EXHIBIT A – SCOPE OF SERVICE

Project Title: **BRIDGE DECK WITH LINK-SLAB**

for FPID: 435390-1-52-01: US 41 from Midway Blvd to Enterprise

Contract Number: BDV34 986-02

Deliverable 1 - TASK 1 – Literature Review

Submitted by: Principal Investigator: **Adel ElSafty**, Ph.D., P.E.
University of North Florida
Address: School of Engineering, 1 UNF Drive, Jacksonville, FL 32224-2645
Email Address: adel.el-safty@unf.edu
Phone Number: (904) 620-1398

Submitted to: Steven Nolan
The Florida Department of Transportation
State Structures Design Office
605 Suwannee Street, MS 33
Tallahassee, FL 32399-0450

Dr. Cheresa Y. Boston
Director of Sponsored Research,
University of North Florida, Office of Research and Sponsored Programs
1 UNF Drive, Jacksonville, Florida 32224
Phone: (904) 620-2455, Fax: (904) 620-2457, Email: cheresa.boston@unf.edu

Project Manager: Steven Nolan
Florida Department of Transportation
State Structures Design Office
Email Address: Steven.Nolan@dot.state.fl.us , Phone: (850) 414-4272

February 28, 2019

BACKGROUND STATEMENT

Bridge deck joints are costly to buy, install, and maintain. They have provided severe performance and maintenance problems as water and deck drainage contaminated with chemicals leak through the superstructure and onto the pier caps below, thus damaging or eventually completely destroying some vital parts of bridges such as prestressing cable anchorage systems, beams, bearings, substructure seat areas, and end diaphragms. Also, debris accumulation in the joints may restrain deck expansion (ElSafty 1994).

One of the best solutions is to adopt jointless bridges and elimination of expansion joints in bridge decks. That has been an effective method of constructing bridges. It corresponds to reduced maintenance and improved bridge-deck life expectancy. It is possible to replace bearing devices with simple elastomeric pads, or totally integrate the superstructure with the supports without any bearings. With the use of jointless bridge decks, there are no joints to purchase nor bearings to maintain, the riding surface is smoother, the initial and life-cycle cost are lower, and there will be a reduction in span bending moments and deflections. In conclusion, using a link-slab and making the bridge girders (partially continuous) continuous for live load provides lower cost, improved durability, longer spans, improved seismic performance, better resistance to wind loads and storm wave loads, improved structural integrity, and improved riding quality. Current consensus seems to allow elimination of expansion joints on bridges as long as 650 feet. Much longer bridges have occasionally been constructed without reported distress. There is a need for simple guidelines for design and detailing of the popular continuous-for-live-load connection system. An options for jointless bridge deck link-slab is shown in Fig. 1.

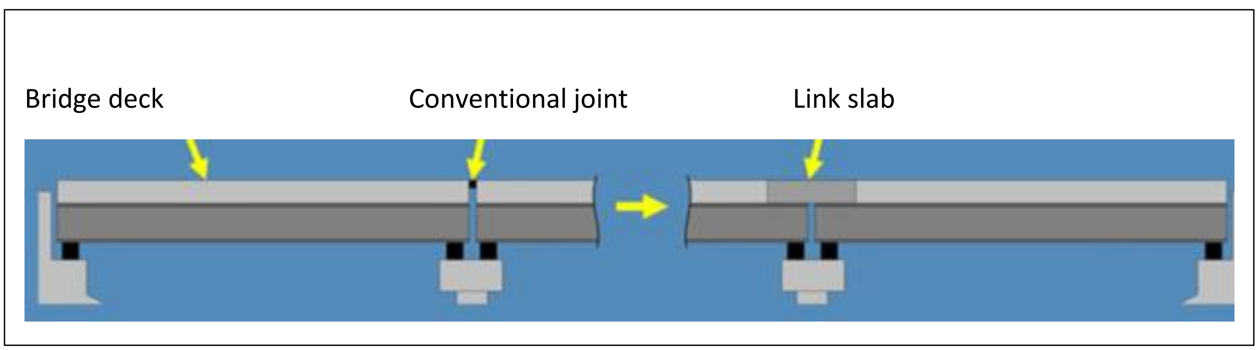


Fig. 1: Link-slab option

LITERATURE REVIEW:

The national bridge inventory indicates that a big percentage of the highway bridges in United States are designed as single or multiple simple-span girders supported at the piers and abutments, and separated by joints (FHWA 2004). These joints are provided at the girder ends of each simple span to allow the movement of the deck and superstructure due to temperature changes, shrinkage, creep, and other effects. These deck joints generally lead to water, sometimes contaminated with chlorides, leaking through the joints causing deterioration and corrosion of the bridge deck, girders, bearing, and supporting systems. Joints can also get filled with debris and fail to allow expansion and contraction of the superstructure. Therefore, the joint systems affect the durability of bridge structures and do not provide a reliable and leak-proof performance. In addition, joints and bearings can be expensive to install and maintain.

