ABC-UTC 2015

PROGRESS REPORT

A. PROJECT TITLE:

Material Design and Structural Configuration of Link Slabs for ABC Applications

B. START & END DATE:

12/1/15 – 11/30/17

C. PI & Co-PI(s):

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D. PROPOSAL ABSTRACT: (Not to exceed 300 words)

Accelerated Bridge Construction (ABC) is now being widely used by the Departments of Transportation because of the reductions of traffic disruption, social cost, environmental impact, and lost time. ABC is also known to improve the work-zone safety, on-site constructability, and project completion time. One of the common techniques in ABC is using Prefabricated Bridge Elements and Systems (PBES). The bridge components are built outside of the construction area, transported on site, and then rapidly installed. Time lost due to concrete placement, curing in the construction zone, and formwork erection/removal is reduced. Another benefit to using prefabricated structural elements is the improved quality control. Damaging effects due to weather is minimized because elements are built in a controlled environment. Considering the advantages of PBES, a number of research projects have been conducted on the prefabrication and installation of the main structural elements of the bridges. However, there is a gap in the literature on how the long-term performance and durability concerns associated with the joints that connect already high-quality bridge elements may be addressed. One approach that has gained significant attention is to eliminate the joints through revised design strategies. While such strategies have been successfully developed for integral abutments used for

ABC applications, no systematic study on removing the expansion joints between bridge girders has been found. To address this issue, the current research project investigates the use of a precast, flexible link slab through a comprehensive set of experimental tests and numerical simulations. The outcome of this project is expected to provide the design guidelines and practical recommendations necessary to properly implement a link slab in the jointless bridges constructed with ABC techniques.

E. DESCRIPTION OF RESEARCH PROJECT

E.1. PROBLEM STATEMENT (Include project objectives)

Application of ABC techniques has been significantly increased over the past ten years owing to the unique advantages of the bridges built with ABC, including short duration of construction and high quality of prefabricated bridge elements. By decreasing the construction time from months to days, the ABC techniques contribute to the safety of work zones by minimizing the on-site activities that can cause accidents for construction workers and motorists. On the other hand, with improved product quality, which can be achieved in prefabricated bridge elements built under controlled environmental conditions, the durability and performance of bridges are enhanced during the design life. Despite major advances in the design and construction of the main bridge elements for ABC applications, the joints that connect the bridge spans are still in need of improvement and further investigation. The expansion joints play a critical role in accommodating unrestrained deformations of adjacent spans due to thermal expansion and traffic loads [7,25]. The existing joints, however, deteriorate rapidly and require major maintenance efforts. To address this issue, the idea of using link slabs to eliminate the joints has been explored to a limited extent for conventional bridges [7,13,23,25]. There is, however, no study available in the literature on how link slabs can be properly utilized for ABC applications. The proposed research project aims to investigate various aspects of this subject through a comprehensive set of experimental tests and numerical simulations.

E.2. CONTRIBUTION TO EXPANDING USE OF ABC IN PRACTICE

This research project directly contributes to expand the use of ABC in practice. Further to address the long-standing issues associated with the performance and maintenance of joints in bridges, the main advantages of ABC techniques, including the promise of time and cost saving, are incorporated into the design and configuration of the proposed link slab. This is achieved through a precast, flexible link slab, which not only satisfies the strength and serviceability requirements, but also contributes to improve the long-term durability of the other connecting bridge elements, which are already of high quality and constructed under exceptional quality control.

E.3. RESEARCH APPROACH AND METHODS

This research project benefits from experimental tests as well as numerical simulations to fully understand the structural behavior and performance of the proposed link slab under the expected loading conditions. The required design guidelines will then be developed for the implementation of the link slab in ABC applications. A range of important aspects, including crack criteria, bonding/debonding requirements, and rebar configurations, are investigated.

E.4. DESCRIPTION OF TASKS TO BE COMPLETED IN RESEARCH PROJECT

The proposed research project will identify the required material properties and structural configurations to be used for the design of a link slab for ABC applications. The performance and durability of the proposed link slab will be evaluated through a comprehensive study as outlined in the following tasks:

Task 1 - Literature Review

To prepare the current proposal, the research team has conducted a preliminary review of relevant studies and projects completed to date in the United States and beyond. As the first task of this project, the research team will compile all related information available in journals, conference proceedings, and technical reports in a concise summary usable by the involved researchers and engineers. The main objective of this task is to obtain a comprehensive understanding of the existing practices for the construction of jointless bridges with a special focus on ABC applications.

