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A SYMPOSIUM HONORING KHALED SOUDKI

Towards Sustainable Infrastructure with Fiber Reinforced Polymer Composites

1967-2013

Editor:
Raafat El-Hacha

SP-322

American Concrete Institute
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In Tribute to Professor Khaled Soudki

Professor Khaled Soudki, PhD, PEng, FACI, passed away on September 17, 2013 after a long battle with cancer. He is survived by his wife, Rana Shami, and daughter Sara and son Adnan. He was a graduate of the American University of Beirut (BEng, 1987), Cornell University (MSc, 1989) and the University of Manitoba (PhD, 1994), and held a postdoctoral position at Queens University in Kingston, Canada. Professor Soudki joined the Department of Civil and Environmental Engineering at the University of Waterloo as an Assistant Professor in 1996. A prolific and well-respected researcher, he quickly progressed to Associate Professor in 2001 and full Professor in 2006. He was appointed Canada Research Chair in Innovative Structural Rehabilitation in 2003 and was reappointed in 2006 for a further five-year term. He was also the founding Dean of Engineering at the American University in Dubai, UAE and a visiting scholar at the Swiss Federal Laboratory for Material Testing (Empa) in Dübendorf, Zurich, Switzerland. He was very active on many international scientific committees and was a Fellow of the American Concrete Institute. Khaled was an internationally distinguished researcher in the field of reinforced and prestressed concrete structures with emphasis on the use of advanced fibre reinforced polymers for the repair of structures. His research on the repair of corrosion-damaged reinforced concrete structures led the field and significantly advanced the application of fiber-reinforced polymers. His work in prestressing of fiber-reinforced polymers was similarly groundbreaking, including the development of an anchorage system that is now widely used. Khaled leaves behind a legacy of scientific research in Canada and around the world. His research contributions resulted in more than 300 publications, including patents, book chapters and many journal and conference publications. His publications have been cited more than 1000 times. He supervised 20 PhD students, 25 Master's students and 10 postdoctoral fellows; 15 former students and postdocs have gone on to careers in academia in universities around the world.

On a personal note, I mourn the loss of a true friend and brother. I will always remember Khaled as an outstanding researcher, talented professor, knowledgeable scholar, successful colleague, mentor, kind and humble person, and a true gentleman. His passing is a great loss to the field and to all of us as his friends. Words are not enough to express our sorrow for losing him. I am proud to have had the opportunity to be his co-author on the invited paper "Prestressed near-surface mounted fibre reinforced polymer reinforcement for concrete structures — a review". This paper is one of a selection of papers in the special issue of the Canadian Journal of Civil Engineering to honour the 20th anniversary of the Advanced Composite Materials in Bridges and Structures (ACMBS) conference Series. His last email to me on August 29, 2013 when he was in a critical condition at the hospital: "Congrats on our joint publication". Unfortunately, he was not with us on May 30, 2014 in Halifax at the Canadian Society for Civil Engineering (CSCE) Awards Gala Dinner when this paper won the Casimir Gzowski Gold Medal for the Best Civil Engineering Paper in structural engineering.

Khaled was highly respected by his students and colleagues and many wished to express their feelings.

"There are moments in our lives when we feel helpless in front of the scale of sadness that conquers our heart and mind. This is one of them. The only relief is to cry a brilliant student, a brilliant professor and colleague, and above all a very good friend. God help his family" (Bilal Hamad).

"It is indeed very sad news. Khaled, a CEE-AUB graduate, was a true friend and colleague for most of us. We will surely miss him. May his soul rest in peace" (Muhamad Harajli).

"I am very sorry to lose a friend and member of my family. I knew Khaled for many years; I started as his academic advisor for his Ph.D. He was a model graduate student at University of Manitoba. I have traveled several times with Khaled and we have shared a hotel room attending several conferences and we became very close as colleagues and family. I have traveled with him to Lebanon and I was the first friend to have been introduced to his lovely wife. He was a sincere husband and proud father. He devoted his life to research and teaching and became a full professor in a short time. He has achieved everything he wished for with dignity. I was very sorry to hear about his battle with cancer and shared with him many times his suffering and physical pain but he did not lose his faith with God. I know now he is in peace without suffering and I will really miss him until we meet again in the peaceful land. Mary and I send our sincere condolences and love to his wife and children and will pray to God to give them peace and understanding. I will miss him tremendously" (Sami Rizkalla).