A growing trend in bridge design has been toward the elimination of joints and bearings in the bridge superstructure. Yet, the behavior of jointless bridge deck is not precisely known and the designs could have some uncertainties. Despite the numerous benefits of jointless bridge decks, there is no standardized design procedures for these bridges and there is only a list of specifications and design recommendations available. Therefore, there is a need to further investigate the feasibility of an innovative system for reducing or eliminating the number of bridge deck joints. The alternatives include using a concrete or ultra-high-performance concrete (UHPC) link-slab reinforced with steel or fiber-reinforced polymer (FRP) rebar to join adjacent bridge decks without imposing girder continuity.

Over many years, the use of jointless bridges has proven to be an excellent alternative to preserve bridges from the adverse effects of debris, leaking water, and salt induced corrosion damage. The jointless bridge option had also proven to be an economical option that provided several inherent design advantages. In the AASHTO LRFD Bridge Design Specifications, there are no requirements for maximum bridge length allowed without expansion joints. Most state highway agencies allow eliminating joints for bridges whose lengths are less than 350 feet for bridges with steel beams and 650 feet with concrete beams; however, there are some bridges over 1000 ft long that have performed well without expansion joint (Tadros 2016).

Several researchers indicted the effect of deck continuity over the piers on the moment developed in the spans, the reduction in deflection and vibration than simple span bridge girders, the improved durability and riding quality after eliminating the joints. Gastal and Zia (1989) performed an analysis of bridge beams with jointless decks. ElSafty (1994) conducted an analysis and investigation of jointless bridge decks with partially debonded simple span beams. Zia et al. (1998) investigated casting fully-continuous deck over simply supported girders with partial debonding of the deck from the girders ends at supports, using both numerical and experimental analysis, as shown in Fig. 2. Okeil and Elsafty (2005) investigated the partial continuity in bridge girders with jointless decks and the effect of the system's support configuration on the axial force developed in the link-slab. Caner and Zia (1998) presented the results of a test program to investigate the behavior of link-slabs connecting two adjacent simple-span girders, and proposed a simple method for designing the link-slab. ElSafty and Okeil (2008) also investigated extending the service life of bridges using continuous decks, as shown in Fig. 3 and Fig. 4.

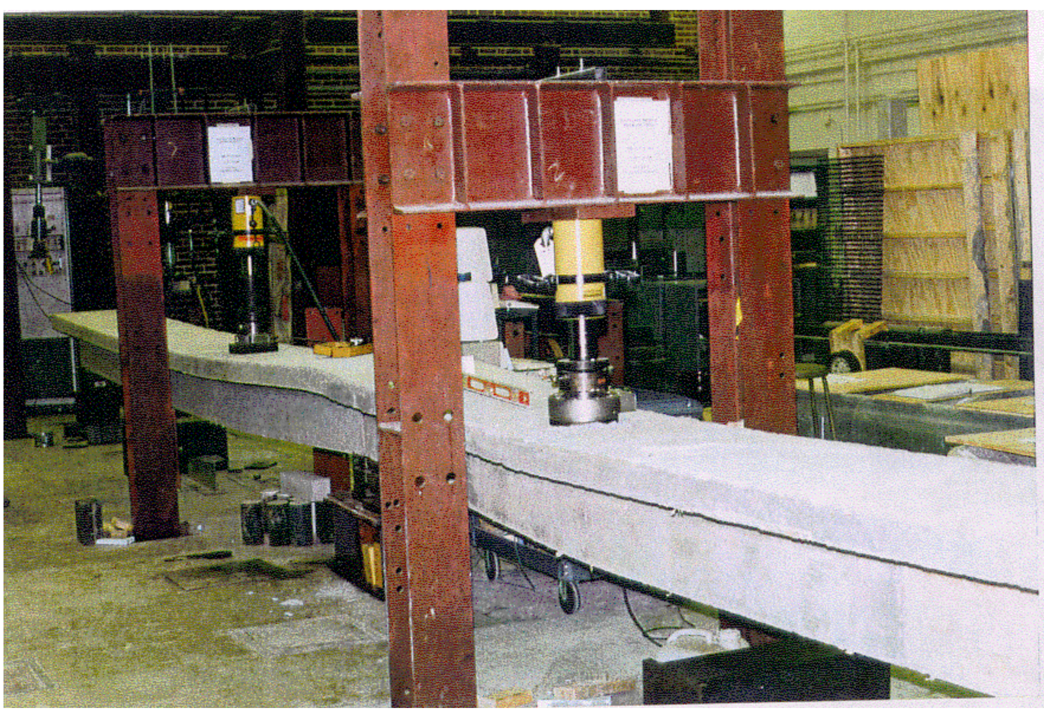


Fig. 2: Testing of a 2-span bridge model - Zia et al. (1998)

