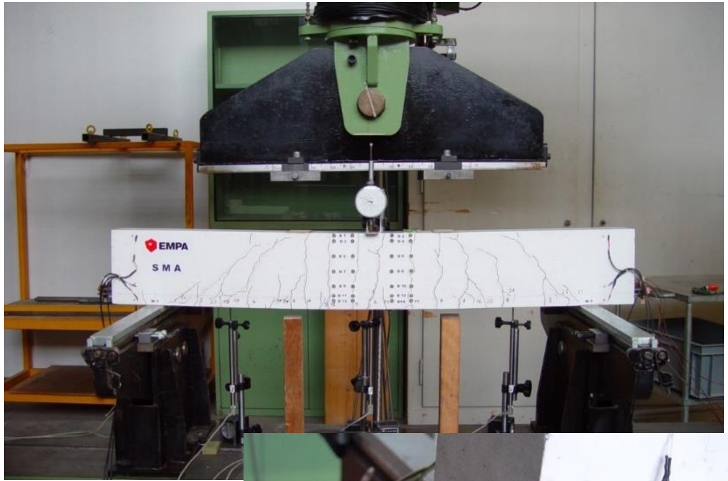
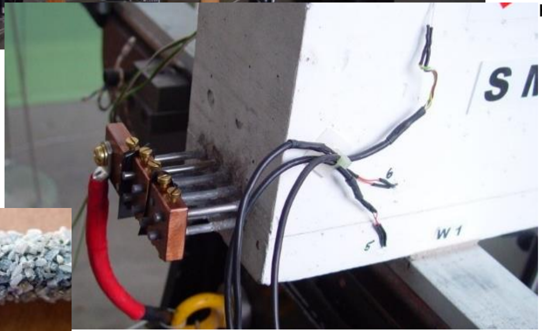
Forschung und Entwicklung

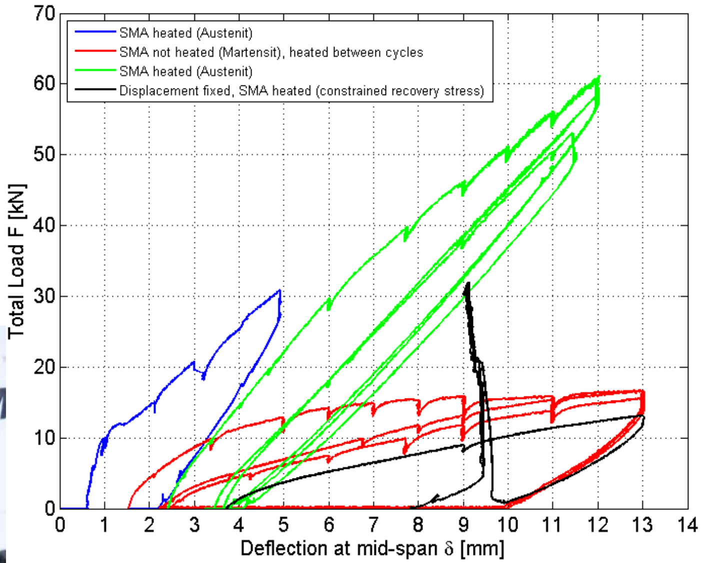
re-fer Fachtagung «Tragwerksverstärkung mit memory-steel»

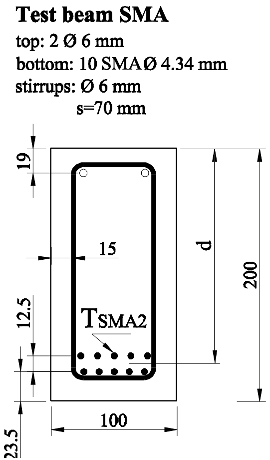
Dr. Christoph Czaderski
Senior Researcher in der Abteilung Ingenieur-Strukturen

2003: NiTi Draht als Betonbewehrung (Masterarbeit B. Hahnebach)









Czaderski, C., B. Hahnebach and M. Motavalli (2006). "RC beam with variable stiffness and strength." *Construction and Building Materials* **20**(9): 824-833.

2003-2004: NiTi wires as discrete fibers for cement embedment (Project SMASH

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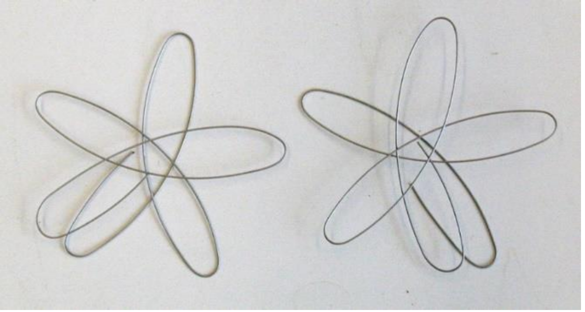
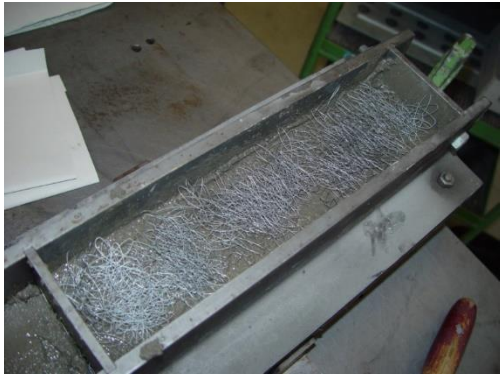
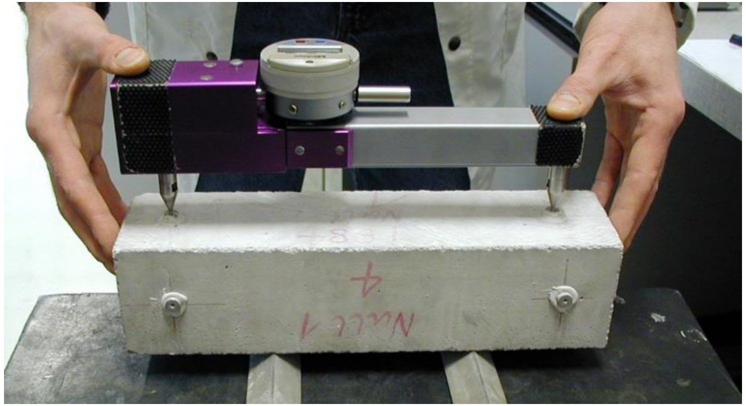


Fiber content ~1.2%





- σ_p NiTi bei 180°→ 845 MPa
- 1.2% Fasergehalt→ 10.1 MPa
- Zufällige Verteilung 2D: Faktor $2/\pi$ → **6.5MPa**

Moser, K., A. Bergamini, R. Christen and C. Czaderski (2005). "Feasibility of concrete prestressed by shape memory alloy short fibers." *Materials and Structures* **38**(279): 593-600.

