SUSTAINABLE INFRASTRUCTURE ENGINEERING: INTEGRATING MATERIAL AND STRUCTURAL DESIGN WITH LIFE CYCLE ANALYSIS

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Abstract

Recently, increased emphasis placed on the sustainability of the built concrete environment has shifted the focus of engineers towards use of "greener" materials to lessen environmental impacts. However, commonly incorporated waste streams may reduce the mechanical performance of concrete materials, ultimately requiring increased life-cycle maintenance and resulting in poorer overall sustainability. A systematic and broader approach to linking material greening to infrastructure sustainability indices is necessary for a more complete life cycle impact assessment.

This paper presents such an approach, illustrated using a high performance fiber reinforced cementitious composite (HPFRCC) bridge deck application. Emphasis is placed upon quantitative service life prediction models serving as a critical link between material property improvements and infrastructure life cycle analysis. By coupling material and structural deterioration models, a quantitative service life maintenance model is developed for a bridge deck employing green ECC link-slabs. This model can then be utilized to complete a full life-cycle impact assessment of the ECC bridge deck system. Without such an assessment, long term decisions by transportation officials cannot be made accurately. This generalized approach can be applied to a variety of infrastructure systems, provided that the selected deterioration model reflects relevant dominant deterioration mechanisms.

Keywords: ECC, Sustainability, Infrastructure, Life Cycle Analysis, Service Life

Introduction

Projecting current consumption trends, nearly 2.3 planet Earths will be needed to support human life by 2050 [1]. The escalating expansion of infrastructure needed to support a growing population, particularly in developing countries, is a worldwide concern. Likewise, the ability to build infrastructure while maintaining a balanced harmony between built and natural environments is becoming increasingly critical. Further compounding such consumption and environmental concerns, the poor durability and associated short service life of concrete structures worldwide is decidedly non-sustainable. Evidence of such performance has been documented by others [2,3,4]. Therefore, a collective shift in infrastructure design philosophy is needed which integrates materials design, structural engineering, and life cycle analysis for increasingly sustainable design. Until recently, the tools needed for such life-cycle evaluation of complex infrastructure did not exist. Further, existing structural deterioration models have been insufficient in quantitatively predicting the service life of concrete structures. Such predictions are at the center of integration between infrastructure designers and life-cycle analysts. Using such models, a quantitative set of social, environmental, and economic sustainability indicators can be calculated.

Within this research, the structural application of a recently developed cement-based composite, ECC, will be examined. A complete description of the green materials development process of ECC has been detailed elsewhere [5,6,7]. But such sustainability initiatives must eventually be evaluated through complete life-cycle analysis of a structure. Before this analysis is completed however, the missing linkages between infrastructure designers and life cycle analysts must be made. To forge these links, a case study will be performed looking at an innovative bridge system using highly durable ECC materials.

Durable Link Slabs Using Engineered Cementitious Composites

One of the most destructive problems confronting bridge systems are the repeated failure of mechanical expansion joints between adjacent simple span bridge decks. While essential to accommodate large thermal deformations, they eventually fail and leak, creating constant source of deterioration for the entire structure. Solutions to this problem have included continuous bridge decks or integral abutment bridges. However, these solutions are significantly more complicated to design when compared to simple spans. Recently, a new materials-based solution using Engineered Cementitious Composites, or ECC, has been proposed to eliminate leaking bridge deck joints.

The tensile response of Engineered Cementitious Composites, or ECC, are unique even among HPFRCC materials. This is accomplished using micromechanics based design resulting in a material with extreme ductility through controlled tailoring of the fiber, matrix, and interface properties [8,9,10]. As seen in Figure 1, after first cracking the tensile load capacity continues to rise, resulting in the unique macroscopic strain-hardening phenomenon accompanied by multiple microcracking up to between 3% and 5% ultimate strain capacity. The crack width development is also shown in Figure 1, revealing that crack widths increase steadily up to about 60μm, at about 1% strain. Between 1% and 4% strain, the crack width stabilizes and remains constant while crack number increases [11].

