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High Performance Construction Material for Seismic Repair and Rehabilitation

Matériau hautement performant pour la réparation de dommages dûs aux séismes

Hochwertiges Baumaterial für Reparatur und Sanierung von Erdbebenschäden

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SUMMARY

An innovative retrofit technique is presented for improving the seismic resistance of reinforced concrete elements using a newly developed high performance fiber reinforced concrete. The material used in this investigation is made by first placing continuous steel fiber-mats into the form, followed by infiltration of a dense fiber network with a cement-based slurry. The advantages of this novel material - high strength, high toughness, and excellent crack control - makes it ideally suited for increasing strength and energy absorption of structural elements.

RÉSUMÉ

L'article présente un béton de fibres à hautes performances, récemment mis au point pour la rénovation et l'amélioration de la résistance sismique des éléments en béton armé. La méthode consiste à poser des panneaux continus de fibres d'acier dans le coffrage et à enrober ce maillage de fibres très denses par un coulis à base de ciment. Ce nouveau matériau offre une forte résistance, une dureté élevée et un excellent comportement à la fissuration, ensemble de propriétés qui le rendent idéal pour augmenter la résistance et la capacité d'absorption d'énergie des éléments structuraux.

ZUSAMMENFASSUNG

Als innovative Sanierungstechnik zur Verbesserung des Erdbebenwiderstands von Stahlbetonelementen wird ein neuentwickelter hochwertiger Faserbeton vorgestellt. Dabei wer-den zuerst zusammenhängende Stahlfasermatten in eine Schalung eingelegt und danach als dichtes Fasernetzwerk mit einem zementgebundenen Schlamm durchsetzt. Die Vor-teile dieses neuartigen Materials sind seine hohe Festigkeit, hohe Zähigkeit und hervor-ragende Rissebeschränkung und machen es daher ideal geeignet, um die Festigkeit und das Energieabsorptionsvermögen tragender Bauteile zu verbessern.

1. INTRODUCTION

Older reinforced concrete frame structures are usually non-ductile and are thus identified as hazardous. While laboratory studies show that the use of High Performance Fiber Reinforced Concretes (HPFRCs) leads to substantial improvement in seismic response [1-3], conventional materials have been exclusively used in seismic retrofit up until the present. The advantage of HPFRCs is that, when loaded beyond the elastic limit, they exhibit significant increase in both stress and strain capacities, which translates into an enormous increase in the energy dissipation capacity — a feature particularly desirable for earthquake-resistant design.

An existing HPFRC, called Slurry Infiltrated Fiber Concrete (SIFCON), has already been successfully used in the field for non-seismic repair and new construction [4-7]. However, its comparatively high cost and limitations associated with material placement have prevented a widespread field use. Recent development of a new generation of HPFRCs, called Slurry Infiltrated Mat Concrete (SIMCON), promises to eliminate shortcomings of existing HPFRCs and to provide a cost-effective long-term repair and retrofit solution that can be readily implemented in the field. This paper introduces a novel SIMCON-based technique for flexural retrofit of reinforced concrete beams. Research described in this paper is a part of the first stage of a larger ongoing project that aims at developing a SIMCON-based design and construction method for seismic repair and rehabilitation of non-seismically designed beam-column sub-assemblages.

2. BACKGROUND ON HPFRC

Fiber Reinforced Concrete (FRC) is a composite material consisting of cement paste, sand and/or aggregate, as well as fibers made of steel, glass, polypropylene or other tension materials. Presented investigation is focused on steel fibers. Two distinct groups of FRC are: conventional FRC and HPFRC. Conventional steel FRCs are made by premixing up to approximately 3% fiber volume fraction of the discontinuous fibers with concrete [8]. At such a low fiber volume fraction, fibers mainly contribute to the post-cracking ductility and impact resistance. Improvements in first cracking strength, tensile strain capacity, and peak load are not as significant [9]. On the contrary, HPFRCs exhibit significant improvement in both strength and toughness, as shown in Figure 1 a. This is achieved by using continuous steel fibers or high fiber volume fractions of discontinuous steel fibers. However, manufacturing of HPFRCs requires special fabrication methods and careful engineering of the material components. Examples of existing HPFRCs are: fiber reinforced densified small particles (FR-DSP) [10, 11], SIFCON [8, 12, 13], and SIMCON [14]. FR-DSP is made by premixing very short fibers (6 mm in length) with a specially designed matrix. SIFCON and SIMCON are made by pre-placing short, discontinuous steel fibers or continuous stainless steel fiber-mats, respectively, followed by infiltrating the fibers with a cement-based slurry.

