Rubber	27	2.1	13	>600	-	-	1.25	55

4.3. Experimental test

A 1:6 scaled joint prototype with respect to the joint dimensions in the 20-m span arch truss described in section 2 was fabricated via fused deposition modelling. SMP filaments were used as raw material. The joints are designed so that the axis of connecting elements (tubular) meet in the common intersection point which is indicated by a cyan dot in figure 6. The element cross sections intersect pair-wise on each side at a certain distance from this point. The geometry shown is in figure 6 is obtained by building a 4-way insert holding the tubular elements to avoid intersections. The edges of the 4-way insert are curved to connect the elements using minimum volume. Four 12 mm diameter rods (light grey) are extruded from the central part of the joint (dark grey) to couple with 15 mm diameter tubular elements. A 5-mm diameter hole is made in each rod to secure the elements via a pin.

Resistive heating is used as SMP activation method. A pattern made of 2-mm diameter through holes was drilled to allow a 1-mm diameter steel wire (represented by a purple curve in figure 6) to pass through which works as a resistive heater. This pattern performed comparatively well against other patterns attempted because it allows the heating wire to go through the depth of the joint as well as its width.

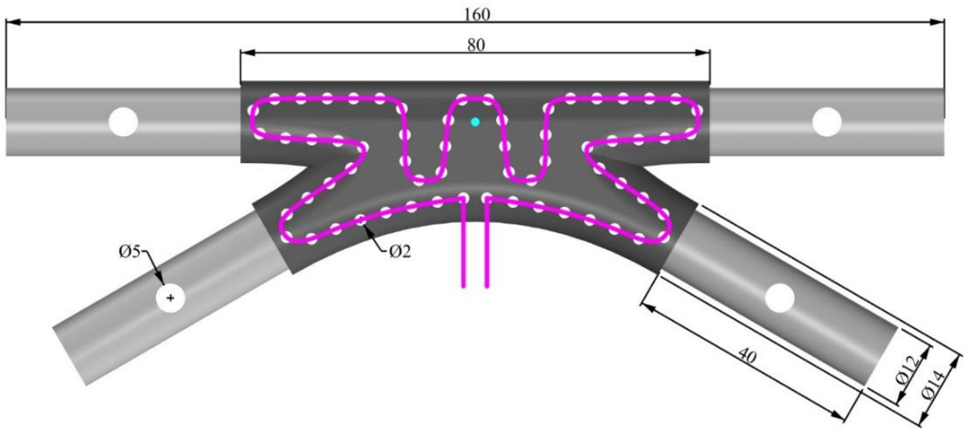


Figure 6: 4-bar SMP joint. Scale1:1.3

Figure 5 (a) shows the joint configuration before heating. A 30W (30V, 1A) power supply was utilised to heat the steel wire. A temperature sensor (thermocouple) was used to monitor the joint surface temperature. It was possible to easily deform the joint into the configuration shown in figure 5 (b) after 35 seconds when the internal temperature reached approximately the transition value (55°C) and the surface temperature was recorded at 35°C. Figure 8 shows two snapshots of the heating phase taken with a thermographic camera – (a) the temperature starts to diffuse from the heating wire to the body, (b) after 35 seconds heat propagates though the whole depth of the body. After cooling, the joint remains in the configuration shown in figure 5 (b) without clamps or applied forces holding it.