Progress from January 1, 2016 to March 31, 2016

The main goal of this research project is to investigate the use of a precast, flexible link slab through a comprehensive set of experimental tests and numerical simulations. For this purpose, the research team has initiated a comprehensive survey of the existing literature to understand the state of the practice and come up with a detailed plan to address the key research gaps through the next stages of the project. The main focus of this survey has been on jointless bridges, particularly for ABC applications.

Progress from April 1, 2016 to June 30, 2016

An extensive review of the existing literature was carried out in order to identify the available useful information for the research project as well as find gaps in the literature to further explore. Particular interest for ABC link slab applications was kept in mind when reviewing the available information. Early link slab research was conducted by Caner & Zia, which was one of the first attempts to formulate a link slab design procedure based on laboratory testing and Finite Element (FE) analysis. This research resulted in the first Reinforced Concrete (RC) link slab design procedure, based on applied moments from adjacent girder rotations as well as crack width criteria on the exposed link slab surface. A debonded zone under the link slab equal to 5% of the two adjacent girder spans to prevent stress concentrations was suggested [9]. This work was followed up by Wing & Kowalsky, who used this RC link slab design to implement and monitor the performance of the first link slab bridge in North Carolina by performing controlled live load tests on the bridge which was fitted with remote data collection instrumentation. The authors suggested that a mid-span saw cut be made in the link slab and sealed to prevent excessive cracking from tensile strain [35]. Okeil & ElSafty added to previous research by further investigating the effects of girder support conditions on the stresses developed in the link slab. It was found (contrary to Caner & Zia) that support conditions have a large effect on the stresses developed in the link slab. Design moment coefficients for roller and hinge support configurations were developed [25]. Ulku et al. further expanded on this research by using FE analysis to investigate the effects of support configuration, debonded length, girder height and span ratio under combined thermal and live loading on stresses in the link slab. The authors found that thermal loads are very significant and suggested the use of AASHTO LRFD Service 1 limit state for combined live and thermal loads as well as an axial force and moment interaction relation for link slab design [31]. Kim et al. explored the use of Engineered Cementitious Composite (ECC) for link slabs. ECC is a highly ductile fiber reinforced cementitious material that exhibits strain hardening and micro-cracking at strains up to 4%. The ECC link slab specimens were tested in lab under monotonic and fatigue loading and far outperformed RC link slabs in all aspects due to enhanced ductility and small crack width [15]. An ECC link slab design procedure was suggested by Lepech & Li which takes into account the post cracking tensile strength of the ECC material [17]. The first ECC link slab was installed on a bridge in Michigan and monitored by Li et al. It was found that early age shrinkage cracking was an issue with ECC due to the high cement content [18]. Other studies by Au et al. and Ho & Lukashenko documented the retrofitting of link slabs on in-service bridges using normal RC material. It was found that the presence of a link slab will decrease stresses in adjacent girder mid-spans and that measured girder strains were always less than girder strains derived through FE modeling and numerical simulations [4,14]. Although the literature provided a good review of the state of practice for link slab design and testing, there is yet to be a meaningful investigation into how link slabs can be utilized in ABC. This will be the main focus of the research herein.

<u>Progress from July 1, 2016 to December 31, 2016</u>

Literature pertaining to possible concrete materials for ABC link slabs has been reviewed to develop an understanding of fiber reinforced concrete and fiber reinforced cementitious composite materials. Three different material types have been identified as potential candidates for ABC link slab construction, each possessing their own relative advantages and disadvantages.

Kim et al. and Li et al. have demonstrated that ECC can perform well for link slab applications [15,18]. According to Wang & Li, ECC utilizes polyvinyl alcohol fibers, high fines content and high fly ash content to obtain a hardened composite that can produce up to 4% strain in tension while exhibiting strain hardening and micro-cracking properties. These cracking characteristics are achieved through tailoring fiber-matrix interactions and ensuring that the energy from fiber bridging strength is greater than the matrix fracture toughness [32]. Hajj et al. have demonstrated that Modified ECC with locally sourced aggregate materials can exhibit ductility that could satisfy the strain demand of a link slab [12]. Local aggregate materials could represent a large cost savings if performance criteria can be met.