Structural Use of HPFRC: Existing SIFCON applications show an unprecedented performance in both repair and new construction. Its use substantially improved durability, ductility, strength, energy dissipation, and eliminated the need for stirrups [1-7, 15]. However, high placement cost and lack of fiber uniformity, associated with manual distribution of discontinuous fibers, prevented a widespread field use. All of these limitations can be overcome using recently developed SIMCON, which is made by infiltrating *continuous fiber-mats* with cement slurry. It thus provides structural performance superior to other HPFRCs [14]. Furthermore, fiber distribution and orientation can be accurately controlled, which allows manufacturing of a unique cement-based fiber composite.

3. EXPERIMENTAL INVESTIGATION

Eight reinforced concrete beams, shown in Figure 1, were tested in flexure. Two beams were used as reference specimens, while the remaining six were retrofitted following three different layouts shown in Figure 1 b. Fiber volume fraction of SIMCON used in this investigation was 5.25%. Sixteen 7.6 cm x 15.2 cm (3 in. x 6 in.) compressive concrete cylinders were cast to determine concrete strength at the time of testing. Behavior of SIMCON in tension and compression was determined in a separate investigation [16]. Average SIMCON strength in tension and compression were determined to be 15.9 MPa (2.3 ksi) at 1.1 % of strain and 68.9 MPa (10 ksi) at a strain of 0.5 %, respectively. Representative behavior of SIMCON in tension is shown in Figure 3.

Materials: SIMCON slurry mix proportions were 1 / 0.31 / 0.6 / 0.3 / 0.045 by weight of Type I Portland cement, water, Ottawa Silica Sand #250, superplasticizer, and microsilica, respectively. Mmat TEC (Ribbon Technology Corporation, Ohio) continuous fiber-mats were used for SIMCON reinforcement. Concrete mix proportions were 1 / 0.47 / 2.60 / 1.27 / 1.33 by weight of Type III Portland cement, water, sand, 0.96 cm. (3/8 in.) size aggregate, and 1.92 cm (3/4 in.) size aggregate, respectively. The yield strengths of the reinforcement was 413.7 MPa (60 ksi).

Specimen Casting and Testing: Light vibration of the forms was used to compact concrete during casting. Cast specimens were moist cured for 9 days, and then left to dry in room atmosphere until retrofitted at the age of 5 weeks. Prior to retrofitting, beams were wetted, wrapped by fiber mats, and placed into forms. Cement slurry was then infiltrated using a manual grout pump. Specimens were demolded after one day, were moist cured for four weeks, and were tested under stroke control in a third point loading, as shown in Figure 1 a.

Observed Behavior: Representative moment-curvature responses are shown in Figure 2 b. Average compressive concrete strength at the age of beam testing was 41.4 MPa (6 ksi). The presence of SIMCON in the compression zone increased strength and strain capacity of the compression zone, thus increasing the lever arm, and leding to an overall increase in strength, energy absorption and curvature at maximum moment. However, delamination of the SIMCON layer occurred shortly after the anticipated flexural capacity was reached [17]. After delamination and with the further increase in beam deflections, significant interfacial friction developed between SIMCON layer and reinforced concrete beam. Hence, after an initial load drop-off, an increase in the load capacity was observed. It can be thus anticipated that if the bond failure was prevented even higher curvature at maximum moment would have been observed.

When SIMCON was cast on all three beam sides both flexural capacity and energy absorption up to the maximum moment exhibited an unprescendented increase of 2.2 and 1.9 times the reference values, respectively. A 25% increase in curvature at maximum moment was also observed. Furthermore, even prior to beam failure maximum crack sizes were less or equal to 0.09 mm (0.0039 in.). Hence, crack sizes were well within the crack size limits of 0.198 mm (0.0078 in.) required by ACI standards for the reinforced concrete elements exposed to severe environments [18].

Analytical Modeling: Behavior of retrofitted beams was further analyzed using the approach described in [17]. Behavior of concrete in compression was represented using the standard model developed by Kent and Park [19], while behavior of reinforcing steel in both compression and tension was defined using the modele developed by Sargin [20]. Behavior of SIMCON in compression was represented using the model developed for SIFCON by Naaman et al. [21, 22], while the behavior in tension was modeled as:

$$\sigma = \sigma_{cu} \left[1 - \left(1 - \frac{\varepsilon}{\varepsilon_{cu}}\right)^A \right] \qquad \text{for } \sigma \le \sigma_{cu} \qquad (1)$$

$$\sigma = \sigma_{cu} \left[1 - (13 - 2\, V_f)\, \frac{2\,\delta}{L} \right]^5 \qquad \text{for } \sigma > \sigma_{cu} \qquad (2)$$

$$A = \sqrt{E_c \frac{\varepsilon_{cu}}{\sigma_{cu}}} \qquad (3)$$

where σ_{cu} is the ultimate composite tensile strength, ε_{cu} is the strain at the ultimate strength, E_c is the composite elastic modulus, δ is the width of the crack opening, V_f is the fiber volume fraction, and L is the fiber length. Predicted analytical response is compared to the experimentally obtained values in Figure 2 b.