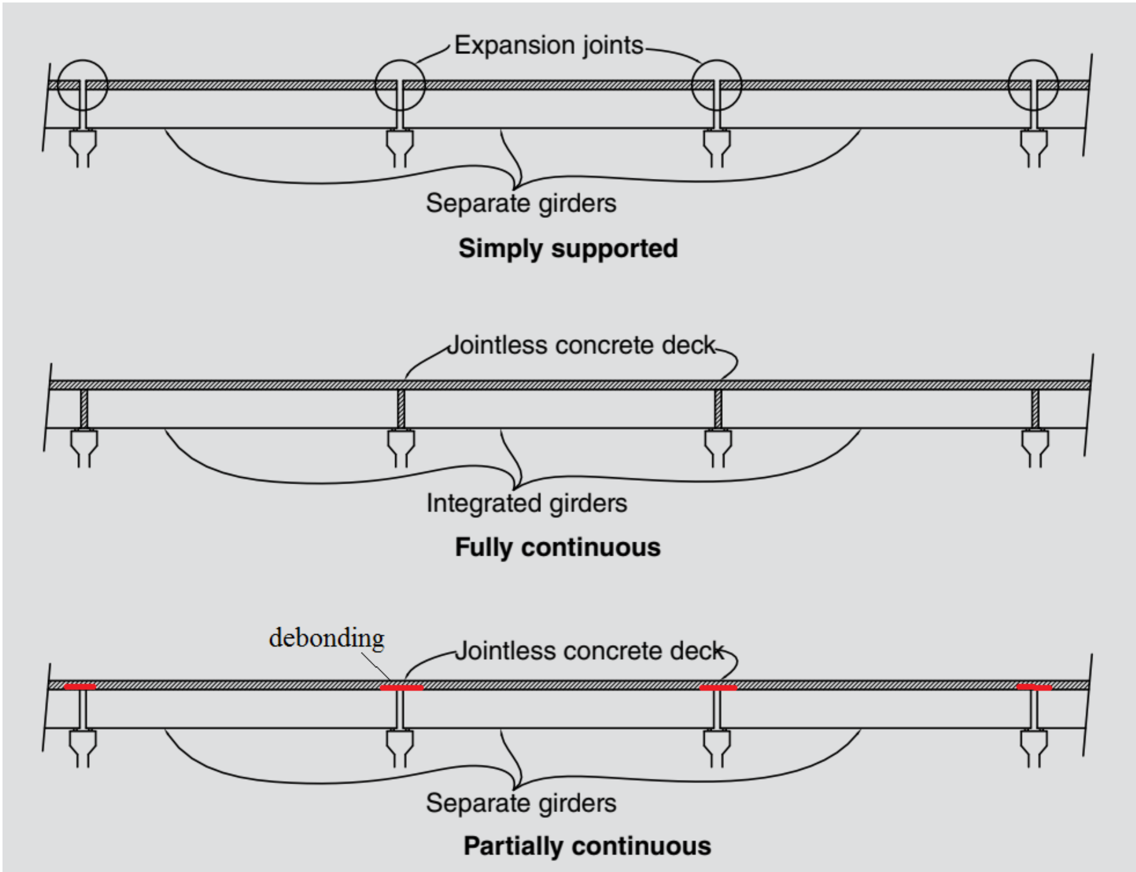


Fig. 3: Some types of jointless bridge decks

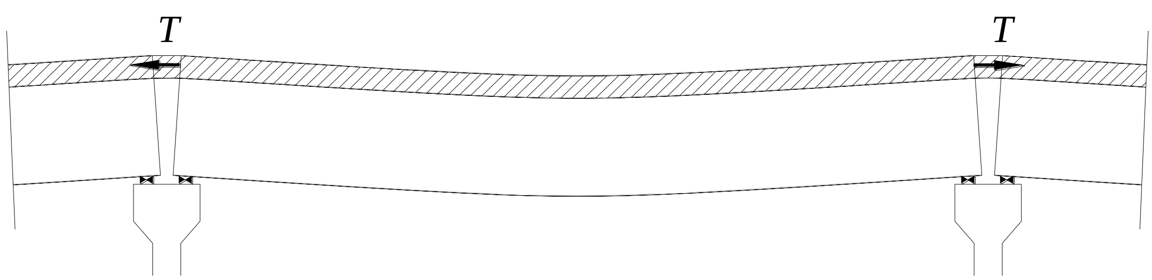


Fig. 4: Continuity caused by linking concrete decks in adjacent spans

Thippeswamy et al. (2002) conducted an investigation on jointless bridges to study the behavior of jointless bridges supported on piles and spread footings and subjected to varying load conditions. In addition, time-dependent material properties have also been investigated. In their study, Thippeswamy et al. (2002) presented synthesized analytical data to understand the performance under varying load combinations, field testing and monitoring results of a jointless bridge West Virginia, and effects of primary versus secondary loads, boundary conditions, and system flexibility on induced stresses at various bridge locations.