Most concrete contractors are not familiar with making ECC mixes. This introduces uncertainty in the finished product which may bring rise to concerns about the quality and performance of the ECC. Literature from Thomas & Ramaswamy, Shafiq et al., Mohod, and Branston, among numerous other authors pertaining to the reinforcing effectiveness of different fiber types in normal fiber reinforced concrete has been reviewed in attempt to find a less technically advanced alternative to ECC [8,21,27,30]. Johston and Bentur & Mindess outline the fundamental properties and concepts of Fiber Reinforced Concrete and Fiber Reinforced Cementitious Composites. This literature led to an understanding of how aggregate size, aggregate volume, fiber type, fiber aspect ratio, fiber geometry, fiber volume, paste volume, matrix strength, and admixtures can affect the rheological and hardened properties of a fiber concrete system [6,14]. The different types of concrete fibers that are available on the North American market and their reinforcing potential in normal fiber reinforced concrete have been investigated in this task.

Textile concrete made with polypropylene matt reinforcement has shown to possess high strain capacity in tension as well as strain hardening and micro-cracking properties. Mumenya et al. showed that when used in relatively thin sheet components, tensile strain capacities well above 5% can be reached with no large cracks forming [23]. These composites are made sequentially laying up woven matts of fiber and cement mortar to a desired thickness. Mumenya explains that high strain capacity and strain hardening with micro-cracking are achieved because a very high fiber volume (well above the critical volume) can be reached with tensile concrete cast in this manner. The fibers are also preferentially aligned parallel to the direction of load, causing greater reinforcing effectiveness [22].

This task has been completed.

Task 2 - Experimental Tests on Link Slab Materials

The proposed research project aims to develop a flexible link slab to accommodate the deformations due to the extension/contraction and rotation of adjacent girder ends. For this purpose, ductile materials similar to Engineered Cementitious Composite (ECC) is expected to be used. Past studies available in the literature have demonstrated the capabilities of ECC to carry high tensile strains up to 4%. Furthermore, considering the concerns about the formation and propagation of cracks in conventional concrete [15,17,18], ECC is proven to limit the crack width under the large tensile strains that a link slab may undergo. To evaluate if the proposed material is capable of providing a satisfactory performance, dog-bone shaped specimens are constructed and tested under direct tension. The outcome of this test provides the stress-strain relationship further to the patterns of crack initiation and development. This is, as a matter of fact, one of the most important tasks of the current project because exceeding certain crack sizes can result in the penetration of water and aggressive agents into the link slab and eventually to the substructure components of the bridge.

In addition to stress-strain characteristics, the criteria to choose appropriate materials for reinforcement will be developed through this task. Contrary to the previous studies [4,10,25,35], which utilized steel rebars for reinforcement, the current project plans to benefit from Fiber Reinforced Polymer (FRP) materials for reinforcement. This choice has been made in line with the "low stiffness" design philosophy for link slabs. FRP rebars are particularly desired because of low elastic modulus, large linear elastic strain capacity, adequate bond with concrete, and high corrosion resistance compared to steel rebars. The tensile tests conducted through this task provide invaluable information about the interaction between the FRP reinforcement and surrounding cementitious matrix. A relation between transverse cracking and debonding at the rebar-matrix interface will also be established. This relation helps to determine the reinforcement requirements for the optimal performance of a link slab.

Progress from January 1, 2016 to March 31, 2016

N/A

Progress from April 1, 2016 to June 30, 2016

An extensive review of literature pertaining to ECC link slabs and ECC specimens in tension and/or flexure has been initiated to understand the fracture mechanics and mechanical behavior of Fiber Reinforced Concrete (FRC) and Fiber Reinforced Cementitious Composites (FRCC). Alternative cementitious materials that could potentially perform well for link slab applications are also being considered. The goal will be to find one or more additional concrete material that can perform in a similar manner to ECC in tension and flexure. Materials conducive to ABC, i.e. that have high early strength gain, or that could be used in a pre-cast situation will be the focus of this task.

Progress from July 1, 2016 to December 31, 2016

ECC has been identified as an “ideal” material for link slabs due to its highly ductile properties and low stiffness. Due to the reported impressive mechanical properties of ECC, the project will attempt to create an ECC mix that can exhibit satisfactory performance in ABC link slab applications. Drawbacks of ECC include material availability, expense, relatively slow strength gain and unfamiliarity among most concrete contractors. The project will attempt to expand possible material choices for link slabs beyond ECC to include less costly and technically advanced material that can satisfy ABC link slab design and serviceability criteria. Substantial research and literature reviews have been invested into developing an alternative link slab FRC material that is more conventional for concrete contractors. Interactions between FRC performance, rheology and different mixture components have been studied. Fundamentals of how fibers interact with the concrete matrix in the fresh and hardened state was explored and conclusions were drawn to identify fiber properties that would be conducive to ABC link slab performance criteria. The presence of coarse aggregate will reduce material cost but change the cracking properties of the FRC composite compared to ECC. However, by limiting the maximum size of aggregate, and including a sufficient fiber volume of high performance fibers, it is expected that the reinforcing effectiveness of fibers will be increased and crack widths can be controlled by the composite action of FRP rebar and reasonably high fiber content. Research has been initiated to explore the different potential types of commercially available fiber that can be used for FRC and each of their potential benefits. Once a complete understanding of different fiber types is reached, a number of potential top fiber types will be selected and their performance will be compared by laboratory tests.