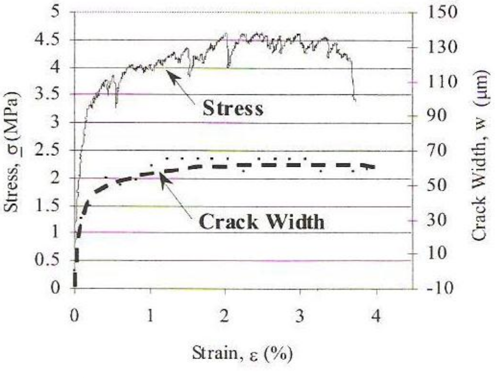

Figure 1: ECC tensile stress-strain response

To increase durability, high tensile ductility combined with tight control of steady-state crack widths, as in ECC, has been shown critical [12]. For the elimination of bridge expansion joints, the use of ECC "link slabs", rather than mechanical expansion joints between adjacent bridge spans, has been proposed [13]. By removing the expansion joint and replacing a portion of the two adjacent decks with section of ECC overtop the joint, a continuous deck surface can be constructed (Figure 2). The unique capability of ECC material to deform up to 4% strain in uniaxial tension while maintaining low crack widths allows the ECC link slab to accommodate the deformations imposed by the adjacent decks (i.e. due to thermal expansion and contraction) while protecting the underlying superstructure and substructure from corrosives present on the deck surface.

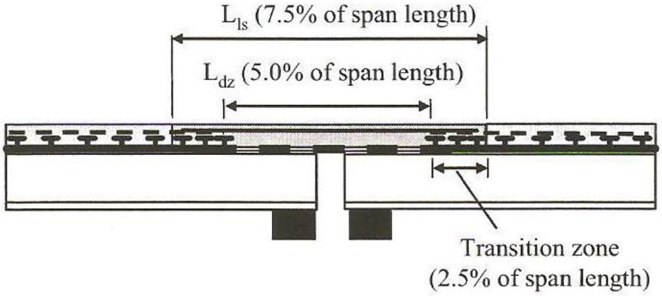

Figure 2: Schematic of ECC link slab

Measuring Sustainability through Life Cycle Assessment

Throughout their development over the past 30 years, methods for evaluation of sustainable performance or sustainable initiatives, such as life cycle analysis, have not been widely applied to large scale infrastructure. Yet without performing a complete analysis of the system life cycle, claims of increasing overall system sustainability remain unsubstantiated. Without feedback information regarding the sustainability of infrastructure applications, further improvement of the design is not possible. To provide this level of analysis, a collaborative framework has been established linking material design, structural applications, and sustainability modeling [7].

But to accurately assess the life cycle costs and impacts of highly durable goods, such as public infrastructure, a detailed estimation of service life is essential. Additionally, this estimate must contain schedules of repairs, rehabilitation, or additional costs between initial construction and end of service life. Such service life and maintenance estimates are critical when determining the future impacts of construction repair events accounting for increases in traffic flow and financial discounting over decades of use.

Linking Structural Design with Life Cycle Analysis: Service Life Estimation

A new coupled deterioration model is proposed for estimating service life and associated maintenance schedules of bridges with ECC link slabs for comparison with bridges using conventional joints. Linking a phenomenological bridge deterioration model with a mechanistic ECC material deterioration model, the service life of such structures can be estimated. This coupled phenomenological/mechanistic technique takes into account field conditions including numerous mechanical and environmental loads, scheduled maintenance, unforeseen overloads, and years of potential neglect which are nearly impossible to capture in a numerical model, while incorporating the effects of jointless ECC link slabs upon overall structural deterioration.