Memory Metalle

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- Legierungen auf der Basis von NiTi
  - Ni-Ti
  - Ni-Ti-Cu
  - Ni-Ti-Nb
  - Ni-Ti-X
  - …
- Legierungen auf der Basis von Kupfer
  - Cu-Zn-Al
  - Cu-Al-Ni
  - …
- Legierungen auf der Basis von Eisen
  - Fe-Ni-Co-Ti
  - Fe-Mn-Si
  - …

- Deutlich tieferer Preis (…als NiTi)
- Höherer Elastizitätsmodul (…als NiTi)
- Brauchbare Rückumwandlungsspannung
- Brauchbare Umwandlungstemperaturen

2005-2008: Post doc Dong

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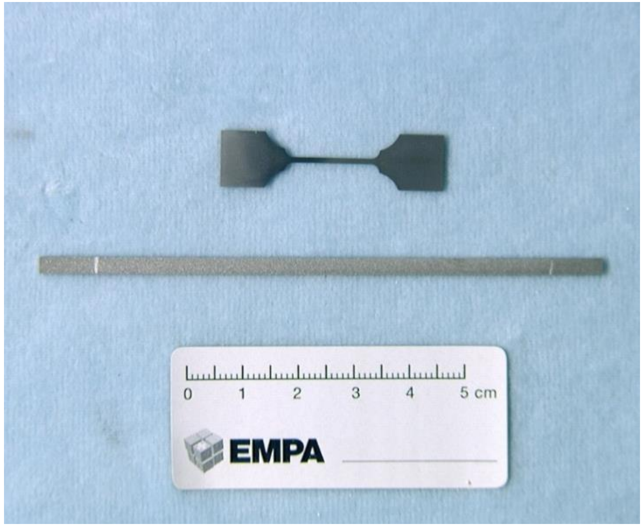
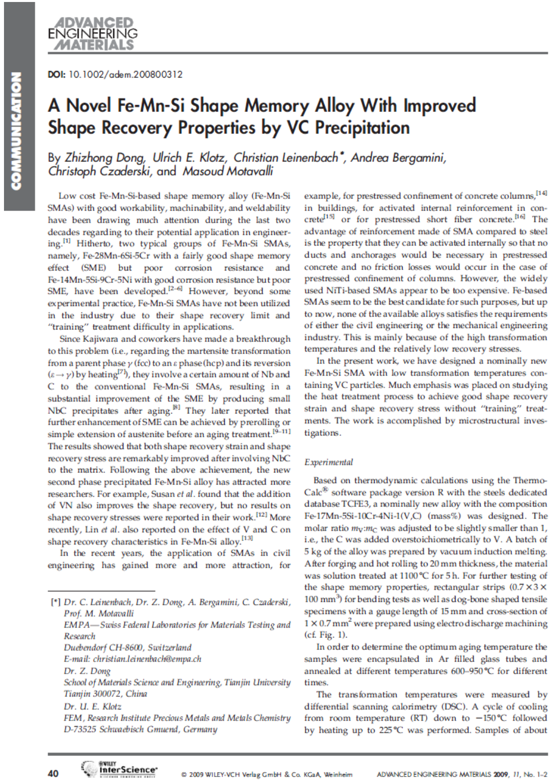
→ Fe-17Mn-5Si-10Cr-4Ni-1(V,C) (mass%)



Europäische Patentanmeldung Nr. EP 2 141 251 A1, "Auf Eisen, Mangan und Silizium basierende Formgedächnislegierungen", 16.6.2009



COMMUNICATION

ADVANCED ENGINEERING MATERIALS

DOI: 10.1002/adem.200800312

A Novel Fe-Mn-Si Shape Memory Alloy With Improved Shape Recovery Properties by VC Precipitation

By *Zhizhong Dong, Ulrich E. Klotz, Christian Leinenbach*, Andrea Bergamini, Christoph Czaderski,* and *Masoud Motavalli*

Low cost Fe-Mn-Si-based shape memory alloy (Fe-Mn-Si SMAs) with good workability, machinability, and weldability have been drawing much attention during the last two decades regarding to their potential application in engineering.[1] Hitherto, two typical groups of Fe-Mn-Si SMAs, namely, Fe-28Mn-6Si-5Cr with a fairly good shape memory effect (SME) but poor corrosion resistance and Fe-14Mn-5Si-9Cr-5Ni with good corrosion resistance but poor SME, have been developed.[2–6] However, beyond some experimental practice, Fe-Mn-Si SMAs have not been utilized in the industry due to their shape recovery limit and "training" treatment difficulty in applications.

Since Kajiwara and coworkers have made a breakthrough to this problem (i.e., regarding the martensite transformation from a parent phase γ (fcc) to an ε phase (hcp) and its reversion ($\varepsilon \rightarrow \gamma$) by heating[7]), they involve a certain amount of Nb and C to the conventional Fe-Mn-Si SMAs, resulting in a substantial improvement of the SME by producing small NbC precipitates after aging.[8] They later reported that further enhancement of SME can be achieved by prerolling or simple extension of austenite before an aging treatment.[9–11] The results showed that both shape recovery strain and shape recovery stress are remarkably improved after involving NbC to the matrix. Following the above achievement, the new second phase precipitated Fe-Mn-Si alloy has attracted more researchers. For example, Susan *et al*. found that the addition of VN also improves the shape recovery, but no results on shape recovery stresses were reported in their work.[12] More recently, Lin *et al*. also reported on the effect of V and C on shape recovery characteristics in Fe-Mn-Si alloy.[13]

In the recent years, the application of SMAs in civil engineering has gained more and more attraction, for example, for prestressed confinement of concrete columns,[14] in buildings, for activated internal reinforcement in concrete[15] or for prestressed short fiber concrete.[16] The advantage of reinforcement made of SMA compared to steel is the property that they can be activated internally so that no ducts and anchorages would be necessary in prestressed concrete and no friction losses would occur in the case of prestressed confinement of columns. However, the widely used NiTi-based SMAs appear to be too expensive. Fe-based SMAs seem to be the best candidate for such purposes, but up to now, none of the available alloys satisfies the requirements of either the civil engineering or the mechanical engineering industry. This is mainly because of the high transformation temperatures and the relatively low recovery stresses.

In the present work, we have designed a nominally new Fe-Mn-Si SMA with low transformation temperatures containing VC particles. Much emphasis was placed on studying the heat treatment process to achieve good shape recovery strain and shape recovery stress without "training" treatments. The work is accomplished by microstructural investigations.