Progress from January 1, 2017 to March 31, 2017

After completing a review of potential fiber choices for the previously mentioned contractor friendly fiber reinforced concrete link slab material, four synthetic macro fiber types were selected to be investigated for their concrete reinforcing potential. Four separate concrete fiber suppliers generously donated samples of fiber to the project for preliminary testing. The four fibers that were selected based on potential performance from literature and availability in the current market were High Strength Polyethylene (HSPE), Polyvinyl Alcohol (PVA), Polypropylene (PP), and Basalt. HSPE fibers were of the trade name Dyneema and were sourced from a third party as a waste fiber cut at ¾ inch length. This fiber has very high tensile elastic modulus and has been shown to have high reinforcing potential in concrete mortar and paste [5, 19]. There is a lack of studies conducted on its reinforcing potential in plain fiber reinforced concrete but good performance in mortars, high strength and elastic modulus as well as low cost made it logical to investigate HSPE as a potential fiber option. PVA fibers are used in ECC, however ECC utilizes micro PVA fibers, not macro. It was decided to investigate ¾ inch long, macro PVA fibers and their reinforcing effectiveness in concrete. Various studies have reported that PVA fiber performs better than other synthetic fibers in FRC due to its ability to form a chemical bond with the concrete matrix. The reported performance of PVA fiber in concrete and mortar made it an attractive fiber to explore for use in link slabs [7, 24, 27,]. Polypropylene is one of the most widely used synthetic fiber in concrete materials due to its low cost and chemically inert properties. A high performance polypropylene fiber under the name Forta Ferro was selected to be investigated for its reinforcing effectiveness. These fibers are a 1.5 inch long blend of mostly monofilament fibers with some fibrillated fibers mixed in. This product was highly recommended by the supplier as their “high performance” fiber as they claimed it was developed to outperform conventional polypropylene concrete fibers. A type of basalt fiber marketed under the name Basalt Minibars were also selected for testing. These fibers are 1.7 inches long and made by coating strands of extruded basalt rock with a proprietary resin that enhances bond with concrete and prevents alkali attack on the core fibers. These fibers are essentially a smaller version of GFRP rebar. Basalt Minibars were selected based on previous studies that have shown the product to mix very well with little effect on rheological properties as well as provide high post crack strength and toughness [8, 20, 26].

The four previously mentioned fibers were tested under 3rd point bending flexure to evaluate their reinforcing effectiveness. It is generally accepted that macro fibers do not change the matrix strength but are helpful in controlling the size and propagation of cracks once they form. Therefore the goal of this preliminary study was to evaluate the post crack performance of the four selected macro fiber types. Three fiber volumes were tested, 0.5%, 1.0% and 1.5% by volume, for each type of fiber. Since this material is intended to be contractor friendly, close attention was paid to how each type of fiber behaved when mixed into the concrete. Care was taken to ensure proper dispersion, workability and consolidation were achieved for each mix in order to get a fair comparison of each fibers performance at each of the tested volume fractions. The data from these tests will be analyzed and the most effective fiber type will be selected to move forward. An optimal macro fiber content will be selected to use in the final mix design.

Consideration is being given to adding a relatively small volume fraction of micro carbon fiber to the mix design in order to create a hybrid fiber mix. Literature suggests that hybrid fiber composites possess greater reinforcing potential than single fiber composites. The main reasoning behind adding micro carbon fiber is to control micro cracking at early ages as the concrete will be exposed to service loads at early ages due to ABC. Carbon fiber is chemically inert, has high elastic modulus and tensile strength, and is readily available for purchase making it a good choice for concrete micro fiber. It is expected that in the hybrid system the carbon fibers will be beneficial on a micro scale and the macro fibers will be beneficial on a macro scale and together their reinforcing effectiveness will be compounded. Thought has given to addressing high early strength requirements for this contractor friendly material as it will most likely be a cast in place option. It is hoped that through admixtures and properties of cementitious materials that 3000 psi will be reached in 24 hours. Shrinkage will also need to be addressed due to the need for a high cementitious content. These issues are being considered and will be addressed as the project progresses.