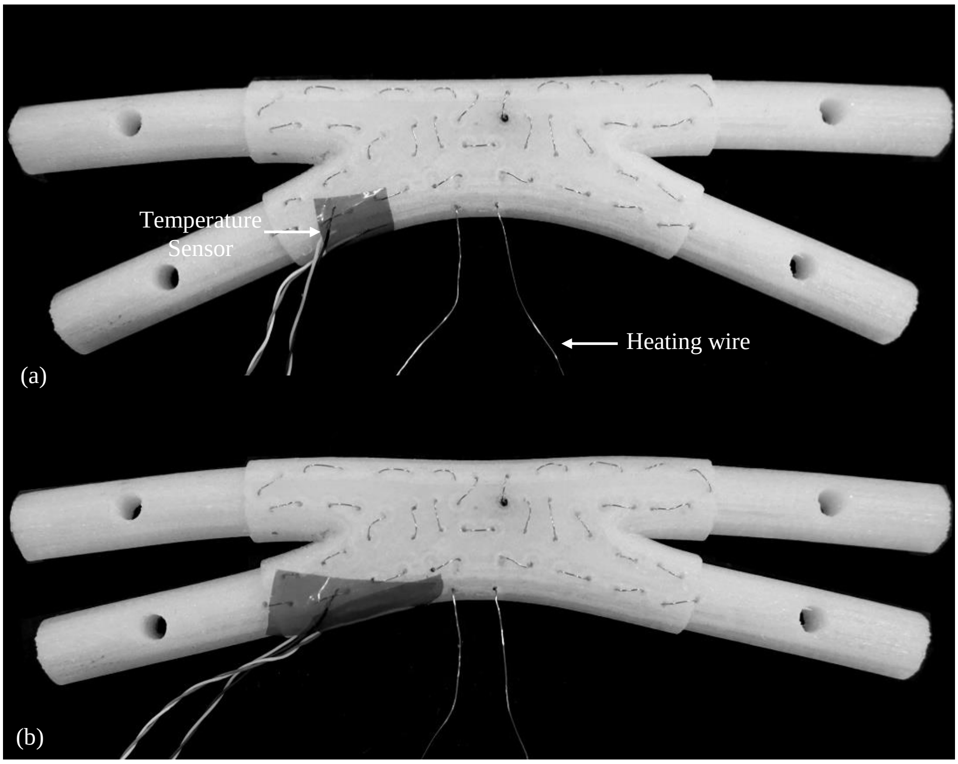
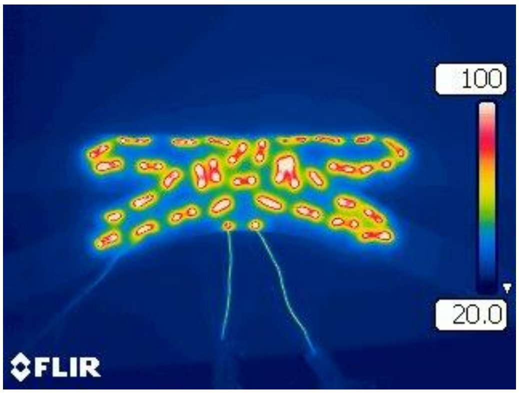


Figure 5: (a) joint shape before heating; (b) joint deformed at surface temperature of 35°C

Because during fabrication via fused deposition the SMP is melted before being extruded, it is effectively trained to “remember” the printed shape. As expected, it was observed that when heated again the joint recovers the undeformed shape (figure 5 a) from the deformed configuration shown in figure 5 (b). No test was made to quantify the magnitude of forces that could work against shape recovery at this stage.

(a) 

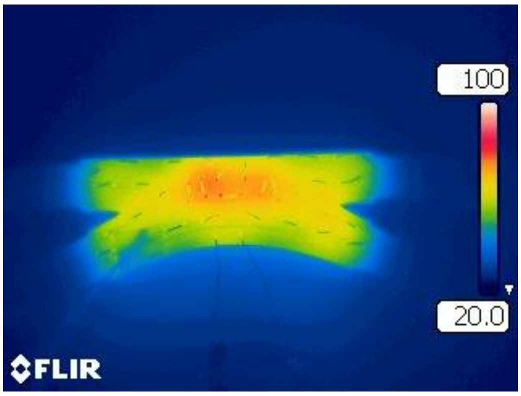
(b) 

Figure 8: SMP joint temperature gradient during heating (a) after 5 seconds, (b) after 30 seconds

A 1:25 scaled version of the case study model was fabricated via additive manufacturing. The truss elements are made of polyactic acid (PLA) and the joints are made of SMP. Both elements and joint were printed using fused deposition modelling. The truss elements change length via a telescopic mechanism and connect to the joints as described previously. A heat gun blowing air at 200°C was used as activation method. The joints soften substantially after 10 seconds allowing the structure to be deformed significantly. Figure 7 shows the truss deformed into a similar shape to S3, the optimal shape under load case L3 (see also figure 2). As observed for the 1:6 joint test model, after cooling the truss preserves the new shape because the joints gain rigidity turning back into full glassy state.