Reyes and Robertson (2011) investigated the use of high-performance fiber-reinforced cementitious composite (HPFRCC) reinforced with glass fiber reinforced polymer (GFRP) bars as link-slabs to replace the bridge expansion joints. Several small-scale specimens were tested. Then, a full scale test specimen with a full scale bridge expansion joint was investigated to characterize the performance of HPFRCC with GFRP reinforcing bars. The full-scale bridge expansion joint specimen emulated an expansion joint condition of a composite steel girder to concrete deck slab section. The link-slab was subjected to cyclic axial strains in both tension and compression and later in direct tension until failure. It was found that the cast-in-place link-slab had the advantage of providing good continuity with the bridge deck. The failure was due to rupture of the anchorage at the ends of the link-slab.

Virginia DOT also suggested the shown link-slab detail, Fig. 5.

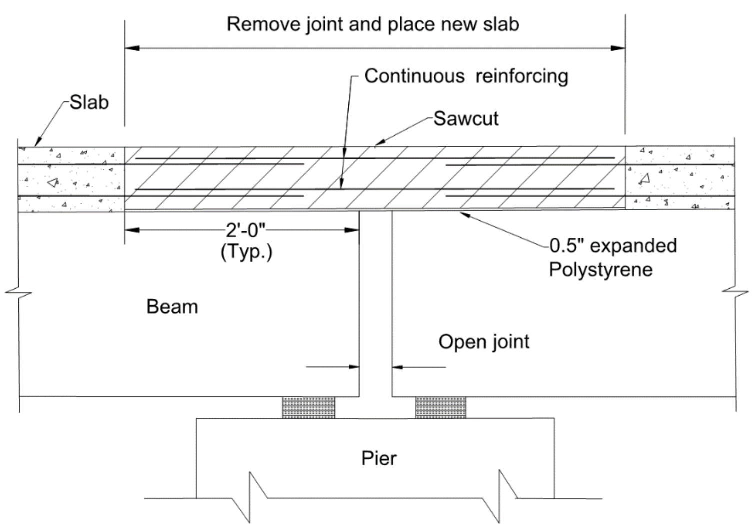


Fig. 5: Use of link-slab by VDOT for rehabilitation work to eliminate expansion joint

Virginia DOT also listed the following types of joint systems used in Virginia, as shown in Figs. 6-13:

