**Proceedings of the 7th GACM Colloquium on Computational Mechanics
for Young Scientists from Academia and Industry
October 11-13, 2017 in Stuttgart, Germany**

Realization of Adaptive Prestressing

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Micro Abstract
Adaptive Prestressing is based on the conventional passive design principle of prestressed concrete combined with active self-adjustment of structures. For realization of these systems a closed-loop control is developed utilizing Artificial Intelligence techniques like Fuzzy Logic, expert knowledge and machine learning processes. In the context of a feasibility study experiments on two prototypes – an aluminium truss and a concrete T-beam – are conducted to exhibit applicability and potentials.

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Introduction

Based on the natural biologic principle of self-adjustment (adaptation), constructions are enabled to a reactive modification of structural responses by utilization of appropriate control procedures. These adaptive structures are capable of adjustments to the load situation and therefore of reduction or avoidance of critical structural conditions [2]. In practice, the primary field of application for adaptability is the control of the structural vibration behavior for wind effects and especially for earthquake safety. Furthermore, adaptive systems are utilized for ultra-lightweight constructions, such as tensegrity structures (Smith et al.), a prototype for the load path management 'Stuttgarter Traeger' (Teuffel) or the very slender wooden shell structure 'Stuttgart Smartshell' (Sobek et al.), which leads to the development of hybrid intelligent construction elements 'HIKE' (DFG research unit 981). Adaptive Prestressing is based on the conventional passive design principle of prestressed concrete featuring an active self-adjustment of typical system properties to the load situation. Through the resulting real-time optimization of structural responses, a homogenization of stresses, a minimization of deflections, a capacity increase and a significant enhancement of the common design principle as well as various additional potentials are rendered possible. Previous projects verify the benefits of self-adjusting prestressed structures with respective realization methodologies. Important principles are, for instance, active deformation control (Domke et al.), organic prestressing (Pacheco et al.) and a specialized concept for adaptive prestressed concrete bridges (Barin). Additional information to these approaches can be found in [3]. For realization of Adaptive Prestressing a new implementation approach is developed, that is based on the application of Artificial Intelligence techniques like Fuzzy Logic, expert knowledge and machine learning [4]. By means of feasibility studies, applicability of the developed system is verified and potential of intelligent Adaptive Prestressing is emphasized [1].

1 Technology of intelligent Adaptive Prestressing

Self-adjustment of adaptive prestressed structures is realizable through control of the prestressing force or of the deviation profile of the tendons. For this purpose, application of a closed-loop control system is recommended, since the typical response feedback enables a realistic evaluation of the structural state and an inclusion of unexpected influences. Information about applicable technologies for sensor and actuation systems as well as influential criteria can be found in [2]. The control algorithm includes the functional mapping of structural responses onto optimizing adaptations with multiplex demands, that can be fulfilled by utilization of Artificial Intelligence

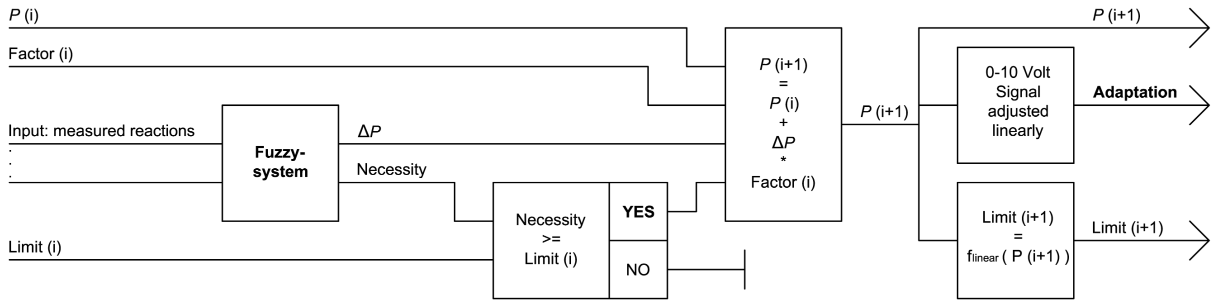

Figure 1. Block diagram of the developed control algorithm [4].

