Adaptive joints with variable stiffness
Strategically arranged materials with transduction properties

Bier, Henriette; Wang, Qinyu; Teuffel, Patrick; Senatore, Gennaro

DOI
10.7480/spool.2019.2.4367

Publication date
2019

Document Version
Final published version

Published in
Spool

Citation (APA)
Bier, H., Wang, Q., Teuffel, P., & Senatore, G. (2019). Adaptive joints with variable stiffness: Strategically arranged materials with transduction properties. *Spool*, *6*(2 #5), 11-16. https://doi.org/10.7480/spool.2019.2.4367

Adaptive Joints With Variable Stiffness

Strategically Arranged Materials with Transduction Properties

Henriette Bier [1], **Qinyu Wang** [2], **Patrick Teuffel** [2], **Gennaro Senatore** [3]

[1] *Faculty of Architecture and the Built Environment*
Delft University of Technology
[2] *Faculty of the Built Environment*
Eindhoven University of Technology
[3] *Applied Computing and Mechanics Laboratory*
École Polytechnique Fédérale de Lausanne

Abstract

The environment around buildings keeps changing, while the static design solutions of buildings cannot perform well during the whole service life. In order to improve structural performances including strength (i.e. avoid collapse) and serviceability, adaptive structures are likely to establish as one of future trends in both research and application for the built environment.

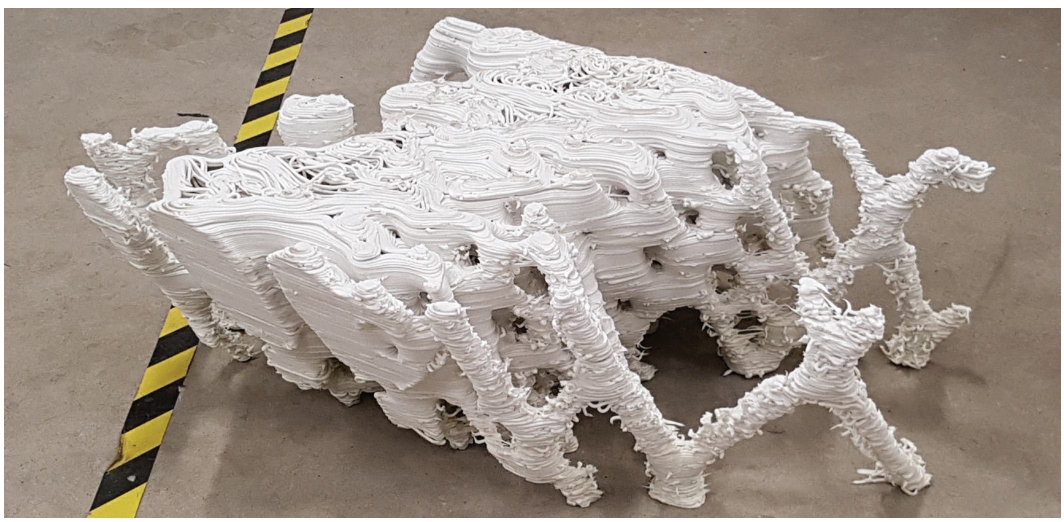
This project aims to synthesize a type of structural joints with variable stiffness capabilities. Stiffness variation is achieved by strategically arranged materials with transduction properties. Shape memory polymers (SMPs) feature large variation of stiffness between a glassy and a rubbery state, which makes them good candidates for application in shape control of adaptive structures. The structures will change themselves into optimal shapes corresponding to different load conditions. 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 showed the potential for application of joints with variable stiffness in adaptive structures.