Experimental

Based on thermodynamic calculations using the Thermo-Calc® software package version R with the steels dedicated database TCFE3, a nominally new alloy with the composition Fe-17Mn-5Si-10Cr-4Ni-1(V,C) (mass%) was designed. The molar ratio m_V:m_C was adjusted to be slightly smaller than 1, i.e., the C was added overstoichiometrically to V. A batch of 5 kg of the alloy was prepared by vacuum induction melting. After forging and hot rolling to 20 mm thickness, the material was solution treated at 1100 °C for 5 h. For further testing of the shape memory properties, rectangular strips ($0.7 \times 3 \times 100\ mm^3$) for bending tests as well as dog-bone shaped tensile specimens with a gauge length of 15 mm and cross-section of $1 \times 0.7\ mm^2$ were prepared using electrodischarge machining (cf. Fig. 1).

In order to determine the optimum aging temperature the samples were encapsulated in Ar filled glass tubes and annealed at different temperatures 600–950 °C for different times.

The transformation temperatures were measured by differential scanning calorimetry (DSC). A cycle of cooling from room temperature (RT) down to −150 °C followed by heating up to 225 °C was performed. Samples of about

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Dong, Z., U. E. Klotz, C. Leinenbach, A. Bergamini, C. Czaderski and M. Motavalli (2009). "A Novel Fe-Mn-Si Shape Memory Alloy With Improved Shape Recovery Properties by VC Precipitation." *Advanced Engineering Materials* **11**(1-2): 40-44.

Unterschiede zwischen Fe-SMA und NiTi

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- Fe-SMA hat praktisch keine Superelastizität
- Fe-SMA hat keine vollständige Rückverformung

aber, Fe-SMA hat

- höhere Steifigkeit
- grössere Temperatur Hysterese
- gute Umwandlungstemperaturen
  d.h. praktisch keine Schäden für Beton
- tieferer Preis

2012-2014: KTI Machbarkeitsstudie (Innosuisse)

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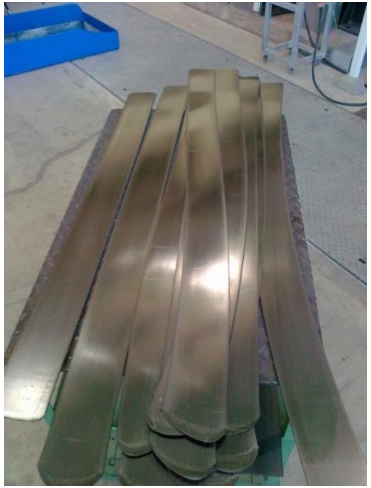
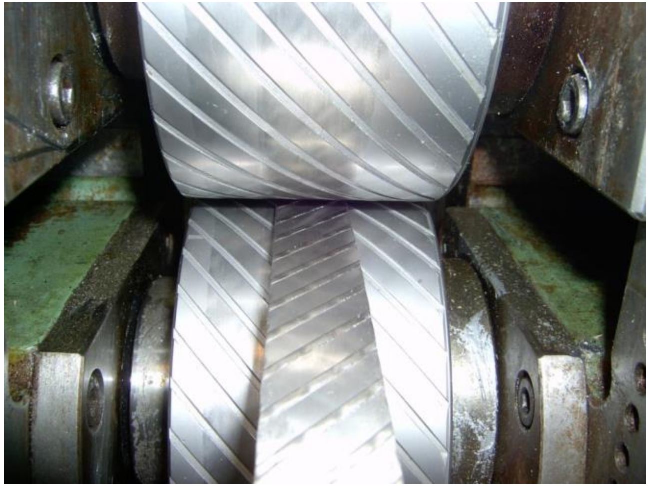
MONTAN UNIVERSITÄT
WWW.UNILEOBEN.AC.AT

Giessen Fe-SMA Block



BERGAKADEMIE FREIBERG
TECHNISCHE UNIVERSITÄT

Rollen von Lamellen (1.5 m lang, 2mm dick)



G.RAU
PFORZHEIM

Kalt verformen und lösungsglühen von gerippten Lamellen

2012-2014: KTI Machbarkeitsstudie (Innosuisse)

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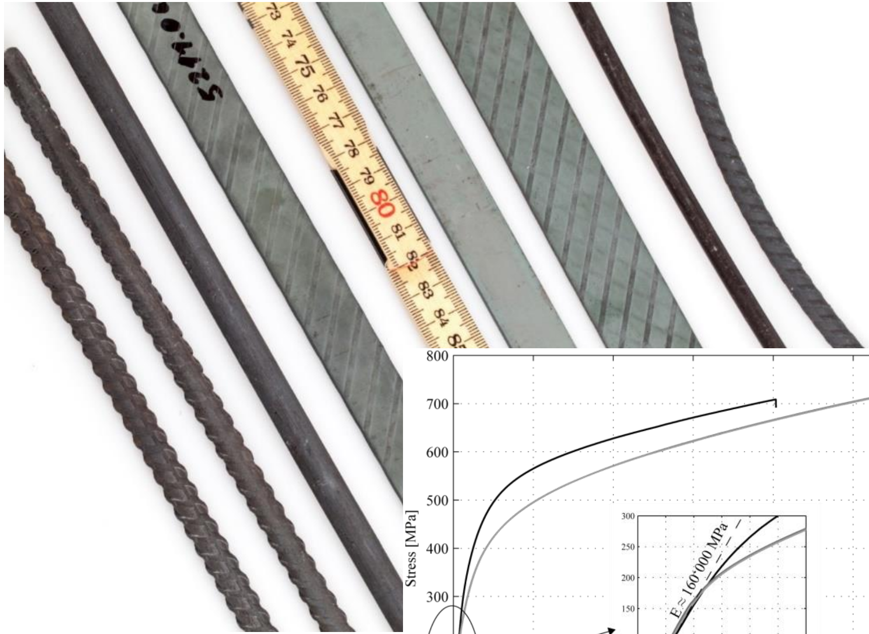
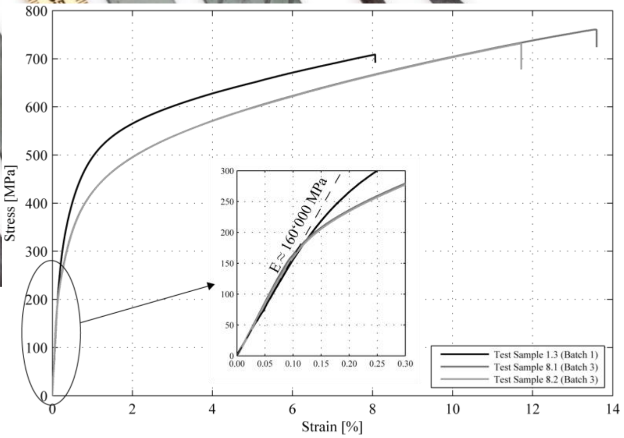
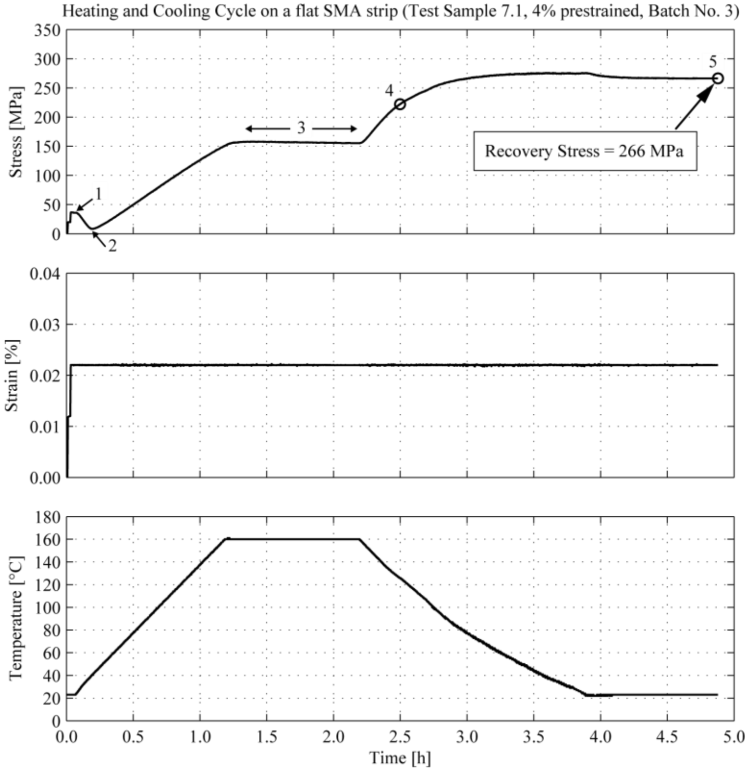
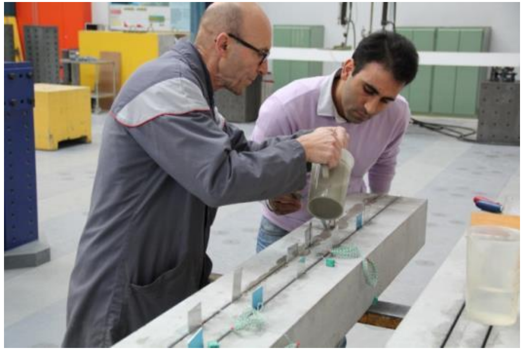