"I will always remember Khaled Soudki as an outstanding researcher, scholar, and friend. Ever since he came to Queen's from Manitoba as a postdoctoral fellow, our careers have been intertwined. His subsequent research on the repair with FRP of corrosion-damaged reinforced concrete structures has led the field and significantly advanced applications of FRP. Khaled's work in prestressing of FRP was similarly groundbreaking including the development of an anchorage system that is now widely used for FRP prestressing. He was also a great mentor and I have also been impressed by the students he has supervised. His genial but hardworking manner has inspired many others. I will always value our friendship and his passing is a great loss to the field and to us as his friends" (Mark Green).

"Khaled was one of the finest individuals I've ever known. I thought that he was an exceptionally devoted son, husband, father, and professor, and certainly dearest of friends. I am heartbroken that he is among us no more. He leaves behind a tremendous void in our lives" (Marie-Anne Erki).

"Khaled was a wonderful man with many quality friends and colleagues. We are better for having had him in our lives" (Pat Heffernan).

"I have known Khaled since he was a Ph.D. student working with Dr. Sami Rizkalla. I got to know him on a more personal basis when we co-organized a National Science Foundation workshop in Dubai in April 2005. It was a pleasure to work with him and we became very good friends. Khaled is a true gentleman and I have the utmost respect for him. I will surely miss him" (Issam harik).

"Khaled will always be remembered with fondness and appreciation for the true scholar and wonderful person that he was. A wonderful person and academic who will be missed by all of us" (Riadh El-Mahaidi).

"Khaled was truly a considerate nice person in parallel to being a superb and successful scholar. It always saddened him observing some of the unhealthy competitions and behaviors that occasionally occur in academia or scientific communities. I will never forget a statement I once heard him saying: "It is ok to grow and have big ambitions, ... but leave others grow also" (Amir Fam).

"On a personal note, I greatly miss Khal. He was hired shortly before me at UW and I took great joy in trying to convert him to becoming a pavement engineer. Obviously, bridges were his passion. His strength of character will always be admired and he will be fondly remembered by all of us here" (Susan Tighe).

"It is very difficult and hard to imagine that Prof. Soudki is no longer with us. No words can help ease the pain and loss we are feeling right now. Prof. Soudki was a great person. He will be in our every prayer and thought. May Allah shower him with mercy and provide us and his family the necessary strength and patience to withstand this great loss" (Tamer El-Maaddawy).

"Khaled will be missed at all levels. He will be missed as a professor, as a supervisor, and as a friend. He was the nicest person I have ever met. When I remember the small details that I lived with Khaled as his graduate student, I feel that I wanna cry! I cannot imagine going to Waterloo without passing by his office or his house. I will never forget that Khaled was always there whenever I asked for help or assistance. His last advice to me was that "life is short". That was when I visited him for the last time in the hospital. He will always be remembered as one of the best persons I have ever met" (Ahmed El-Refai).

"God knows how much we are sad regarding his death. Whatever we write about Khaled, we will never give him what he deserves. He was a brother and a friend, and I do not remember that he put someone down. He never made anyone upset even if he has the reason to do. We will never forget the moments when he gathered all of us in house and celebrated the holy Eid as we were his family members. At the end, everyone will die, but some of us will die with a goodwell as Khaled Soudki. May Allah bless his soul. I will never stop praying for him. We should always remember that we are as human being we have a mercy on people, never mind Allah who is greatest and the most merciful on his worshipers" (Moataz Badwi).

"I had the privilege of working with Khal over the last four years as a PhD student. No student could have asked for more from a graduate supervisor; he was a mentor, a colleague and friend in one. He was always professional, yet always personable, genuine and supportive. Khal was rare in that he had high intellect and achieved much success, yet remained humble to a fault. I hold him in the highest regard, both personally and professionally, and will miss him greatly. I am proud to have had the opportunity to learn from his example" (Martin Noël).