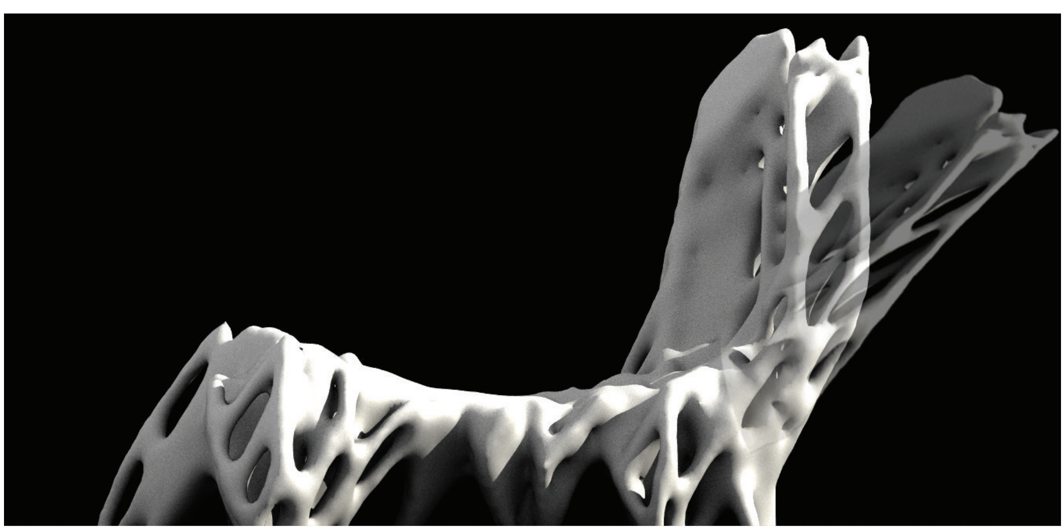
Keywords

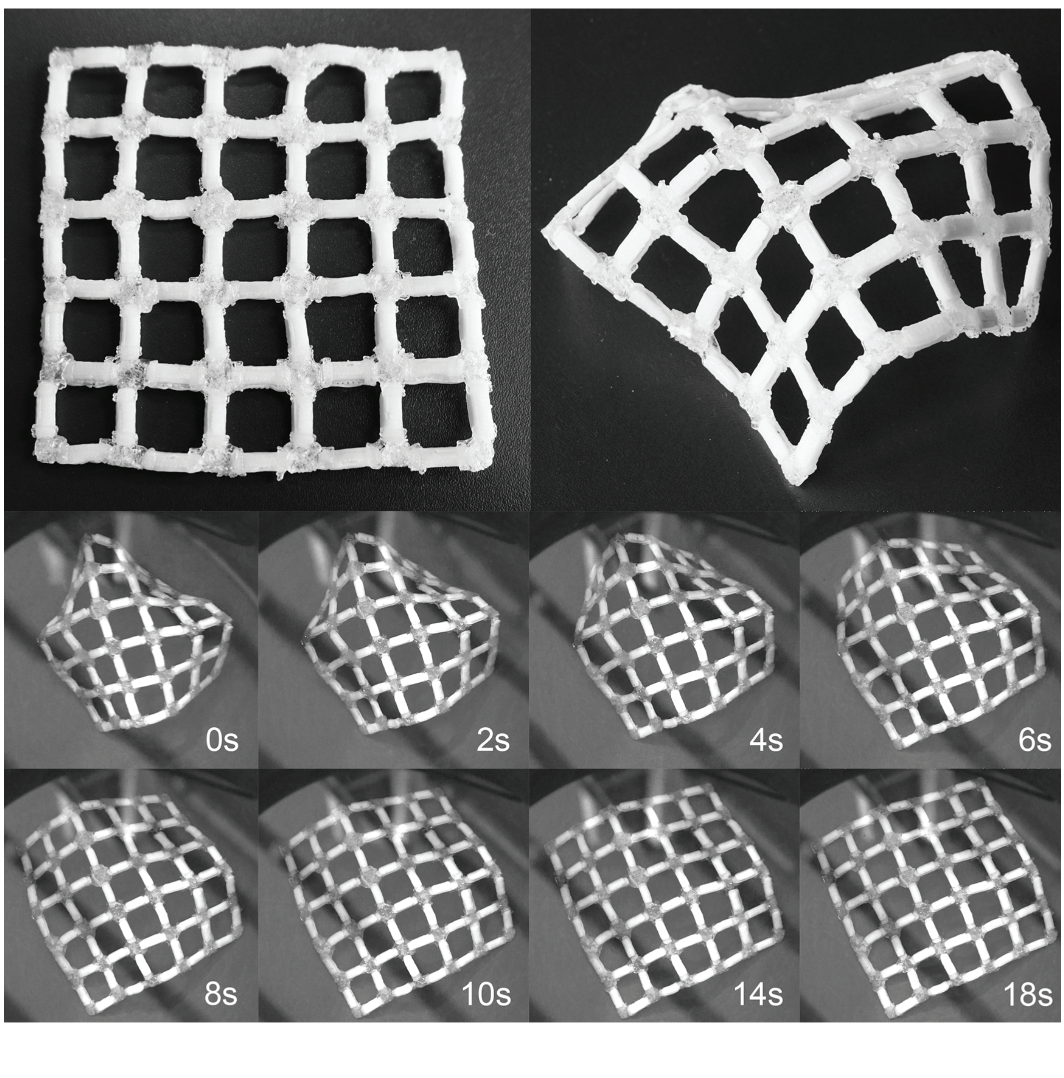
structures, joint, control, shape, stiffness, adaptive, changes, load

Structural design and control strategy.

Conventional structural design solutions relying on passive technologies have limited capabilities against large changes in the external environment. Adaptive structures are defined here as structures capable of actively counteracting 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 project 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 an 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. A case study has been conducted on an arch truss model. The numerical results of this case study show that when large shape changes are considered in the building design, less material mass (and thus embodied energy) will be used 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.






0s
2s
4s
6s
8s
10s
14s
18s

Problem statement

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. In this way, actuation energy can be reduced while control accuracy can be increased.