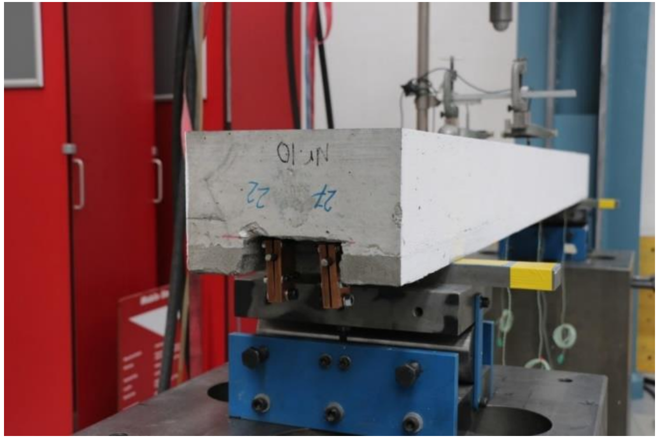


Czaderski, C., M. Shahverdi, R. Brönnimann, C. Leinenbach, and M. Motavalli, Feasibility of iron-based shape memory alloy strips for prestressed strengthening of concrete structures. *Construction and Building Materials*, 2014. 56: p. 94-105.

2012-2014: KTI Machbarkeitsstudie (Innosuisse)

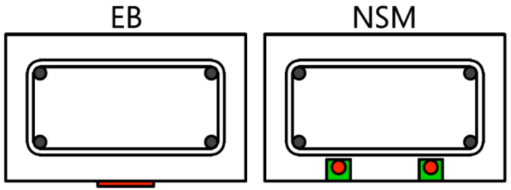


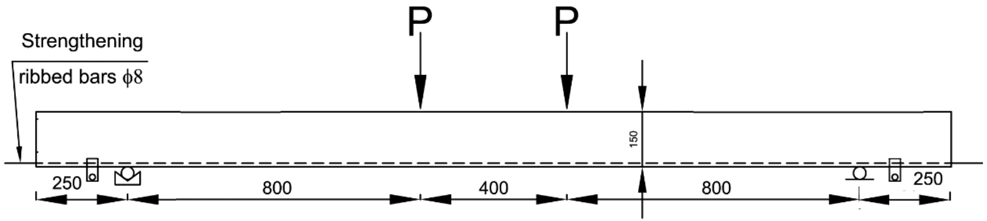
EB: extern aufgeklebt
NSM: near surface mounted reinforcement with grout (eingemörtelt in Schlitze in Betonüberdeckung)



CR: cover replacement with mortar (Ersatz Betonüberdeckung)

Aktivierung mit Widerstandsheizung





Shahverdi, M., Czaderski, C., and Motavalli, M., Iron-based shape memory alloys for prestressed near surface mounted strengthening of reinforced concrete beams. *Construction and Building Materials*, 2016. **112**: p. 28-38.
Shahverdi, M., Czaderski, C., Annen, P., and Motavalli, M., Strengthening of RC beams by iron-based shape memory alloy bars embedded in a shotcrete layer. *Engineering Structures*, 2016. **117**: p. 263-273.

2012-2014: KTI Machbarkeitsstudie (Innosuisse)

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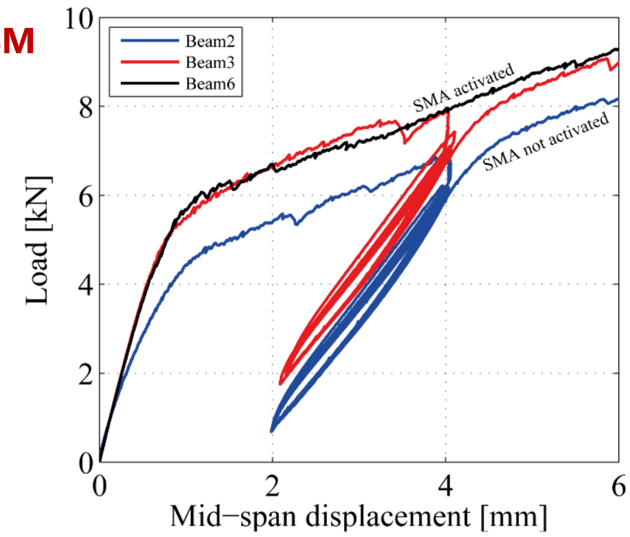
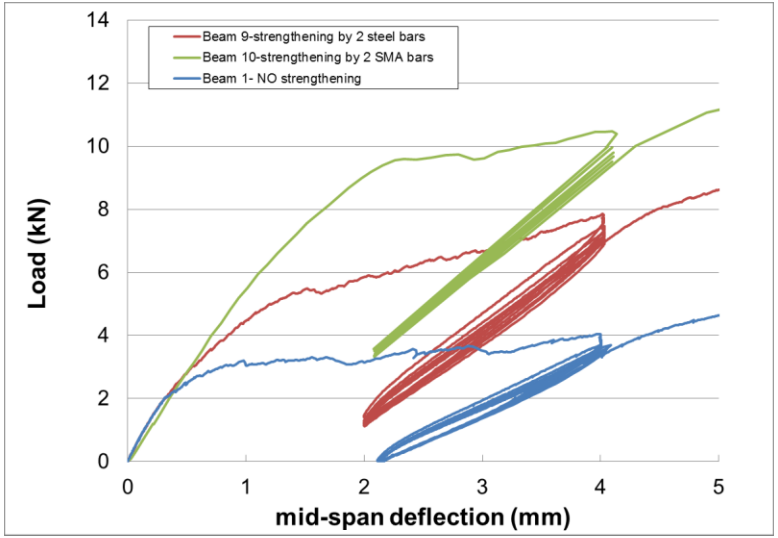
NSM