"I was one of the lucky people to work closely with Professor Soudki for about 7 years as his student then his postdoc. He was a very knowledgeable talented professor. More importantly, from my first day working with Dr. Soudki, I found him to be one of the finest people one could ever meet; a very decent caring loving compassionate and polite person. Even during his illness, he was still showing his care, support and love to all his students. He was always there for me, during the bad times and the good times. He was a vivid example of what a good heart means. His loss is irreplaceable. Today, I mourn the loss of a true friend and a brother I never had. Dr. Soudki, words are not enough to express my sorrow for losing you. You are leaving a very big space but you will always be remembered with all the good laughs, thoughtful actions and good memories" (Noran Wahab).

Khaled, will surely be missed greatly by all of us and you will always be remembered.

Rest in peace.

A Symposium Honoring Khaled Soudki

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Preface

The use of Fiber-reinforced polymer (FRP) composite materials in new construction and repair of concrete structures has been growing rapidly in recent years. FRP provides options and benefits not available using traditional materials. The promise of FRP materials lies in their high-strength, lightweight, noncorrosive, nonconducting, and nonmagnetic properties. ACI Committee 440 has published several guides providing recommendations for the use of FRP materials based on available test data, technical reports, and field applications. The aim of these document is to help practitioners implement FRP technology while providing testimony that design and construction with FRP materials systems is rapidly moving from emerging to mainstream technology.

In addition to this publication, ACI Committee 440 organized four special technical sessions entitled "Towards Sustainable Infrastructure with Fiber Reinforced Polymer Composites," two sessions at the ACI Fall 2014 Convention in Washington, DC, on October 26, 2014, and two sessions at the ACI Spring 2015 Convention in Kansas City, MO, on April 13, 2015. These sessions provided a worldwide state-of-the-art forum for researchers, civil/structural engineers, contractors, consultants, practitioners, and regulatory authorities to exchange recent advances in both research and practice, and to share information, experience, and knowledge in the implementation of FRP technology. The technical papers presented at the sessions and published in this volume included the most recent analytical and experimental research work as well as selected field applications, design, and construction guidelines. The sessions were well attended and generated substantial technical discussion and exchange of new technology. Attendees were able to:

a) Learn about the wide usage of FRP in new construction and repair of concrete structures
b) Understand the design process available in several design guidelines that provides recommendations for the use of FRP materials based on available test data, technical reports, and field applications
c) Demonstrate how to evaluate existing structures prior to strengthen/rehabilitation using FRP
d) Recognize examples of the types of evaluation that can be performed on existing structures

This Special Publication consists of a total of 22 papers, of which 13 papers were presented in the four special sessions sponsored by ACI Committee 440 at the ACI Fall 2014 and the ACI Spring 2015 conventions. These papers are SP-322—3, SP-322—4, SP-322—5, SP-322—9, SP-322—10, SP-322—11, SP-322—12, SP-322—13, SP-322—14, SP-322—15, SP-322—16, SP-322—17 and SP-322—18.

In addition, the following 19 presentations were presented in the four sessions, however, and were not submitted for publication:

1. FRP for Sustainable Precast Concrete Double Tees
   By: Sami Rizkalla, North Carolina State University, USA
2. Fibre-Reinforced Cementitious Matrix Systems for Shear Strengthening of RC Beams
   By: Jeffrey West, University of Waterloo, Waterloo, ON, Canada
3. Effect of FRP Repair on the Bond Behavior of Corroded Reinforced Concrete Beams
   By: Rania Al-Hammoud, University of Minnesota Duluth, USA
4. Corrosion in Reinforced Concrete Columns Wrapped with Carbon Fiber Reinforced Polymer Sheets
   By: Mark Green, Queen's University, Kingston, ON, Canada
5. Development Length of CFRP Rods Bonded to Concrete
   By: Issam Harik, University of Kentucky, Lexington, KY, USA