<u>Progress from April 1, 2017 to June 30, 2017</u>

Testing of four different types of concrete fibers for their effect on rheological properties in the fresh state as well as pre and post crack flexural properties was carried out. Polypropylene (PP), High Strength Polyethylene (HSPE), Polyvinyl Alcohol (PVA), and Basalt fibers were mixed at 0.5%, 1.0% and 1.5% by volume (HSPE was not mixed at 1.5% volume because of drastic effects on workability and clumping at 1.0%).

Fresh properties were evaluated using the Vibrating Kelly Ball (VKelly) test, which was originally developed for slip form paving applications and is gaining attention for other concrete applications (29, 28, 34). The VKelly test produces two parameters, the VKelly slump, and the VKelly index. The VKelly slump is obtained by doubling the penetration of the Kelly ball into the concrete under its own weight and is a measure of the static yield stress of the concrete, similar to the standard slump cone test. The VKelly index is obtained by introducing a controlled rate of vibration to the Kelly Ball and timing the penetration of the ball into the fresh concrete. This measures how well the mixture responds to vibration for placement and consolidation. This test was deemed suitable to gauge the fresh properties of the FRC mixtures since it could provide comparisons for both the static and dynamic properties of the FRC. It was found that three of the four fibers tested could be dispersed well at 0.5% volume. HSPE formed clumps at this volume (or any volume) due to the fibers affinity for each other prior to and during mixing. It was clear that the mixing energy provided by a gravity based drum mixer was insufficient to disperse the HSPE clumps, even at the lowest volume tested. PVA fibers mixed well at 0.5% volume, however when the volume fraction was increased to 1.0%, the fibers had a tendency to re-aggregate into clumps containing fiber, sand and paste. This was true for the 1.5% PVA mixture as well. PP fibers mixed well at 0.5% and 1.0%, however at the 1.5% volume fraction, they produced a very stiff mix that was difficult to consolidate and finish. Basalt fibers showed the most desirable fresh properties at all volume fractions. Even at 1.5% volume, the mix was still suitably workable as indicated by a much higher VKelly index that other 1.5% volume mixtures.

Flexural performance of the FRC mixtures were assessed using the ASTM C1609 standard (2). The standard tests 4”x4”x14” beams under third point bending and evaluates flexural strength as well as post crack residual strength and toughness. It was found that as a trend for all fibers, increasing the volume fraction increased the post crack performance. The same trend was noticed for pre crack strength (Modulus of Rupture), but there were some exceptions for PVA and HSPE likely due to fiber clumps producing weak spots in the cross section. Of the four fibers tested, PVA consistently showed the lowest flexural performance results. Basalt FRC produced the highest flexural performance results for 1.0% and 1.5% mixes, while surprisingly HSPE produced the highest flexural performance results at 0.5% volume despite the presence of clumps. PP mixtures produced flexural performance results that were relatively high but consistently lower than Basalt mixtures.

It was decided to move forward with Basalt Minibar fibers for increased toughness and crack control in the FRC link slab material due to the best performance in both the fresh and hardened state. Subsequent flexural tests for 0.75% and 0.9% Basalt fiber volume showed that 1.0% Basalt fiber volume was a reasonable optimal volume in the current mix design since 1.5% volume mix did not provide substantial increase to post crack performance compared to increase in cost.

<u>Progress from July 1, 2017 to September 30, 2017</u>

It was decided that the next logical step in the development of a cast in place, contractor friendly FRC ABC link slab material was to investigate the early age strength and restrained shrinkage of the concrete mix design. A 24 hour compressive strength of 3000 psi was deemed reasonable for ABC cast in place applications. Restrained shrinkage ring tests were conducted to quantify the shrinkage potential of the mixture, especially under high restraint from reinforcing congestion as would be expected in a link slab using conventional FRC.

The cementitious materials were adjusted to 20% replacement of type I/II Portland cement with class C fly ash. This was deemed suitable because the class C fly ash had more cementitious properties and increased the early age strength compared to the previously used class F fly ash. 20% Portland cement replacement was deemed suitable because this ratio could give compressive strengths that were consistently above 2500 psi, and the remaining strength would be gained through experimentation with high strength and modulus carbon fiber as well as accelerating admixture (ACC).