CR

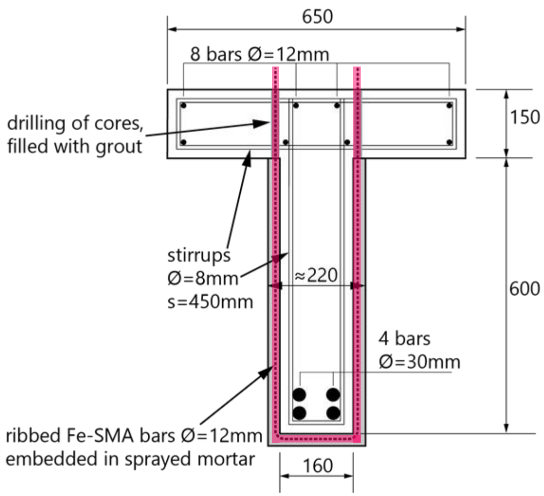


- Höhere Risslast
- Kleinere Verformung

Shahverdi, M., Czaderski, C., and Motavalli, M., Iron-based shape memory alloys for prestressed near surface mounted strengthening of reinforced concrete beams. *Construction and Building Materials*, 2016. **112**: p. 28-38.
Shahverdi, M., Czaderski, C., Annen, P., and Motavalli, M., Strengthening of RC beams by iron-based shape memory alloy bars embedded in a shotcrete layer. *Engineering Structures*, 2016. **117**: p. 263-273.

2016-2019: Schubverstärkung von Beton (Innosuisse Project)

- Verstärkung von T-Trägern
- Spannweite L=4.30 m

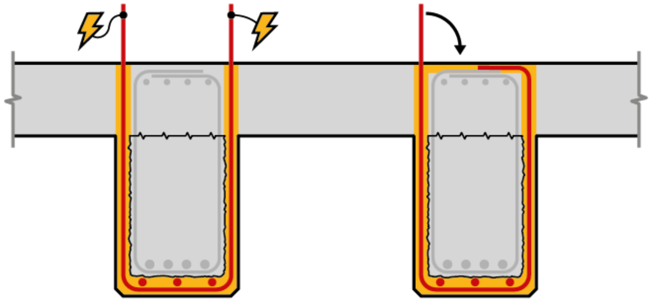


Oberfläche aufrauhen

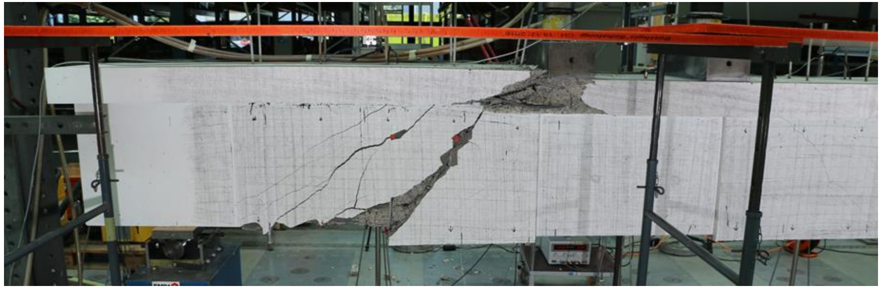
Montage der memory-steel Bügel

Spritzbeton (Sika Monotop)

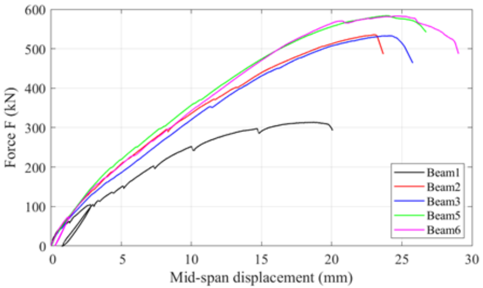
Widerstandsheizung

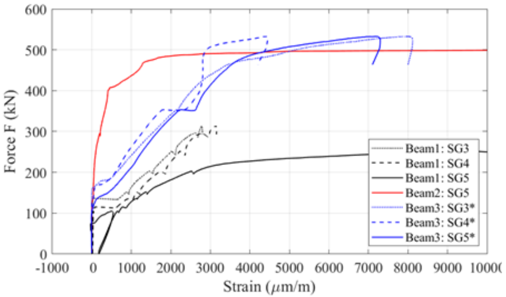


2016-2019: Schubverstärkung von Beton (Innosuisse Project)



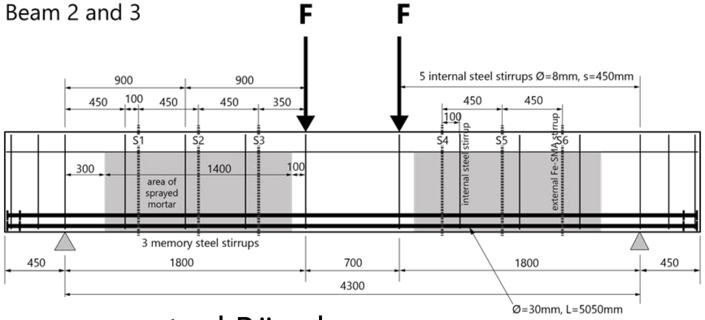
- Schubversagen aller Träger
- Erhöhung der Tragfähigkeit
- Verbessertes Verhalten der Gebrauchstauglichkeit (Durchbiegung und Zugspannung in innenliegender Bewehrung)