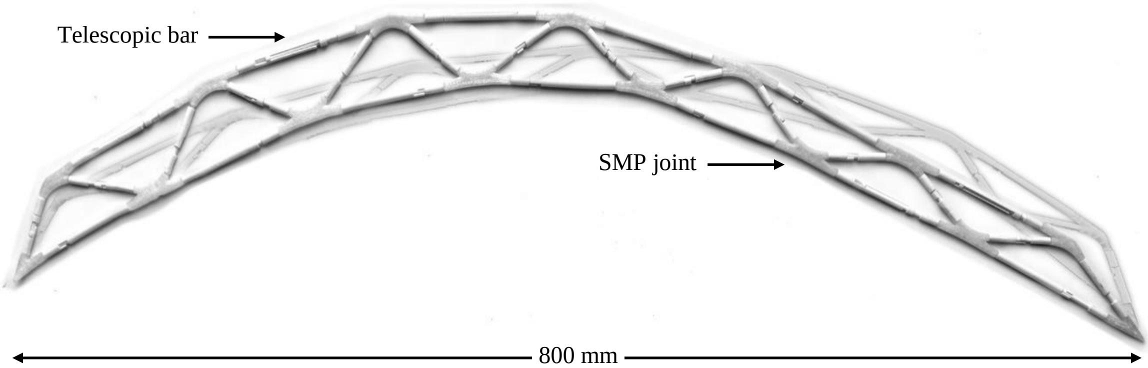


Figure 7: deformed shape (S3) achieved after SMP joints phase change vs undeformed shape. Model 1:25

5. Discussion

This paper presents an application of a new design method whereby structures are designed to perform large shape changes to counteract the effect of the external load. Because the structure is allowed to change shape as the load changes, the stress is homogenised and thus the design is not governed by peak demands that occur very rarely.

Simulation studies presented in this paper show that large change shapes improve further in terms of embodied energy savings with respect to adaptive structures limited to small shape changes. Senatore [13] showed that for geometries already optimised under permanent load (e.g. catenary arches or double curved shells), the energy savings achieved by adaptive structures limited to small shape changes are lower compared to stiffness governed structures (e.g. a slender cantilever) where it is much more challenging to limit deflections by adding more material. Although the configuration taken under consideration is a catenary truss arch, the embodied energy savings achieved using large shape changes are substantive reaching 20% with respect to an optimised passive structure. Savings are the greatest when deformation is not limited by conventional serviceability limits. However, the energy assessment is carried out without taking into account the weight of the actuators because it depends on the type of technology employed for the actuation system. This will be subject of future investigation.

The use of large shape changes poses challenges for the joint design. The joint should reduce its stiffness during shape change to minimise actuation work and increase control accuracy. Experimental tests presented in this paper show that drastic stiffness variation was achieved on a 1:6 scaled joint prototype within 35 seconds using a low range power supply. This time range is adequate for shape changes under quasi static loading. Improving heat transmission by increasing surface contact with the heat source as well as using a higher range power supply should reduce the heating phase duration substantially. In addition, SMP could be synthesised to have a lower transition phase temperature so that stiffness reduction could be achieved using less power.

6. Conclusions

The employment of large shape changes to counteract the effect of the external load have potential for significant reduction of embodied energy in structures. Further work will determine whether the whole-life energy which is made of an embodied part in the material plus an operational part for structural adaptation can be reduced. In addition, more complex geometries including spatial layouts will be subject of future investigation.

The use of variable stiffness joints in adaptive structures has the potential to reduce actuation work and improve control accuracy during large shape changes. Experimental tests show that stiffness variation to deal with quasi-static load is feasible. However, because SMP in the glassy state have mechanical properties that might not be adequate in terms load bearing capacity, a blend of stronger and stiffer material (e.g. carbon fibre reinforced plastic) and SMP is envisaged where the latter is strategically distributed within the former to achieve required stiffness variations. Further prototyping together with load testing will be part of future research agenda.