The complete experimental investigation to achieve early strength and manage drying shrinkage cracking involved testing 16 different concrete mixtures, utilizing 4 micro carbon fiber volumes (0.0%, 0.1%, 0.3%, and 0.5%), and set doses of ACC and shrinkage reducing admixtures (SRA) based on manufacturers recommendations. The micro carbon fibers were expected to increase strength parameters, as well as control or even prevent drying shrinkage cracking. Relatively low doses of micro fiber were utilized because the fibers have high aspect ratio and fiber surface, therefore they would be detrimental to workability at higher volumes. The ACC was utilized to achieve early strength for cast in place ABC, but it was also a point of interest to analyze how the ACC would affect the shrinkage of the mixture. The SRA was utilized to control the drying shrinkage strain, but SRA can decrease the compressive strength of the mixture by roughly 10%. It was a point of interest to see how the SRA behaved when used in conjunction with ACC for both early strength and shrinkage, since ACC and SRA are not typically used together.

The results of the early strength tests showed interesting results. Early compressive strengths were generally increased with increasing carbon fiber content. ACC consistently increased early strengths and SRA consistently decreased compressive strengths. It was concluded that the 3000 psi in 24 hour strength goal could be achieved with combinations of micro carbon fiber and SRA or ACC and SRA. Even at the low dose tested, the ACC early strength gain could make up for the loss of strength imparted by the SRA. Although the carbon fibers could increase the early strength sufficiently to above the target for 0.3% and 0.5% mixtures, it was deemed more efficient to increase strength with ACC or further changes to the cementitious material ratios since carbon fibers increase cost and need sufficient additions of superplasticizer to maintain reasonable workability.

The results of the restrained shrinkage ring test showed that carbon fiber content did not affect the rate or amount of shrinkage that specimens underwent, however there was evidence that the strength increase provided by even low additions of carbon fiber prevented cracking in the ring specimens. The only specimen that cracked was the specimen containing no fiber, but including ACC. Specimens with ACC an no SRA consistently produced the highest shrinkage rates and magnitudes. It was interesting to find that even though specimens including fiber, ACC and no SRA had high shrinkage rates and magnitudes, they did not crack. Since the specimen with ACC only cracked, this is evidence that the strength increases provided by the carbon fibers may have been enough to prevent cracking. The shrinkage ring tests results also showed that no adverse effects were found by using binary admixtures of ACC and SRA. Interestingly, when ACC and SRA are used together, similar shrinkage rates and magnitudes can be expected as if SRA was used alone. This compatibility of admixtures is very advantageous for cast in place ABC link slab construction because it shows that early strength can be tuned using ACC while using SRA to control drying shrinkage with no adverse effects.

A second experimental investigation was initiated to identify the potential benefits of using macro basalt minibar fibers at doses around 1.0% volume in conjunction with small additions (around 0.2%) of carbon and fibrillated polypropylene micro fibers separately. 24 hour compressive strengths and ASTM C1609 beam tests were performed in order to potentially identify any fiber synergistic effects between micro and macro fibers. It is hoped that micro fibers will bridge micro-cracks and keep the macro fibers bonded to the matrix during crack formation and opening, effectively increasing the toughness of the composite. These tests have been performed and the data are being analyzed.

Progress from October 1, 2017 to December 31, 2017

Preliminary mixtures of small ECC batches were prepared based on a popular ECC mix design reported in the literature called ECC-M45. The preliminary mixtures were intended for us to get a feel for how ECC behaves during mixing and in the fresh state. It was found that pseudo strain hardening in flexure could be achieved with ECC made with local mortar sand. Two gradations of silica sand have been obtained for ECC ductility testing. It is expected that a finer sand gradation will produce more ductile ECC mixtures and this will be investigated to develop a highly ductile ECC pre-cast ABC link slab.

Reinforcement ratios have been selected for direct tensile testing of large dog-bone shaped specimens including rebar. Fine tuning of the test set up is being conducted and use of Digital Image Correlation (DIC) technology is being considered to monitor cracking patterns of the materials at different tensile strains. Specimens will have varying reinforcement ratios. The results of the direct tension tests will be used to determine optimal reinforcement ratios for different materials in the scaled up link slab lab tests of Task 3.

Task 3 - Experimental Tests on Bridge Joints

To investigate the performance of the link slabs constructed with materials identified in the previous task, full-scale experimental tests will be conducted. For this purpose, a set of prototype slab-on-girder bridges are studied to determine the dimensions to be used for the test specimens. The test model is expected to be a single girder system with necessary support conditions. To understand the structural behavior of the link slab in the real condition, two loading cases will be applied. The first case includes a constantly increasing static load to obtain the load-deformation response further to determine the maximum capacity of the system given the serviceability criteria. The second case consists of cyclic loads to examine the long-term performance of the system under traffic loads. This has a critical contribution to quantify the extent of structural degradation and pattern of formation of cracks under repetitive loads.