(AI) techniques. For Adaptive Prestressing knowledge-based systems including Fuzzy rule-bases are particularly suitable. Additional machine learning processes enable a further optimization of the control behavior. Fuzzy inference systems are common solutions for control mechanisms, as they enable the simulation of human decision-making and understanding of complex issues with high generalization abilities. Knowledge bases for the control functions are compiled with single rules, that are phrased in the form of 'IF (premise) THEN (conclusion)'. In general, Fuzzy controls feature high stability, redundancy and applicability of model-free expert knowledge. Simultaneously, the included extraordinary generalization abilities enable reliability even at unconsidered system states. Real-time optimization of the control quality is enabled through integration of machine learning techniques. Appropriate intelligence methods can be implemented through inclusion of variable control parameters and additional adjustable modifiers. Related updates are determinable by comparison of provided system states with intended conditions after execution of adaptations. Avoidance of unstable progressions and support of convergences are attainable by utilization of AI-based learning techniques for adaptation of the control [3, 4].

To meet the multiplex demands for Adaptive Prestressing an adaptive Fuzzy control algorithm is developed (Figure 1). The included functional mapping is specifiable with model-based or model-free expert knowledge. Adaptability and related optimization is implemented employing two adjustable features. Based on measured structural reactions the Fuzzy system evaluates the required adaptation as well as the necessity for an adaptation. The prestressing adjustment is initiated when necessity passes the current limit. If so, the evaluated adaptation is modified by the teachable factor followed by actualization of the prestressing force. Subsequently, physical adaptation is executed and the necessity limit is adjusted depending on the actualized force. The control feedback is obtained through effects of prestressing modifications on the measured reactions. Adjustment of the teachable factor and related control optimization is based on the comparison of the measured structural state with the nominal condition within the rule-base [4].

2 Experiments on intelligent Adaptive Prestressing

Experiments on two different prototypes are performed to investigate applicability and performance of the developed control system for intelligent Adaptive Prestressing. As test specimen, an aluminum truss and a concrete T-beam (Figure 2) are equipped with a control system and individual variants of the developed algorithm. Variation of the adaptive Fuzzy controls are the input values, the knowledge bases, the necessity definition and the adaptation processes. A cascade control is applied for the test setup. Based on the measured structural reactions the Fuzzy control evaluates the optimized prestressing force and the adaptation necessity as master controller. As auxiliary controller, the PID control of a hydraulic system regulates the structural prestressing [1, 4].

Featuring a robust and nearly linear behavior as well as high deformation capabilities, an aluminum truss was deployed for preliminary experiments with far reaching damage prevention. The single-span girder is equipped with three mono strands, that are deviated in the third-points

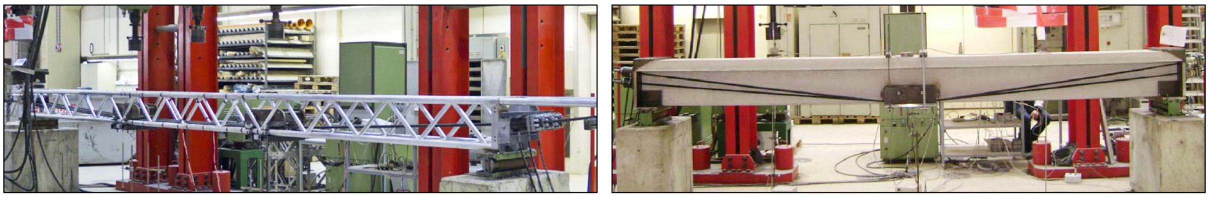

Figure 2. Test specimen: Aluminum Truss and concrete T-beam.

and hydraulically strained. Based on measured displacements at the deviation points, the control performs a minimization of deformations, that is derived from simulations at a computational model of the structure (model-based controller). Adaptation necessity is defined as decision value featuring a range between 0 (no necessity) and 1 (extreme necessity) with an increasing decision at higher deformations. The functional mapping of measured displacements on prestressing adaptation and decision value is implemented by a Fuzzy system of the MA model. The decision limit is raised with increasing prestressing to reduce adaptation frequency at higher profile compression and the teachable factor is actualized after each adaptation directly based on the relation between the actual state and the target condition [4]. Simulations and laboratory tests are conducted considering bridge related load situations. Through Adaptive Prestressing, deflections were effectively reduced to about 3 % to 12 % (Figure 4a,b) with avoidance or extensive prevention of tensile stresses in relation to the structural reactions without prestressing. Due to the learning process, progression of the teachable factor exhibited a volatile behavior [1].

To evaluate of the developed system‘s applicability for concrete structures, further experiments were carried out at a concrete T-beam. Four hydraulically strained mono strands are installed at the single-span structure with midspan deviation. The control function is based on optimization of material stresses towards a constant strain distribution with moderate material utilization. It is modifiable through the multiplier ’X’ in advance (Figure 3). The mapping of measured strains at the quarter points onto correlated optimizing prestressing adjustments is realized through fundamental expert knowledge (Table 1) (model-free controller) with a TSK Fuzzy model featuring higher numerical precision. In the process, measurement locations are considered separately for simplification of the knowledge and are aggregated by the Fuzzy system. Necessity for adaptations is defined as urgency value, that ranges from 0 (no urgency) to 1 (extreme urgency) and rises with increasing differences to the defined optimum.