7. Acknowledgements

The authors gratefully acknowledge 4TU.Bouw Lighthouse Project Programme 2017 and the Applied Computing and Mechanics Laboratory (IMAC) at Swiss Federal Institute of Technology (EPFL) for providing core funding.

References

[1] T. Soong and J. Chang, “Active vibration control of large flexible structures,” *Shock Vib. Bull.*, vol. 52, pp. 47-54, 1982.

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

[3] G. Tibert, “Deployable Tensegrity Structures for Space Applications,” (Doctoral dissertation), Royal Institute of Technology, Stockholm, 2002.

[4] E. Fest, K. Shea, B. Domer and F. Smith, “Adjustable Tensegrity Structures,” *Journal of Structural Engineering*, vol. 129, pp. 515-526, 2003.

[5] B. Adam and I. F. Smith, “Active tensegrity: A control framework for an adaptive civil-engineering structure,” *Computers & Structures*, vol. 86, no. 23-24, pp. 2215-2223, 2008.

[6] A. Hasse and F. Campanile, “Design of compliant mechanisms with selective compliance,” *Smart Materials and Structures*, vol. 18, no. 11, 2009.

[7] C. Jenkins, Compliant Structures in Nature and Engineering, 1st ed., WIT Press, 2005.

[8] W. Sobek, P. Teuffel and A. Landauer, "Stuttgarter Träger," Institute for Lightweight Structures (ILEK), University of Stuttgart, Stuttgart, 2002.

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

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

[11] C. Lemaitre, "Topology Optimized Adaptive Truss Structures," in *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium* , Valencia, 2009.

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

[13] G. Senatore, "Adaptive Building Structures," (Doctoral Dissertation) University College London, London, 2016.

[14] 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.

[15] L. Campanile, "Using compliant and active materials to adapt structural geometry - challenges and good reasons," in *14th International Conference on Adaptive Structures and,* Seoul, 2003.

[16] G. Senatore, P. Duffour, P. Winslow and C. Wise, "Infinite Stiffness Structures via Active Control in Proceedings of the International Association for Shell and Spatial Structures (IASS) Future Visions," in *Proceedings of the International Association for Shell and Spatial Structures (IASS) Future Visions*, Amsterdam, 2015.

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

[18] T. C. CEN/TC250, "Eurocode 1: Actions on structures — General actions — Part 1-4: Wind," 1991.

[19] A. P. Reksowardojo, G. Senatore and I. F. Smith, "Large and Reversible shape changes as a strategy for structural adaptation," in *International Associtaion for Shell and Spatial Structures*, Hamburg, 2017.

[20] 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.

[21] A. Day, "An Introduction to Dynamic Relaxation," *The Engineer,* pp. 220-221, 1965.

[22] M. R. Barnes, "Form finding and analysis of tension space structures by dynamic relaxation," (Doctoral dissertation), City University, London, 1977.

[23] G. Senatore and D. Piker, "Interactive real-time physics: an intuitive approach to form-finding and structural analysis for design and education," *Computer-Aided Design,* vol. 61, pp. 32-41, 2015.

[24] R. Bogue, "Smart materials: a review of recent developments," *Assembly Automation,* vol. 32, no. 1, 2012.

[25] S. Barbarino, E. I. Saavedra Flores, R. M. Ajaj, L. Dayyani and M. I. Friswell, "A review on shape memory alloys with applications to ,orphing aircraft," *Smart Materials and Structures,* vol. 23, no. 6, 2014.

[26] A. Markopoulou, "Design Behaviors; Programming Matter for Adaptive Architecture," *Next Generation Building,* no. 1, pp. 57-78, 2015.

[27] Q. Meng and J. Hu, "A review of shape memory polymer composites and blends," *Composites Part A: Applied Science and Manufacturing,* vol. 40, no. 11, pp. 1661-1672, 2009.