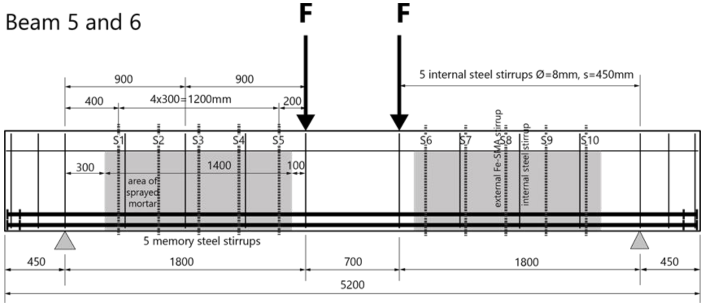
3 memory-steel Bügel

Beam 2 and 3



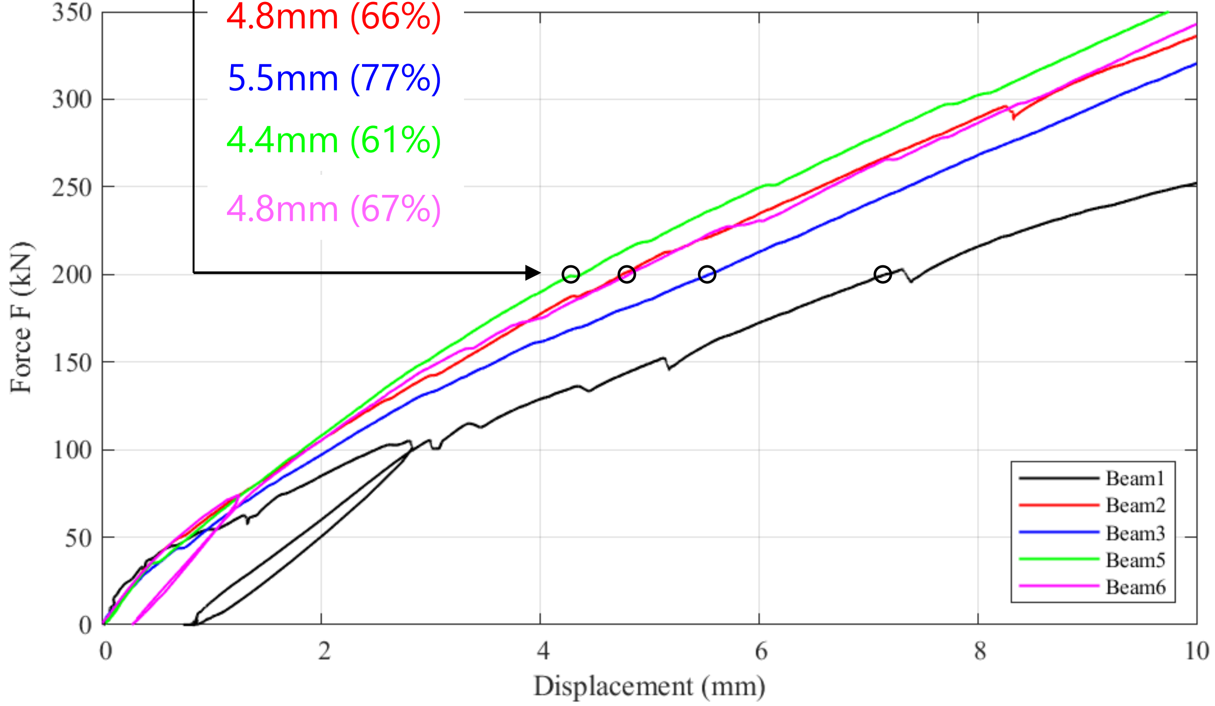
5 memory-steel Bügel

Beam 5 and 6



Czaderski, C., Shahverdi, M., Michels, J.: Iron based Shape Memory Alloys as Shear Reinforcement for bridge girders, *Construction and Building Materials*, 2021 **274**., 121793.

Bei 200kN:
7.2mm (100%)
4.8mm (66%)
5.5mm (77%)
4.4mm (61%)
4.8mm (67%)



Beam 1: keine Verstärkung
Beam 2: drei vorgespannte Bügel
Beam 3: drei nicht vorgespannte Bügel
Beam 5: fünf vorgespannte Bügel
Beam 6: fünf nicht vorgespannte Bügel

Czaderski, C., Shahverdi, M., Michels, J.: Iron based Shape Memory Alloys as Shear Reinforcement for bridge girders, *Construction and Building Materials*, 2021 **274**., 121793.

2019: erste Anwendung im Kurtheater Baden

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Kurtheater Baden vor der Verstärkung

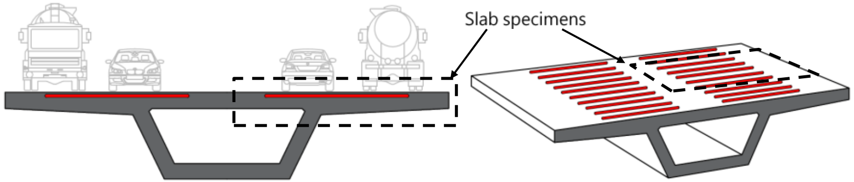
memory-steel Bügel für die Schubverstärkung

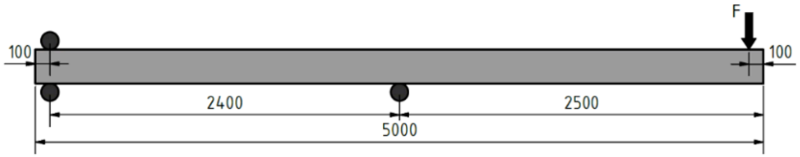
Aktivierung der memory-steel Bügel

Fertige Verstärkung

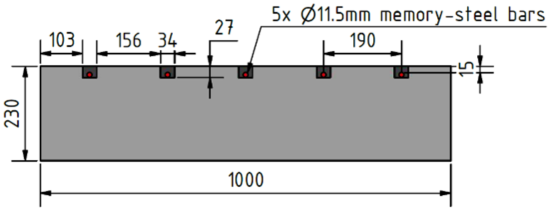
2018-2021: Biegeverstärkung von Stahlbeton (Doktorarbeit B. Schranz, ETH Zürich)

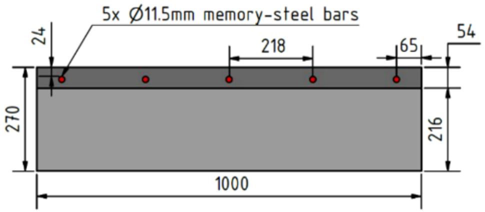
- Beispiel Brücke in Querrichtung: Biegebewehrung für negatives Biegemoment





- Bewehrung eingemörtelt in Schlitze in Betonüberdeckung oder Ersatzbetonüberdeckung





Schranz, B., Michels, J., Shahverdi, M., Czaderski, C., Motavalli, M., Vogel, T., Shahverdi, M. (2021): Strengthening and prestressing of bridge decks with ribbed iron-based shape memory alloy bars. *Engineering Structures* **241**(112467), 876-891.