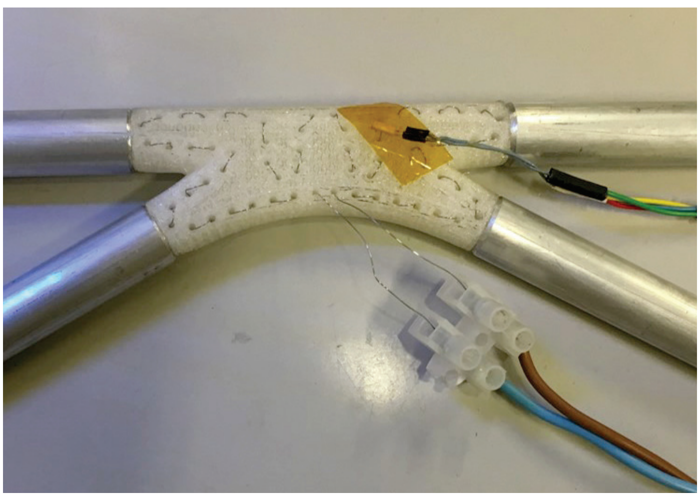
Possible material solution - SMP

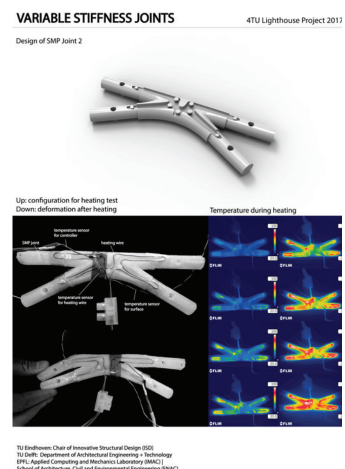
Stiffness variation is achieved by strategically arranged materials with transduction properties. Shape memory polymers (SMPs) can strain up to 400% featuring large variation of stiffness between a glassy and a rubbery state, which makes them good candidates for application in shape control of adaptive 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 whose transition temperature Tg is 55°C.

Experimental test – SMP joints

1:6 scaled prototypes with respect to the joint dimensions in a 20-m span arch truss was fabricated via fused deposition modelling. SMP filaments were used as raw material. The joints are designed to be easily connected to tubular elements with pins. Until now, four editions of such SMP joints have been developed. Resistive heating is used as SMP activation method. Different patterns have been tested using one continuous heating wire which is important to simplify control. A pattern made of 2-mm diameter through holes allows a 1-mm diameter nickel-chromium alloy wire 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. Two thermocouples monitor the temperature of the surface and the heating wire, while a RTD temperature gives the feedback to a temperature controller. It is recorded that aroud 35s after heating, stiffness variation was substancial, and the joint can be deformed by hand.

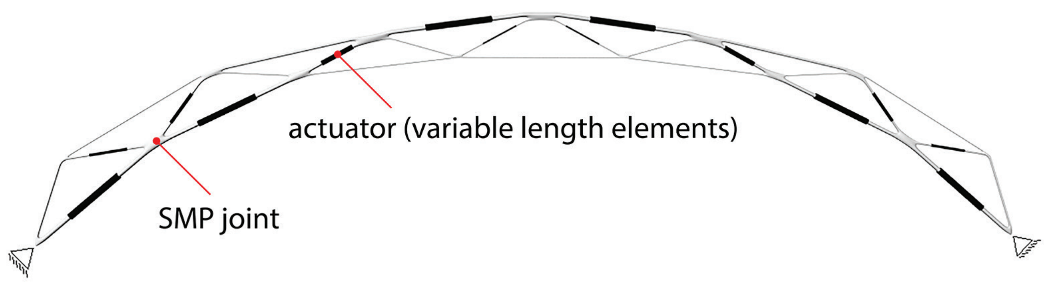
A 1:25 scaled version of the case study model was fabricated via additive manufacturing. The truss elements are made of polyactic acid (PLA) and the joints are made of SMP. The truss elements change length via a telescopic mechanism and connect to the joints as described previously. A heat gun blowing air at 200°C was used as activation method. The joints soften substantially after 10 seconds allowing the structure to be deformed significantly. After cooling the truss preserves the new shape because the joints gain rigidity turning back into full glassy state.





Reinforcement – fiber skinning

During testing we noticed that the material utilised is not adequate in terms of strength. Therefore, we investigated skinning as reinforcement using carbon and Kevlar fibre. Tensile load testing on the specimens (pure SMP and reinforced SMP) , indicated that skinning reinforcement doubled the ultimate strength. The carbon and Kevlar fibre skin was applied successfully to the joint. Heating test showed that stiffness variation is feasible but the carbon fibre caused a short circuit. Therefore, isolation is required to avoid this problem or alternatively use only Kevlar as reinforcement skin. More research on the mechanical properties of reinforced SMP composites will be carried on.



Future research – full scale SMP joints

The use of variable stiffness joints in adaptive structures has the potential for reducing actuation work during structural adaptation. Experimental tests show that joint stiffness variation to deal with quasi-static load is feasible.

Future work will investigate feasibility of a full scale fiber reinforced SMP joint on a simple 4-element frame. The structure will be designed to withstand a load of 1kN applied on the joint in several directions. Practically the load will be applied by a person interacting with the structure, which will react by changing shape.