The full-scale experimental tests are also used to evaluate some of the current construction practices, especially in terms of debonded length. The debonded length is provided mainly to reduce the stiffness of the link slab and minimize the stress due to the distribution of the induced curvature. Although increasing the debonded length can potentially improve the structural performance of the link slab, it may cause issues at the time of construction and even maintenance. Hence, it is important to identify an optimal debonded length considering various performance and durability aspects. While a debonded length of 5% has been recommended in the literature, efforts have been made to evaluate shorter and longer debonded lengths as well [4,31,35]. This important aspect will be explored in a systematic way through the current task.

<u>Progress from January 1, 2016 to March 31, 2016</u>

A preliminary study of requirements for the experimental test setup has also been completed based on the expected performance criteria. This contributes to finalize the configuration of the test setup needed to evaluate the link slab under various loading scenarios.

<u>Progress from April 1, 2016 to June 30, 2016</u>

N/A

Progress from July 1, 2016 to December 31, 2016

Preliminary plans for the structural configuration of link slab testing have been initiated. Link slab specimens will tentatively be tested at 1% strain design as this is a reasonable value for design based on calculation procedures found in literature. Making the link slab cross section thinner may be an option in design to promote low continuity between spans, which results in reducing the intrusiveness to other structural elements of the bridge. Compressive strain should be avoided if thin sections are used in order to avoid buckling of the section. Pre-straining or pre-cracking the link slab specimen as well as strategic timing for placement of the link slab in hot weather may be options to avoid compression in the link slab from thermal expansion loads.

Progress from January 1, 2017 to March 31, 2017

Initial thought and planning has been given to the configuration for full scale link slab testing. The ideal test set up would test the specimens under both axial stress and bending stress which simulates thermal loads combined with girder rotations from live loads. Since more than one type of material is being considered, the details of the test set up for each material may differ. ECC or textile concrete link slabs may be better suited for pre-cast link slab applications and therefore connection details may be a point of interest. More information is available on connections and reinforcement configurations for full depth cast in place link slabs so the material performance and cracking characteristics of the contractor friendly FRC material option may be a point of interest. A preliminary review of available testing equipment and any equipment that may need to be built to carry out the full scale tests has been initiated.

Progress from April 1, 2017 to June 30, 2017

By conducting direct tensile tests on large dog-bone specimens with rebar embedded in the active zone, more information can be gathered about cracking patterns at different strains before full scale testing. This should save large amounts of material and effort by minimizing the number of full scale tests that need to be completed since the dog-bone tests will provide information about optimal reinforcement type (steel or GFRP) and reinforcement ratios.

The test set-up for the full scale lab tests is still under consideration since it may be difficult to provide strain application to the link slab that encompasses both translation and rotation. Some sort of set up allowing initial translational movement followed by pin rotation to desired strain at the top of the link slab would be ideal and different mechanisms are being considered. For pre-cast link slabs, the connection details will be the most important point of interest, some sort of closure pour using rapid set cement material may be the best way to achieve ABC criteria. Connections without a closure pour are being considered however gaps between the link slab and deck and undesirable stress concentrations may be unavoidable if there is no closure pour to tie the link slab to the deck reinforcement and/or girder shear studs.

Progress from July 1, 2017 to September 30, 2017

The large majority of time and effort was designated to task 2 during this quarter. Through the process of executing the material tests, the bridge joint tests are being kept in mind so that the transition from material tests to large slab tests is seamless. As previously mentioned, it is hoped that material and effort can be saved through the utilization of large dog bone specimen direct tensile tests before full slab tests. Preliminary structural configurations for the full slab tests are being considered and evaluated in order to optimize the configurations for both cast in place and pre cast link slabs in advance.

Progress from October 1, 2017 to December 31, 2017

Configurations for the bridge joint tests incorporating full and partial depth ABC link slabs are being investigated in detail. Limitations of previous research efforts of this kind are mostly linked to unrealistic loading of the link slab because of support condition limitations. This effort hopes to be able to successfully incorporate both flexural load and axial load, corresponding to a combination of live load girder rotation and axial deformation from thermal gradient. This loading combination will be more effective in replicating in situ service loads on the slab. Materials are being sourced and quantities required for the tests are being calculated. Connection details for pre-cast link slabs are under further review for the most effective ABC solutions. All possible sources of complications that might be encountered are being considered as we prepare to transition from the materials level tests of Task 2 to the bridge joint tests of Task 3.