	Stress	Location		Adaptation P
IF	Tension	Bottom	THEN	Increase
IF	Compression	Top	THEN	Increase
IF	Tension	Top	THEN	Reduce
IF	Compression	Bottom	THEN	Reduce

Table 1. Basic model-free expert knowledge [4]

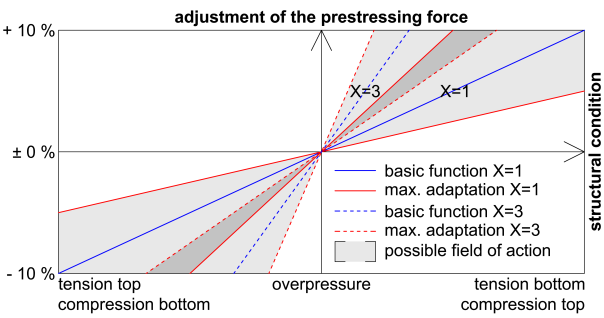

Figure 3. Basic function of the T-beam‘s control [4].

The urgency limit is reduced with increasing prestressing for guidance of the structural condition towards the optimum at higher forces. Additionally, the limit is reduced with adjustments of the teachable factor for an early compensation of insufficient structural adaptations. Adjustments of the teachable factor are implemented utilizing a weighted correction addend and are based on performance evaluation according to the last action and related expert knowledge [4]. Laboratory tests are performed at the unimpaired T-beam and additionally in scheduled pre-damaged state, that presents a distributed bending crack pattern and results in a distinctive non-linear structural behavior. Achievable loads are determined through gradual

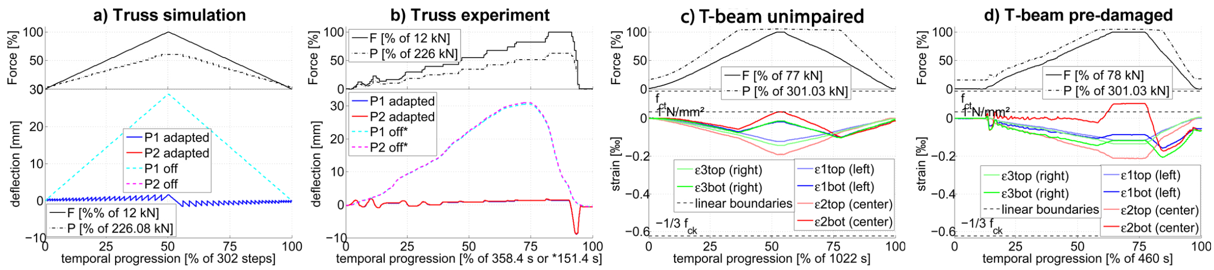

Figure 4. Paradigmatic results with mid-span single load.

raising until occurrence of a material stress of of 1 N/mm^2 (Figure 4c,d). Compared to analytically determined loads inducing 1 N/mm^2 without prestressing, bearing loads of the structure were amplified to about 3 to 15 times. In pre-damaged state, volatile progressions and violation of decompression occur because of crack movement induced structural unsteadiness. Through application of the machine learning principle a smooth learning process is implemented [1].

Conclusions

Within a feasibility study, a self-tuning Fuzzy-based active control system for intelligent Adaptive Prestressing is developed including Artificial Intelligence techniques. Functionality and applicability of the system for Adaptive Prestressing of structures with nearly linear (e.g. new constructions) and strong non-linear (e.g. strengthening purposes) behavior are verified by means of experiments (Table 2). Throughout the tests, optimization of the control performance is achieved through implemented self-adjustment abilities of the adaptive control [1, 2, 4].

Specimen	**Aluminum Truss**	**Concrete T-beam**
Behavior	Linear elastic	Non-linear
Deviation	Third-points	Centric
Measuring points	Third-points	Quarter-points
Control objective	Minimization of deformations	Optimization of material strains
Complementary experiments	Simulations	Predamaged state
Input	Deflections	Strains
Fuzzy model	MA	TSK
Knowledge	Model-based	Model-free
Rule-base	Numerical model	Expert knowledge
Necessity	Decision	Urgency
Learning behavior	Direct (volatile)	Incremental (smooth)
Result	80 - 97 % Deformation reduction	3 - 15 times Load increase

Table 2. Comparison of the specimen [4]

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