- **Armored Joints – Open or Sealed**

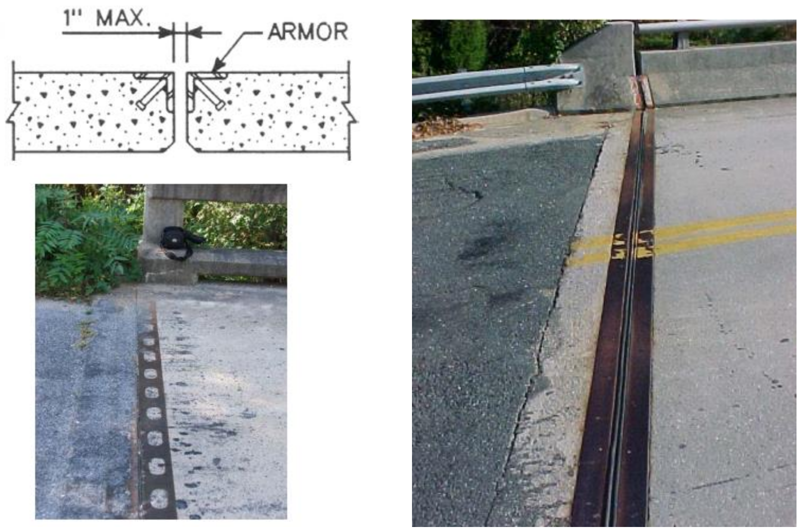


Fig. 6: Armored Joints

- **Hot Poured Sealer /Expansion Material**

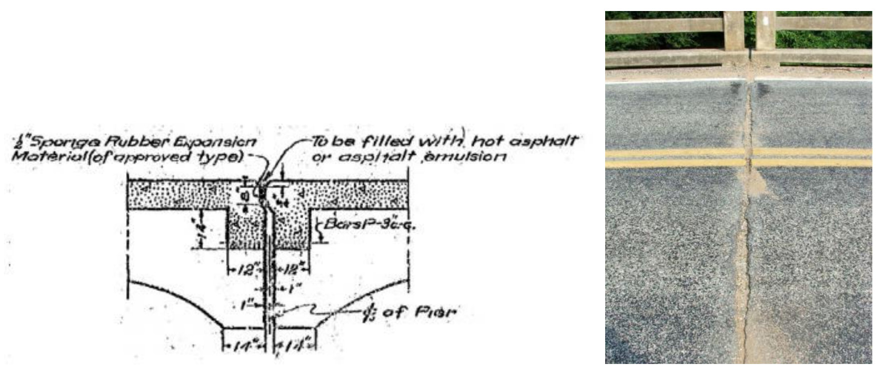


Fig. 7: Hot Poured Sealer

- **Preformed Elastomeric Compression Seals**

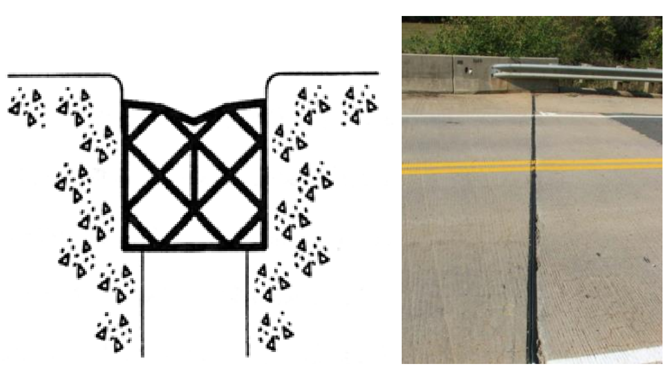


Fig. 8: Preformed Elastomeric Compression Seals

- **Poured (Silicone) Seals**

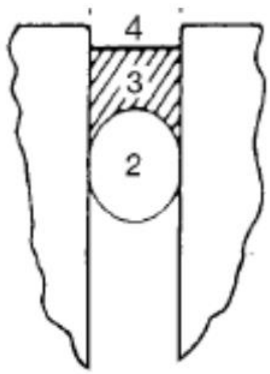


Fig. 9: Poured (Silicone) Seals