5. CONCLUSIONS

Experimental and analytical results clearly show that SIMCON can successfully interact with existing structural elements, substantially increasing load capacity, energy-absorption capacity, and ductility. However, to achieve the maximum benefit of SIMCON retrofit it is important to prevent delamination of the SIMCON layer. Based on the observed cracking mechanism, it can also be anticipated that the use of SIMCON would markedly improve durability of retrofitted elements.

Construction of a SIMCON-based retrofit was much simpler than similar retrofit solutions using SIFCON, reinforced concrete, steel plates or different non-cement based fiber composites. It is thus anticipated that the proposed technique is less labor- and equipment-intensive and more economical than conventional jacketing methods. It uses widely available construction equipment and building expertise, and can thus be easily introduced to the field without major re-training and changes in existing construction practices.

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REFERENCES

1. Naaman, A. E., Wight, J. K., and Abdou, H., "SIFCON Connections for Seismic Resistant Frames." *Concrete International*, November 1987, pp. 34 - 38.
2. Abdou, H. M., Naaman, A. E., and Wight, J. K., "*Cyclic Response of Reinforced Concrete Connections Using Cast-in-Place SIFCON Matrix.*" Report No. UMCE 88-8, Department of Civil Engineering, University of Michigan, Ann Arbor, 1988.
3. Soubra, K. S., Wight, J. K., and Naaman, A. E., "*Fiber Reinforced Concrete Joints for Precast Construction in Seismic Areas.*" Report No. UMCEE 92-2., Department of Civil Engineering, University of Michigan, Ann Arbor, 1992.
4. Mondragon, R., "*SIFCON Bridge Repairs.*" Report No. NMERI-42, New Mexico Research Institute, Albuquerque, 1984.
5. Mondragon, R., and Schneider, B., "*Interstate Highway Bridge Beam Repair with SIFCON.*" Report No. NMERI-43, New Mexico Research Institute, Albuquerque, 1986.
6. Schneider, B., "Design Criteria for Fragment Resistant SIFCON Panels." Report No. NMERI-31, New Mexico Research Institute, Albuquerque, 1988.
7. Schneider, B., "Development of SIFCON Through Applications." *High Performance Fiber Reinforced Cement Composites*, E & FN Spon, 1992, pp. 177-194.
8. Naaman, A. E., and Harajli, M. H., "*Mechanical Properties of High Performance Concretes.*" Report No. SHRP-C/WP-90-004, Strategic Highway Research Program, National Research Council, 1990.
9. Shah, S. P., "*Theoretical Models for Predicting the Performance of Fiber Reinforced Concretes.*" Journal of Ferrocement, July 1988, Vol. 18, No. 3, pp. 263-284.
10. Bache, H. H., "*Compact Reinforced Composite, Basic Principles.*" CBL Report No. 41, Aalborg Portland, Aalborg, Denmark, 1987.
11. Tjiptbroto, P., and Hansen, W., "Tensile Strain Hardening and Multiple Cracking in High-Performance Cement-Based Composites Containing Discontinuous Fibers." *ACI Materials Journal*, 1993, pp. 16 - 25.
12. Lankard, D. R., "Slurry Infiltrated Fiber Concrete (SIFCON): Properties and Applications." "*Potential for Very High Strength Cement Based Materials*," Proceedings of Material Res. Soc. Fall Meeting, 1984.
13. Naaman, A. E., "SIFCON: Tailored Properties for Structural Performance." *High Performance Fiber Reinforced Cement Composites*, E & FN Spon, 1992, pp. 18-38.
14. Hackman, L. E., Farrell, M. B., and Dunham, O. O., "Slurry Infiltrated Mat Concrete (SIMCON)." *Concrete International*, December 1992, pp. 53-56.
15. Naaman, A. E., Reinhardt, H. W., and Fritz, C., "Reinforced Concrete Beams with a SIFCON Matrix." *ACI Structural Journal*, January 1992, pp. 79 - 88.