Task 4 - Parametric Studies and Design Recommendations

Based on the outcome of the previous tasks, a set of numerical simulations will be performed to develop the models that can properly capture the structural response of the link slabs in various structural configurations and loading cases. The obtained information from experimental tests and parametric studies will be utilized to examine the current design recommendations and make the required modifications. The current literature highlights the fact that the models proposed earlier are in need of revision. Further to the contribution of the outcome of this task to improve the design of the link slab for conventional bridges, a special effort will be made to adjust the design guidelines based on the practical considerations demanded by ABC applications.

Progress from January 1, 2016 to March 31, 2016

N/A

Progress from April 1, 2016 to June 30, 2016

N/A

Progress from September 1, 2016 to December 31, 2016

N/A

Progress from January 1, 2017 to March 31, 2017

The creation of preliminary full scale link slab bridge and link slab models has been initiated in the Finite Element program ABAQUS. The preliminary material characteristics gained from small scale material tests is being considered in the link slab models. More accurate material properties will be available once the materials tasks are further advanced. Finite element analysis is expected to validate and expand the data collected during full scale link slab tests as well as help form conclusions about which bridge design configurations would be conducive to link slab installation.

Progress from April 1, 2017 to June 30, 2017

As ABC link slab materials tests advance, more accurate FE models can be produced. More attention has been paid to the material tests during this phase since final material properties are needed to produce accurate FE models to validate data produced in the lab.

<u>Progress from July 1, 2017 to September 30, 2017</u>

Further advancements in material optimization will continue to provide more accurate inputs for FE models. As the in lab tests transition from material level to full slab tests, more attention will be given to this task since the model parameters are highly dependent on the configuration of the full slab tests.

<u>Progress from October 1, 2017 to December 31, 2017</u>

Work has been initiated to increase the accuracy of the FE models in order to represent likely in situ link slab bridge conditions. The main parameters that are being considered are bearing support stiffness, link slab material behavior, and link slab structural configuration (partial depth vs. full depth). As the accuracy of the FE models increases, we will have better insight to effectively develop the final configuration of the bridge joint tests.

Task 5 - Final Report

A detailed final report will be prepared to document the activities of the project further to all the main observations and findings.

<u>Progress from January 1, 2016 to March 31, 2016</u>

N/A

<u>Progress from April 1, 2016 to June 30, 2016</u>

N/A

Progress from September 1, 2016 to December 31, 2016

N/A

Progress from January 1, 2017 to March 31, 2017

N/A

Progress from April 1, 2017 to June 30, 2017

N/A

Progress from July 1, 2017 to September 30, 2017

Significant progress has been made with the completion of the initial drafts of two journal papers describing the results of the first two material test investigations. These works will be used to articulate the results in the final report.

Progress from October 1, 2017 to December 31, 2017

A substantial investment has been given to writing during this quarter, with two journal papers near completion and a third journal paper initial draft under internal review. As more data becomes available from the upcoming lab tests and FE model improvements, the final report will advance further to completion.

E.5. EXPECTED RESULTS AND SPECIFIC DELIVERABLES

The primary deliverable resulting from this work will be design guidelines and practical recommendations for the use of link slabs in the bridges built with ABC techniques.

E.6. TIMELINE (GANTT CHART)

Proposed Tasks	Year 1												Year 2											
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Task 1 - Literature Review	■	■	■	■																				
Task 2 - Experimental Tests on Materials				■	■	■	■	■	■	■														
Task 3 - Experimental Tests on Bridge Elements									■	■	■	■	■	■	■	■	■	■	■	■				
Task 4 - Parametric Studies and Design Recommendations									■	■	■	■							■	■	■	■		
Task 5 - Final Report																					■	■	■	■

F. DISCUSSION OF PERTINENT COMPLETED AND IN PROGRESS RESEARCH. FOR PROJECTS CO-FUNDED BY OTHER SOURCES, COPY OF THE CO-FUNDED PROPOSAL SHOULD BE ATTACHED AS AN APPENDIX.

N/A

G. DESCRIBE THE PLAN FOR COOPERATING WITH OTHER ABC-UTC CONSOURTIUM UNIVERSITY MEMBERS

The research team will form a Technical Advisory Committee (TAC) to oversee and guide the activities planned for this research project. Each of the other ABC-UTC consortium members will be asked to nominate a member to serve on the TAC. The TAC for this project shall meet at least twice a year (to be scheduled in advance) such that the research team can provide regular and timely updates on the progress made and the steps to be taken to successfully complete the project.

H. KEY WORDS

Link slab, jointless bridges, structural performance assessment, durability considerations, Accelerated Bridge Construction

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J. STAFFING PLAN (Should correspond with budget)

This work will be conducted under the guidance of Dr. Behrouz Shafei, Dr. Brent Phares, and Dr. Peter Taylor at Iowa State University.