6. Transfer and Development Lengths of Prestressed CFRP Bars in SCC
   By: Slamah Krem, University of Waterloo, Waterloo, ON, Canada
7. Innovative FRP-Reinforced Decks for Movable Bridges
   By: Amir Mirmiran, Florida International University, USA
8. Effect of Environmental Exposure on Hybrid Composite Beam Bridge Shell Elements
   By: John Myers, Missouri S&T, Rolla, MO, USA
9. Strengthening Using FRP Composite: Case Studies for Design and Constructions Consideration
   By: Tarek Alkhrdaji, Structural Technologies, Columbia, MD, USA
10. Mechanochemistry of NSM CFRP-concrete Interface in Thermally Conductive Distress
    By: Yail Jimmy Kim, University of Colorado Denver, Denver, CO, USA
11. Utilizing FRP Systems for Retrofitting Existing Reinforced Concrete Buildings to Mitigate Against Progressive Collapse
    By: Khaled A. El-Domiaty, Stone Security Engineering, Arlington, VA, USA
12. Shear Behavior of Concrete Masonry Beams Reinforced with FRP Reinforcing Bars
    By: Ted Sherwood, Carleton University, Ottawa, ON, Canada
13. A Study of Recovery Stresses Generated by NiTi Shape Memory Alloy Wires in CFRP/SMA Patches
    By: Riadh Al-Mahaidi and Abdul Jabbar Abdy, Swinburne University, Australia
14. Life-Cycle-Based Environmental Assessment of Different Shear Strengthening Options for RC Bridge Piers
    By: Andrea Prota, Costantino Menna, Loredana Napolano, and Domenico Asprone, University of Naples, Naples, Italy
15. Coupled EBNSM Strengthening for Concrete T- and Rectangular Beams with Corrosion Exposure
    By: Hayder A. Rasheed, Kansas State University, Manhattan, KS, USA and Augustine F. Wuertzb, White Engineering Associates, USA
16. Effects of Concrete Steam-Curing on the Mechanical Behavior of CFRP Bars—9:45 am
    By: Jonathon D. Tanks and Stephen R. Sharp Virginia Center for Transportation Innovation & Research, Charlottesville, VA, USA
17. Advances in FRP Products for Infrastructure Renovation
    By: Mohammad R. Ehsani, QuakeWrap Inc., Tucson, AZ, USA
18. Numerical Comparison between TRM and FRP in Strengthening Corroded Reinforced Concrete Beams
    By: Ahmad A. Rteil and PKM Moniruzzaman, University of British Columbia, Kelowna, BC, Canada
19. FRP-Strengthened Reinforced Concrete Beams with Basalt Composite Sheets
    By: Rami A. Hawileh, American University of Sharjah, Sharjah, United Arab Emirates

In accordance with the standard review procedures established by ACI, all papers were reviewed by at least four experts in the subject area and approved for publication. All submitted papers were given serious consideration before a decision regarding publication was made.

This volume could not have been put together without the, dedication, cooperation, and assistance of many volunteers and ACI staff members. First, we would like to thank the authors for meeting our various deadlines for submission. We are also grateful to the many distinguished reviewers and members of ACI Committee 440 who have carefully evaluated and thoroughly reviewed the technical papers, and whose input and advice have been a contributing factor to the success of this volume.

Last, but not least, this symposium is dedicated to the memory of Professor Khaled A. Soudki and I am pleased to offer this symposium as a tribute to an internationally distinguished researcher in the field of using FRP in concrete structures. Khaled leaves behind a legacy of scientific research all over the world. He will always be remembered for his contribution to civil engineering, and we will all miss him dearly.

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Effect of FRP Wrapping Stiffness and Concrete Cover on Lap Splice Failure Behavior

Rayed Alyousef, Timothy Topper, and Adil Al-Mayah

Synopsis: Lap splices are an easy to implement low cost method of transferring force between reinforcing bars in concrete structures. However, the bond between lap spliced bars is usually the weakest region in a reinforced concrete structure. Fiber reinforced polymer materials (FRP) are widely used to strengthen and repair lap splices because of their high strength, durability and ease of handling. Researchers have found that increased concrete cover provides an increase in bond strength similar to that supplied by wrapping with FRP sheets. Currently the FRP industry produces a new generation of high stiffness FRP sheets that provide a high degree of confinement and large increases in bond strength to lap splices.

This paper compares the effectiveness of wrapping with very high stiffness carbon FRP sheets (CFRP 900), wrapping with low stiffness glass FRP sheets (GFRP 430) and no wrapping on the bond strength of lap splice connections for various concrete covers. The test variables were the amount of concrete cover and the wrapping condition. The results showed that the GFRP wrapped beams had an increased in bond strength of approximately 25% compared to the unwrapped beams for each of the concrete covers. However, the CFRP wrapped beams had a percentage increase in bond strength that decreased as the concrete cover increased. The CFRP wrapped beams had increases in bond strength of 71%, 60% and 44% compared to the unwrapped beams for concrete covers of 20mm, 30mm and 50 mm, respectively.