- **Asphalt Plug Joints**

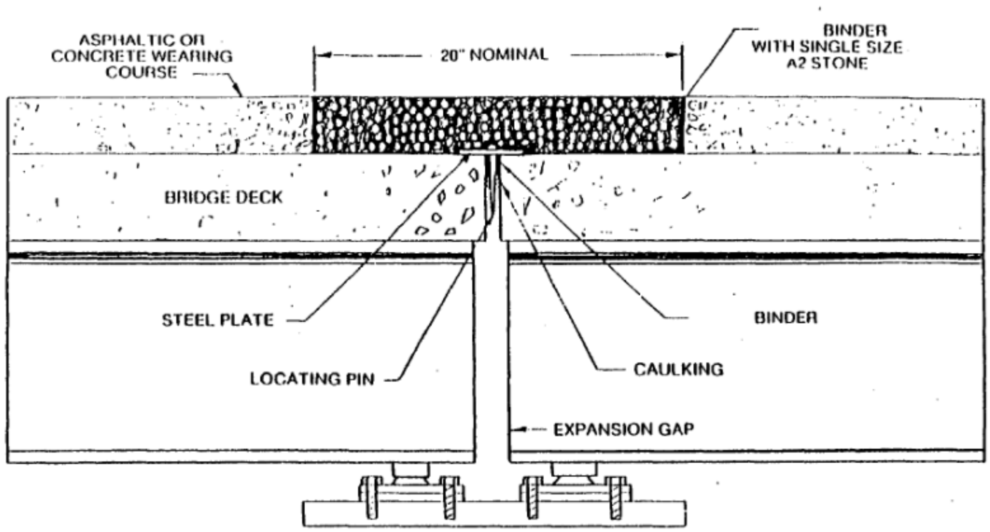


Fig. 10: Asphalt Plug Joints

- **Strip Seals**

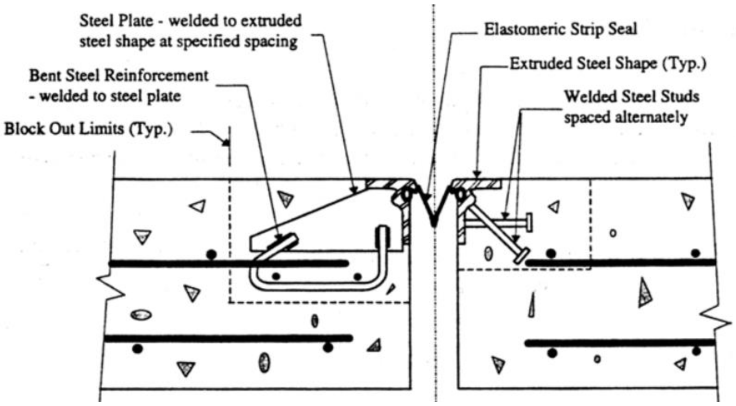
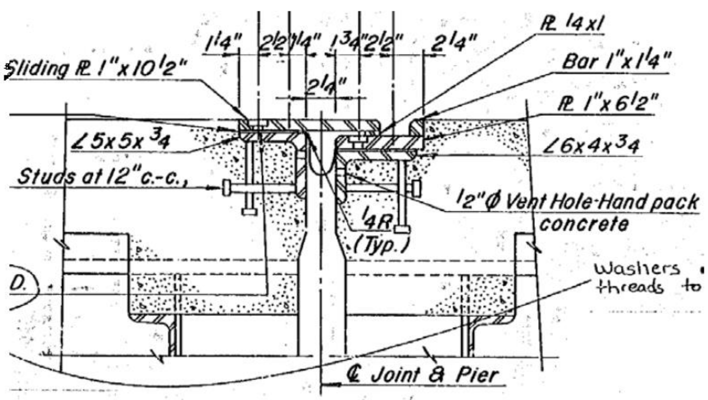


Fig. 11: Strip Seals

- **Sliding Plate Joints**



- **Finger Joints**

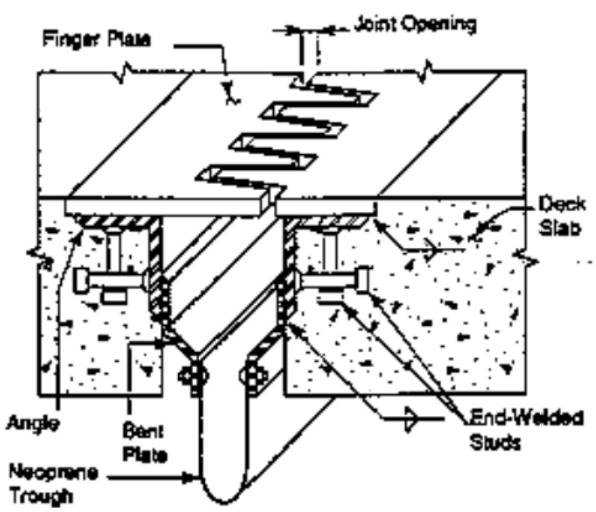


Fig. 12: Finger Joints

- **Cushion Seal (Elastomeric Expansion Dam)**

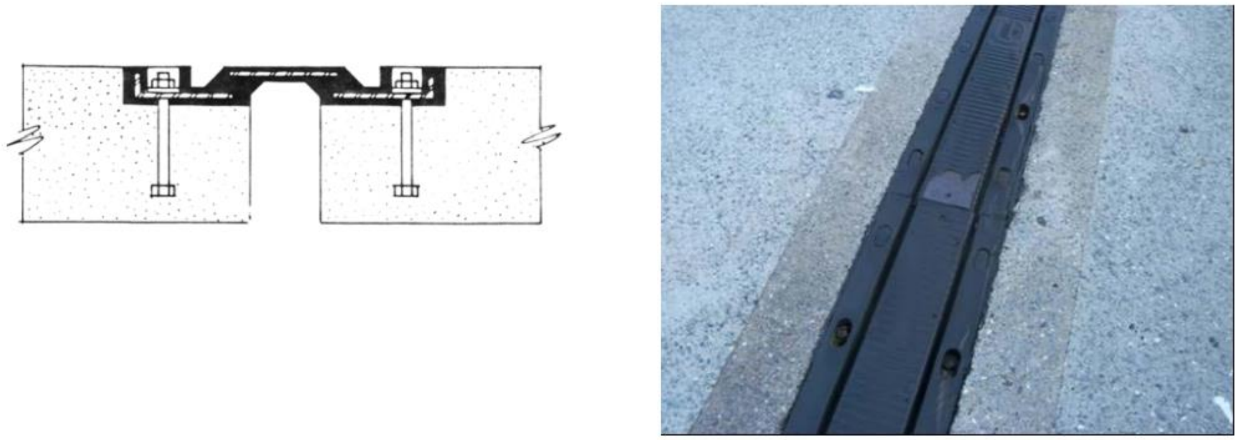


Fig. 13: Cushion Seal (Elastomeric Expansion Dam)