Estimating the service life of steel reinforced ECC link slabs begins with prediction of R/ECC material deterioration within the structure. This is accomplished through a mechanistic steel corrosion model. Modeling the corroding rebar as an expanding cylinder which creates hoop strains within the surrounding ECC cover, the time to failure of the material can be calculated as the time it takes for growing hoop strains within the ECC cover to exceed the ultimate tensile strain capacity of the ECC.

This mechanistic ECC material deterioration model is then coupled with a structural deterioration model based upon the effect of failing joints on overall bridge deterioration. A phenomenological bridge deterioration model developed previously which examined the effect of joints on bridge deterioration was used [14]. The effect of eliminating joints has a profound impact on the deterioration rate of a bridge deck. Applying a defined minimum structural rating, spans with joints have been shown to require repair after roughly 13 years, while spans without joints can last between 25 and 28 years before requiring major repair.

Using the jointed bridge deterioration model [14] in combination with the planned maintenance schedule from the Michigan Department of Transportation [15], a multi-linear structural deck model was developed to predict the structural service life and maintenance schedule of a jointed bridge (Table1). To expand this methodology to jointless bridges using ECC link slabs, the phenomenlogical structural deterioration model for jointless bridges is applied (Table 1). Within both models, a multi-linear modeling approach is used to characterize the deterioration of structural deck rating over time.

Table 1: Predicted Maintenance Schedule for Steel Girder Bridges with Epoxy Rebar incorporating mechanical expansion joints or ECC link slabs

	Event	
Year	**Jointed Bridge**	**ECC Link Slab Bridge**
0	New Deck	New Deck
12	Deck Patch and Joint Replacement	
25	Deck Patch and Joint Replacement	Deck Patch
40	Deep Overlay and Joint Replacement	
50		Deep Overlay
52	Deck Patch and Joint Replacement	
65	Shallow Overlay and Joint Replacement	
70		Deck Patch
80	Deck Patch and Joint Replacement	
90	New Deck	New Deck

Application to Life Cycle Modeling

Implementing this service life model, a complete life-cycle analysis is performed to compare overall bridge system sustainability between conventional bridges and those incorporating ECC link slabs. This analysis assesses all components of service life (i.e. fabrication or construction, user phase or service life, end of life, etc.). Results from the life cycle modeling which examined a fictional bridge near Ann Arbor, MI have been detailed by others [16]. Building from bridge service life models described earlier and combining these with construction data, user data, and national agency and social discount rates, a full assessment of ECC material within the link slab system shows significant benefits to using ECC link slabs over conventional expansion joints. Overall this results in a decrease in life cycle cost from US$22 million for the conventional bridge to US$18.5 million for the ECC link slab bridge, a 16% reduction in total costs. While only a small portion of this cost, approximately 2.5%, is borne directly by the transportation agency, the reduction in overall cost borne by society as a whole is substantial when using the ECC link slab system. Additionally, due to less use of construction material and fewer vehicles caught in construction traffic congestion over the bridge service life, environmental cost burdens, such as the cost of greenhouse gas emissions, were reduced by 28%.

Conclusion

While the need for increasingly more sustainable infrastructure worldwide is unarguable, the roadmap toward meeting this goal remains unclear. Currently, the disconnected disciplines of structural design and materials development allow for little improvement in overall sustainability. To facilitate such improvements, a collaborative platform is proposed to guide efforts among materials developers, structural designers, and life cycle analysts. While a number of these collaborative efforts have been described elsewhere, the development of predictive service life models discussed within this article is a crucial link toward accurately applying complex life cycle models.

Within this work, predictive structural deterioration models were developed which account for the impact of new materials on structure service life. Without such service life predictions, new design philosophies and technologies cannot be correctly assessed against traditional designs through comparative LCA. Without comparative LCA results, claims of increased infrastructure sustainability remain unsubstantiated and innovative ideas are potentially discarded. In the case of ECC link slabs, this new material was used in an application which ultimately had large positive sustainability impacts. These impacts were only discovered though the integrated application of LCA modeling. Such multidisciplinary efforts, and the development of collaborative tools needed to apply them, look to push sustainability initiatives in infrastructure design and planning to the forefront of the infrastructure design community.