2018-2021: Biegeverstärkung von Stahlbeton (Doktorarbeit B. Schranz, ETH Zürich)

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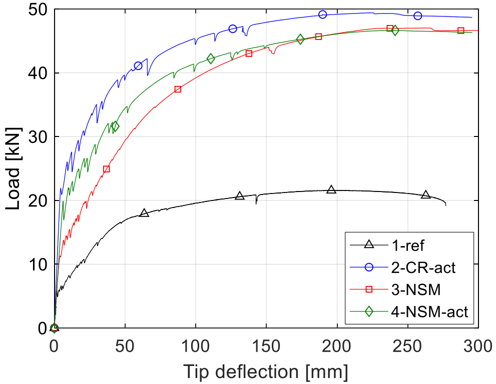
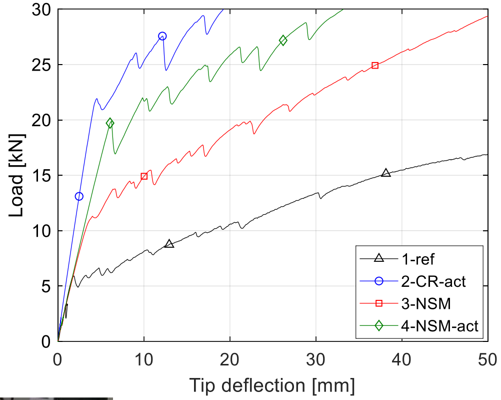
- Statischer Belastungsversuch
- Erhöung der Risslast und duktiles Bruchverhalten (Betonstauchen während Stahlfliessen)





Schranz, B., Michels, J., Shahverdi, M., Czaderski, C., Motavalli, M., Vogel, T., Shahverdi, M. (2021): Strengthening and prestressing of bridge decks with ribbed iron-based shape memory alloy bars. *Engineering Structures* **241**(112467), 876-891.

Biegezugverstärkung einer Stahlbetondecke in einem Schulgebäude in Winterthur

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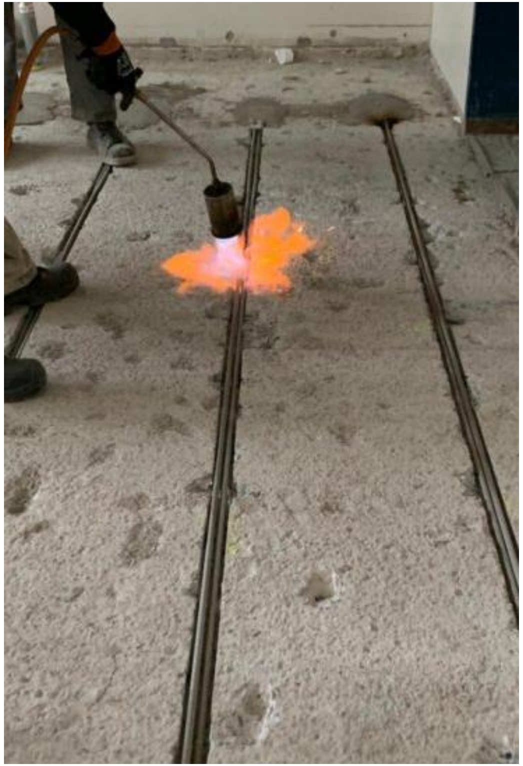
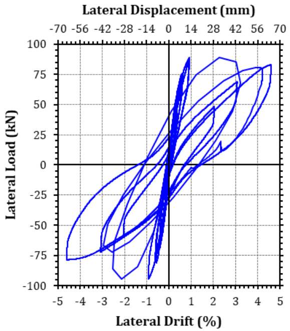
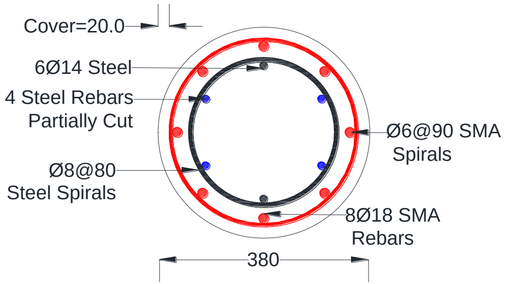


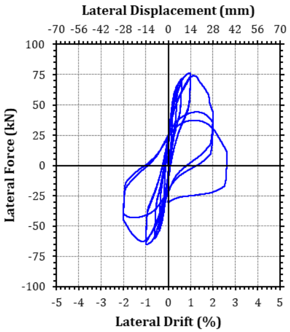
2021-2024: Verstärken von Stützen mit memory-steel (Innosuisse Projekt)

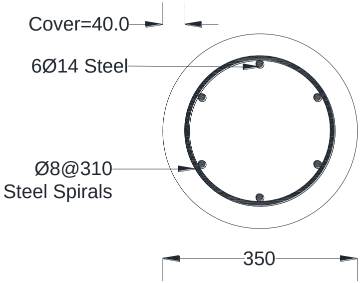
2008 Wenchuan, China Erdbeben (Wibowo 2012)