Xu et al. 2018 discussed an approach taken to rehabilitate the Shili Bridge by eliminating expansion joints and retrofitting the structure from simply-supported concrete box girders into a continuous bridge. Condition assessments were performed before retrofitting. In addition, several design options and construction procedures were considered and analyzed. Static and dynamic load tests were carried out after the completion of rehabilitation. The lessons learned in this project are presented and discussed. This practical and novel methodology was a step forward toward improving safety, sustainability, reliability, and quality of such existing bridges in China and elsewhere. It was concluded that Continuity of side-by-side box girders not only eliminated joints between the spans, but also reduced the positive moment at midspan by introducing negative dead load bending moment over the supports. Removal of joints over the abutments enhances bridge durability and eliminates the typical bump at the ends of a bridge. These factors would contribute to improved bridge durability, better ride quality, and reduced maintenance costs. The rehabilitation and strengthening of Shili Bridge provides a basis for the retrofitting of similar existing bridges to address durability and deterioration problems. Providing continuity can also reduce the amount of strengthening materials (CFRP and metal plates) that may be needed along the bottom of the girders. This is because the length of the positive bending moment region would be shortened after continuity of girders is achieved, thus reducing construction quantities and achieving overall cost savings. Steps must be taken to limit any restraints to the free sliding of the approach slab. A separation is needed between the sliding approach slab and the curbs to ensure that the approach slab can slide as freely as possible.

Groli et al. (2014) conducted an experimental campaign aimed at validating a previously published simplified serviceability design method of the columns of long jointless structures. The proposed method was also extended to include tension stiffening effects which proved to be significant in structures with a small amount of reinforcement subjected to small axial loading. This refinement allowed significant improvement of predictions for this type of element. The campaign involved columns with different reinforcement and axial load ratios, given that these parameters had been identified as crucial when designing columns subjected to imposed displacements. Experimental results were presented and discussed, with particular regard to cracking behaviour and structural stiffness. Considerations on tension stiffening effects were also made. Finally, the application of the method to typical bridge and building cases was presented, showing the feasibility of jointless construction, and the limits which should be respected.

Mothe (2006) investigated the behavior of the link-slab and its effect on the behavior of the bridge system as a whole. The scope of the study was to develop FE models to analyze the variation of forces, stresses and moments in the link-slab as well as the level of continuity generated in the girder system. The analysis was carried out for different bridge parameters which are likely to affect the behavior of link-slab; namely, bearing stiffness, skew angle, span lengths and debonding length ratio of link-slab. The study helped in understanding the effects of the aforementioned factors on the behavior of the link-slab and the system. The study also proposed development of a modified three moment equation for different parameters. The parameters which influence the three moment expression are the bearing stiffnesses, material properties and geometric information. A thorough parametric study is required to validate the expression. The results can be used for development of a design procedure for the link-slab and the expression can be used for analysis of the link-slab. The results obtained showed that the link-slab behaves more like a tensile member rather than a bending member with the increase in bearing stiffness and debonding length ratios. This observation was consistent in all the bridge types and skew angles considered for the study.

Ho and Lukashenko (2011) described the available design methodologies and provide an example of its application for a bridge retrofit. Link-slabs are currently being installed in new bridge construction, and also used to replace expansion joints in the rehabilitation of existing structures. The applicable use of link-slabs in the field is limited by variables such as girder end rotation from applied loads, bridge skew, and girder depth. Link-slabs are designed to flex, however excessive deflection causes potential for the development of wide cracks, exposing the interior steel reinforcement to susceptibility of corrosion. The concrete deck is typically composite with the supporting steel or concrete girders, but is debonded in the link-slab region to increase the link-slab curvature length, resulting in a reduced slab flexure and minimizing cracking. Although flexural cracking cannot be completely eliminated, water ingress into the cracks can be controlled by the following design considerations: limiting deck crack opening width by limiting end girder rotation; application of waterproofing membrane on top of concrete deck; and use of fiber reinforced concrete in the link-slab. It was indicated that examples of successful link-slab applications have been implemented in Ontario, Canada and Michigan, USA. The benefits of the use of link-slabs include reduced costs for maintenance of expansion joints, and less reinforcing steel in the deck resulting in less construction time and cost. Also with the elimination of expansion joints, there is less likelihood of chlorides permeating through the joint and causing corrosion and damage to the reinforced deck and substructure components. The use of link-slabs are slowly gaining acceptance as Canadian Ministries of Transportation learn more about their benefits of reduced maintenance costs over the lifespan of new or rehabilitated structures. It is recommended that these link-slabs be monitored over their service lives to better determine their long-term effectiveness.

Kendall et al. (2008) developed and applied an integrated life-cycle assessment and life-cycle cost analysis model to enhance the sustainability of concrete bridge infrastructure. The objective of that model was to compare alternative bridge deck designs from a sustainability perspective that accounts for total life-cycle costs including agency, user, and environmental costs. A conventional concrete bridge deck and an alternative engineered cementitious composite link-slab design were examined. Despite higher initial costs and greater material related environmental impacts on a per mass basis, the link-slab design results in lower life-cycle costs and reduced environmental impacts when evaluated over the entire life cycle. Traffic delay caused by construction comprises 91% of total costs for both designs. Costs to the funding agency comprise less than 3% of total costs, and environmental costs are less than 0.5%. These results showed life-cycle modeling is an important decision-making tool since initial costs and agency costs are not illustrative of total life-cycle costs. Additionally, accounting for construction-related traffic delay was vital to assessing the total economic cost and environmental impact of infrastructure design decisions.