References

[1] WWF – World Wildlife Fund (2004) "Living Planet Report 2004" Eds. J. Loh and M. Wackernagel. World Wildlife Fund for Nature. Gland, Switzerland. pp. 19

[2] ASCE - American Society of Civil Engineers (2005) "2005 Report Card on America's Infrastructure", Internet Site: http://www.asce.org/reportcard/2005/page.cfm?id=103. Accessed April 23, 2006

[3] Engineers Australia (2006) "2005 Australian Infrastructure Report Card", Internet Site: http://www.infrastructurereportcard.org.au/downloads/AustralianReportCard.pdf. Accessed March 2, 2006

[4] Mather, B., and J. Warner, (2003). "Why do Concrete Repairs Fail," Interview held at Univ. of Wisconsin, Department of Engineering Professional Development, MD, WI, Internet Site http://aec.engr.wisc.edu/resources/rsrc07.html. Accessed Nov. 2003.

[5] Li, V.C., M. Lepech, S. Wang, M. Weimann, and G. Keoleian, (2004) "Development of Green ECC for Sustainable Infrastructure Systems." in Proceedings of the International Workshop on Sustainable Development and Concrete Technology, Beijing, China, Edited by K. Wang, Published by Iowa State University, 181-192

[6] Lepech, M. D., V.C Li, and G.A. Keoleian, (2005) "Sustainable Infrastructure Material Design", in Proceedings of The 4th International Workshop on Life-Cycle Cost Analysis and Design of Civil Infrastructures Systems, Cocoa Beach, Florida, May 8-11, pp 83-90.

[7] Keoleian, G., A. Kendall, M. Lepech, and V.C. Li, (2006) "Guiding the design and application of new materials for enhancing sustainability performance: Framework and infrastructure application", accepted to Materials Research Society Symposium.

[8] Li, V.C. (1993) "From Micromechanics to Structural Engineering – The Design of Cementitious Composites for Civil Engineering Application", *JSCE J. of Structural Mech. and Earthquake Eng.*, **10**(2). pp. 37-48.

[9] Li, V.C., (1998) "ECC – tailored composites through micromechanical modeling." *Fiber Reinforced Concrete: Present and the Future* edited by Banthia et al, CSCE, Montreal, 64-97.

[10] Li, V.C., (2003) "On Engineered Cementitious Composites (ECC) – A review of the material and its applications." *J. Advanced Concrete Technology*, **1**(3): 215-230.

[11] Weimann, M. B., and V. C. Li, (2003) "Drying Shrinkage and Crack Width of ECC," *Brittle Matrix Composites-7*, Warsaw, Poland, pp.37-46,

[12] Lepech, M. and V. C. Li (2006) "Long Term Durability of Engineered Cementitious Composites" accepted to International Journal of Restoration of Buildings and Monuments.

[13] Lepech, M. and Li, V.C. (2005) "Design and Field Demonstration Of ECC Link Slabs For Jointless Bridge Decks", Proceedings of ConMat'05, Vancouver, Canada, August 22-24.

[14] Yanev, B. and X. Chen. (1993). "Life-cycle Performance of New York City Bridges." Transportation Research Record No. 1389, Transportation Research Board, Washington, D.C.

[15] Michigan Department of Transportation "Bridge Preservation Timeline", Michigan DOT Construction and Technologies Division, Lansing Michigan. USA. (2003)

[16] Keoleian, G.A., A. Kendall, J.E. Dettling, V.M. Smith, R.F. Chandler, M.D. Lepech, and V.C. Li, (2005) "Life Cycle Modeling of Concrete Bridge Design: Comparison of ECC Link Slabs and Conventional Steel Expansion Joints," *Journal of Infrastructure Systems*, ASCE, March, pp 51-60