SMA Prestressed-S1



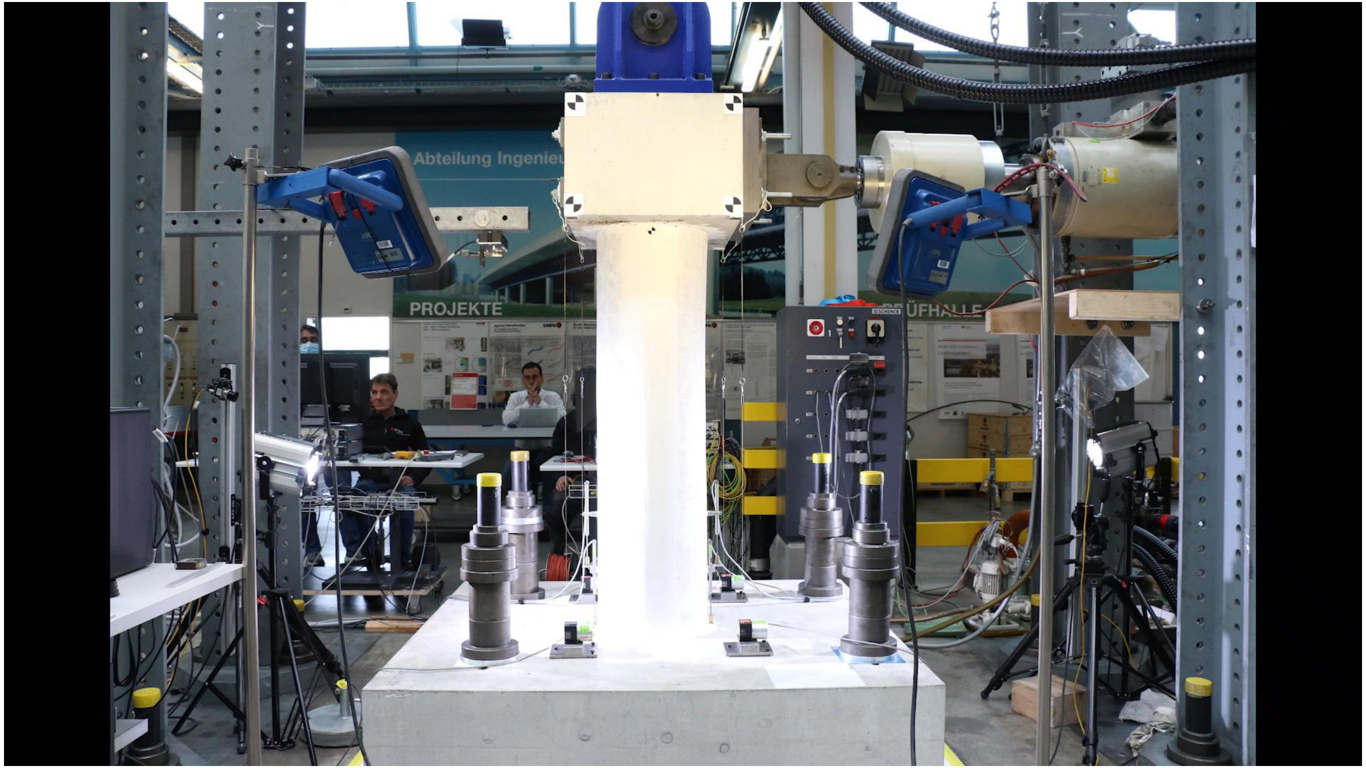


Non-Prestressed-S4

Applied Drift (%)	Residual Drift (%)	
	Non-Pre-stressed	SMA Prestressed
1	0.2	0.1
2	1.16	0.5
2.6	2.6	-
3	-	0.65
4.5	-	1.4

Raza, S. etal (2022) "Shape memory alloy reinforcement for strengthening and self-centering of concrete structures—State of the art", Construction and Building Materials, V. 324, march 2022 126628

2021-2024: Verstärken von Stützen mit memory-steel (Innosuisse Projekt)



2022-2025: Strengthening of bridges with UHPFRC and memory-steel (Innosuisse Projekt)

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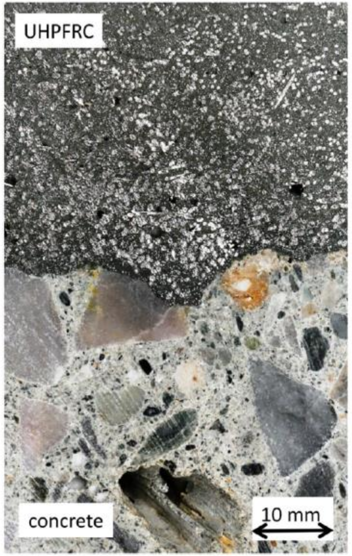


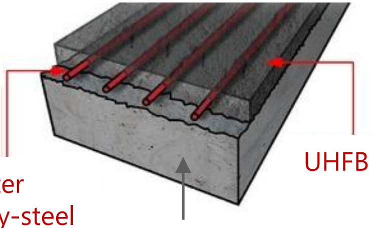
Eugen Brühwiler (2020) UHPFRC technology to enhance the performance of existing concrete bridges, Structure and Infrastructure Engineering, 16:1, 94-105

Konzept:

1) Montage der memory-steel Stäbe

2) Aufbringen einer UHFB Schicht

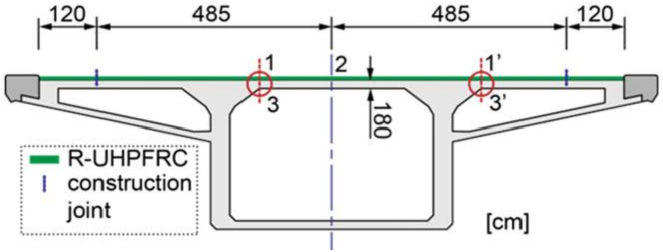
3) Widerstandsheizung zur Aktivierung der memory steel Stäbe



UHFB

Gerippter memory-steel Stab

Vorhandener Beton



Vorteile der Kombination von memory-steel und UHFB

- Die Verstärkung verbessert die Tragsicherheit
- Möglichkeit der Vorspannung der sehr dünnen UHFB Schicht
- Die Vorspannung reduziert die Verformungen, Rissweiten, Zugspannungen im innenliegenden Bewehrungsstahl
- keine mechanische Verankerungen
- Wasserdichte Schicht UHFB
- Duktilies Verhalten des UHFB
- Gutes Verbundverhalten zwischen UHFB und memory-steel

Weitere Forschungsprojekte an der Empa

Empa
Materials Science and Technology

- Kurzfaserbeton mit memory-steel Fasern
- Verbesserung der Rückumwandlungsspannung durch Optimierung der Wärmebehandlung

  Yang Y. etal (2021) Influence of thermal treatment conditions on recovery stress formation in an FeMnSi-SMA, Materials Science and Engineering.

- Untersuchungen zur Pseudoelastizität von memory-steel

  M. Mohri et al., Effect of thermomechanical treatment and microstructure on pseudo-elastic behavior of Fe–Mn–Si–Cr–Ni-(V, C) shape memory alloy, Materials Science & Engineering A 855 (2022) 143917.

- Entwicklungen zur Verstärkung von Stahlbrücken (Ermüdung)

  J. Vůjtech et al., Iron-Based shape memory alloy for strengthening of 113-Year bridge, Engineering Structures 248 (2021) 113231.
  M.R. Izadi et al., Development of an iron-based shape memory alloy (Fe-SMA) strengthening system for steel plates. Engineering Structures 174 (2018) 433–446

- Untersuchung des Kriechens und der Relaxation von memory-steel
- 3D Betondruck und memory-steel Bewehrung

Forschungspartner und Fördereinrichtungen

Empa
Materials Science and Technology

Europa

- Empa – Materials Science and Technology
- re-fer.eu – strengthening solutions
- ETH zürich
- BOKU
- Innosuisse - Swiss Innovation Agency
- Schweizerische Eidgenossenschaft / Confédération suisse / Confederazione Svizzera / Confederaziun svizra
- Swiss National Science Foundation
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- MFPA
- Technische Universität Kaiserslautern
- FH Münster
- Montanuniversität Leoben
- EPFL
- TU Bergakademie Freiberg
- tu technische universität dortmund
- Czech Technical University in Prague
- OST Ostschweizer Fachhochschule
- Uni Kassel Versität
- UIB Universitat de les Illes Balears
- Lodz University of Technology
- Universidade do Minho
- cemsuisse
- Fachhochschule Kärnten
- Ghent University

Amerika

- TEXAS – The University of Texas at Austin
- The University of California Davis
- University of Calgary
- UBC The University of British Columbia

Asien/Australien

- Swinburne University of Technology
- University of Tehran
- 同濟大學 Tongji University
- KITECH Korea Institute of Industrial Technology

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