16. Krstulovic-Opara, N., Malak, S., and Chia-Ming Uang, "Tensile Behavior of Slurry Infiltrated Mat Concrete (SIMCON)." Under review for the *ACI Materials Journal*, 1994.

17. Haghayeghi, A., Krstulovic-Opara. N., "Non-linear Analysis of Composite Beams Made With High Performance Reinforced Concrete and Conventional Concrete." Under review for the *ASCE Structural Journal*, 1995.

18. ACI Committee 318, "Distribution of Flexural Reinforcement in Beam and One-Way Slabs." *Building Code Requirements for Reinforced Concrete* (ACI 318R-89), American Concrete Institute, Detroit, 1992, Section R 10.6.4.

19. Kent, D. C., and Park, R., "Flexural Members with Confined Concrete." *ASCE Journal of the Structural Division*, July 19711, Vol. 97, ST-7, pp. 1969-1990.

20. Sargin, M., "*Stress-strain Relationship for Concrete and the Analysis of Structural Concrete Sections.*" Study No. 4., Solid Mechanics Division, University of Waterloo, Ontario, Canada, 1971.

21. Naaman, A. E., and Homrich, J. R., "Tensile Stress-Strain Properties of SIFCON." *ACI Materials Journal*, March 1989, pp. 244 - 251.

22. Absi, E., and Naaman, A. E., "Modele rheologique pour les betons de fibres." 3rd International Symposium on Fiber Reinforced Cement and Concrete, Sheffield, U.K., 1986.

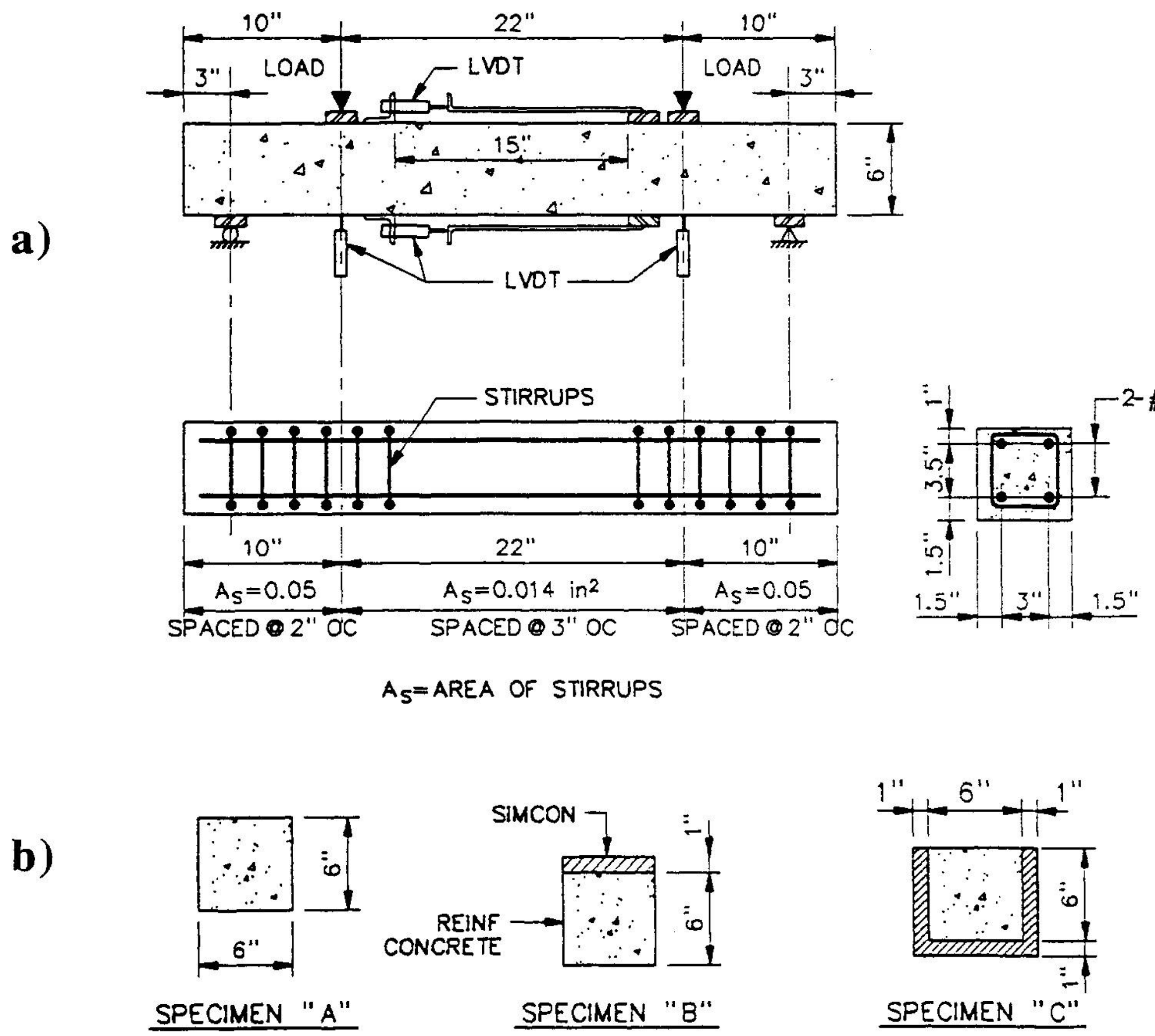
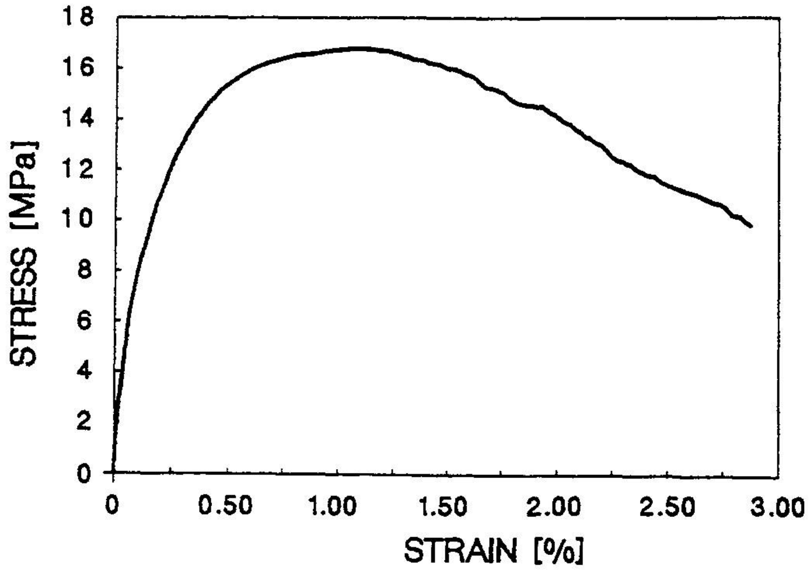