Keywords: bond behavior, thickness of concrete cover, GFRP and CFRP strengthening and lap splice.

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Timothy Topper is a Distinguished Professor Emeritus in the Department of Civil and Environmental Engineering University of Waterloo, Waterloo, Ontario, Canada. His area of research is in the fatigue behaviour of steel and concrete structures.

Adil Al-Mayah is an assistant professor in the Department of Civil and Environmental Engineering/Mechanical and Mechatronics Engineering (cross appointment) at the University of Waterloo, Waterloo, Ontario Canada. His research includes fiber reinforced polymer composite mechanics and applications in the repair and strengthening of concrete structures, imaging-mechanics integration, and the numerical and mathematical modeling of contact surfaces.

INTRODUCTION

General

A lap splice is commonly used to transfer force between steel bars in a reinforced concrete member. It is a simple, effective and cost efficient connection method. Failure of the bond of steel rebars in the absence of stirrups often occurs by splitting of the concrete cover on the tension face or side face of a beam that affects the serviceability of reinforced concrete structures. Moreover, the lap splice connection is usually the weakest link in reinforced concrete structures because it is weak in bond. During monotonic loading, bond deterioration of a concrete member results in an increase in deflection, an increase in the number of cracks, an increase crack widths and a decrease load carrying capacity, which can lead to a brittle failure. The main factors that affect the bond strength of a lap splice are the concrete cover, the lap splice length, the concrete compressive strength and the confinement (stirrups or FRP) (Orangun et al. 1977; Darwin et al. 1996a; Fib 2000; ACI 2008; ACI 2012). The bond failure of the lap splice can occur by splitting or pullout (Orangun et al. 1977; Eligehausen et al. 1983; FIP 2000; ACI 2003). Pullout failure happens when the bond strength of the lap splice is high. This failure occurs by a shearing off of the steel bar ribs from the surrounding concrete (ACI 408, 2003). On the other hand, a splitting failure takes place when the confinement of the steel bar is insufficient and the concrete cover is small resulting in the development of splitting cracks at the steel bar rib (ACI 408, 2003). The splitting cracks are parallel to the steel bar at the thinner of the side or bottom concrete covers or the half of the spacing between the steel bars (ACI 408, 2012). A bond pullout failure is preferable because it is gradual in nature and provides a warning of failure in the form of an increase in deflection before full failure occurs, unlike a splitting failure that occurs suddenly.

Effect of thickness of the Concrete Cover on the Bond Strength of a Lap Splice

The concrete cover is the clear distance from a steel reinforcing bar to an external surface of a beam. The smaller of the side or bottom concrete cover thicknesses governs the splitting failure for a given lap splice length and confinement level. The mode of failure for the lap splice has been found to be strongly affected by the thickness of the concrete cover (Tepfers 1973; Orangun et al. 1977; Darwin et al. 1996a; ACI 2003 and ACI 2012). For a lap splice without stirrups or FRP confinement, the thickness of the concrete cover and the concrete tensile strength govern the splitting bond strength capacity (ACI 2003). Increasing the thickness of the concrete cover leads to an increase in the force transfer between the concrete and the steel bar resulting in a higher bond strength. The relationship between the concrete cover and the bond strength is not linear, because the distribution of the tensile strength of the concrete surrounding the lap splice is not constant (Canbay and Frosch 2005). When the concrete cover or bar spacing is small, a splitting tensile failure takes place at short anchorage lengths. However, for a large concrete cover, a pullout failure may occur. The pullout failure can happen with some splitting cracks if the bond length has higher confinement (stirrup or FRP sheet) along the steel bar. The splitting bond failure results in a lower bond strength than the pullout bond failure (ACI 408, 2003). The confinement effect produced by using FRP wrapping is expected to decrease with an increasing concrete cover because the confinement stresses in the concrete adjacent to the steel bars will be reduced as the cover thickness increases. Furthermore, Canbay and Frosch (2005) studied the relationship between the concrete