Figure 1: (**a**) Layout of the reinforced beam tested in this investigation. (**b**) SIMCON retrofit layouts.

a)



b)

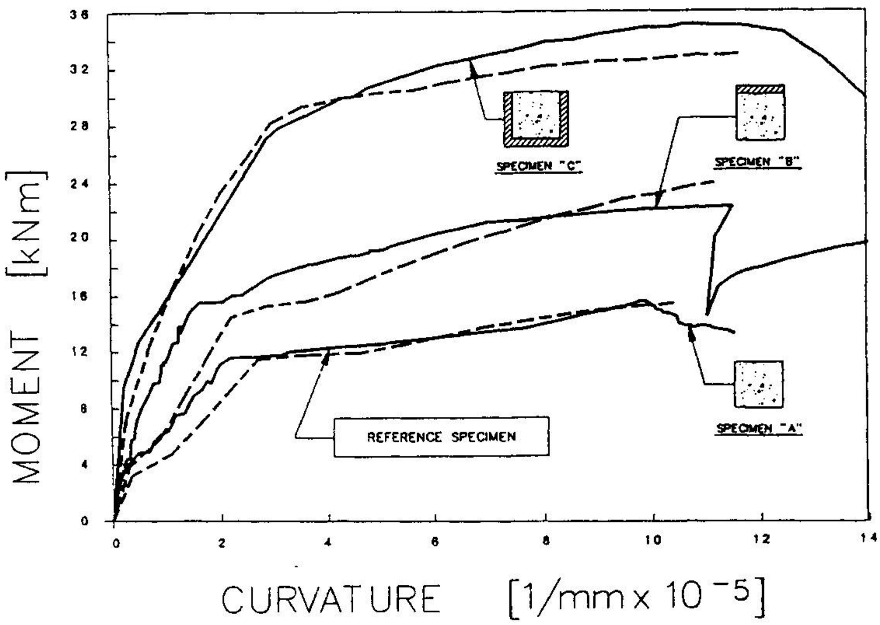


Figure 2: (**a**) Response of SIMCON in tension. (**b**) Experimentally (solid line) and analytically (dashed line) obtained moment - curvature behavior of reinforced concrete beams. Letters "A," "B," and "C" denote specimen types defined in Figure 1b.