New York DOT

New York DOT has been building integral bridges as well as jointless decks since the late 1970s. They performed well from the beginning, but a recent study evaluated their performance to identify details possibly needing improvement in future construction. Ratings obtained during a field survey of numerous integral bridges and jointless bridge abutments were analyzed, as well as condition ratings assigned by bridge inspectors during their biennial inspections (Alampalli and Yannotti 1998). Results indicate that these bridges have been functioning as designed and showed superior performance when compared with conventional bridges. These types thus should be used whenever possible to eliminate joints in bridge construction. Details needing improvement were identified. On the basis of these observations, design changes have been recommended for future construction. Integral bridges will be limited to structures having skews less than 30 degrees pending further study. A research project was initiated for further examination of construction practices and assumptions made during the design process.

North Carolina DOT

Gastal and Zia (1989) performed an analysis of bridge beams with jointless decks. ElSafty (1994) conducted an analysis and investigation of jointless bridge decks with partially debonded simple span beams. Zia et al. (1998) investigated casting fully-continuous deck over simply supported girders with partial debonding of the deck from the girders ends at supports, using both numerical and experimental analysis, as shown in Fig. 2. Okeil and Elsafty (2005) investigated the partial continuity in bridge girders with jointless decks and the effect of the system's support configuration on the axial force developed in the link-slab. Caner and Zia (1998) presented the results of a test program to investigate the behavior of link-slabs connecting two adjacent simple-span girders, and proposed a simple method for designing the link-slab. ElSafty and Okeil (2008) also investigated extending the service life of bridges using continuous decks. Wing and Kowalsky

(Wing 2005) evaluated the link-slab concept proposed earlier by Caner and Zia (1998), constructed, and instrumented a full-scale jointless bridge and its link-slabs for performance evaluation. This study has concluded that although the design rotation of the link-slab, obtained by assuming simply-supported deck, was 0.002 radian, actual rotation was far below this value. However, to control crack width, link-slabs were still heavily reinforced, thus stiffening the slab and decreasing its ability to act as a hinge between the adjacent decks. In addition, the study suggested that the performance of reinforced concrete link-slabs was highly affected by the construction quality, which most often results in large crack width.

Michigan DOT

ECC: To overcome the problem of heavily reinforced link-slabs, Engineered Cementitious Composites (ECC) were proposed to replace conventional concrete slabs. ECC are high performance fiber reinforced cementitious composites that have high durability and strain capacity over 400 times that of a normal concrete. The tensile strain of ECC material was associated with a large number of microcracks that have a limited crack width between 50 μm and 70 μm at 1% tensile strain. These cracks do not increase in width with increasing the tensile strain even up to failure (4% strain) (Lepech and Li - 2009). Kim et al. (2004) have evaluated the performance of bridge deck link-slabs designed with ductile ECC experimentally using full-scale slabs. The results of these experiments have shown significant enhancements in deflection capacity and crack width control of link-slabs when constructed using ECC material.

Li et al. (2003 and 2005) conducted a research project with Michigan DOT describing the development of durable link-slabs for jointless bridge decks based on strain hardening cementitious composite - engineered cementitious composite (ECC). Specifically the superior ductility of ECC was utilized to accommodate bridge deck deformations imposed by girder deflection, concrete shrinkage, and temperature variations, providing a cost-effective solution to a number of deterioration problems associated with bridge deck joints. Current design concept of link-slabs was first examined to form the basis of design for ECC link-slabs. Microstructurally optimized ECC material, with good workability and satisfactory mechanical properties was then developed. After the material design, the shrinkage, shrinkage crack resistance and the freeze-thaw behavior of the pre-selected mix proportion was investigated and revealed excellent for the durability concern. Improved design of ECC link-slab/concrete deck slab interface was confirmed in numerical analysis and further strengthened by excellent reinforcement pullout and shear stud pushout behavior in ECC. Based on the above findings, monotonic and subsequent cyclic tests of full-scale ECC link-slab specimens were performed and compared with those of a conventional concrete link-slab. It was revealed that the inherent tight crack width control of ECC decouples the dependency of crack width on the amount of reinforcement. This decoupling allows the simultaneous achievement of structural need (lower flexural stiffness of the link-slab approaching the behavior of a hinge) and durability need (crack width control) of the link-slab. Overall investigation supported the contention that durable jointless concrete bridge decks may be designed and constructed with ECC link-slabs. Finally, a simple design guideline was presented. Also, the results of full scale mixing trials and demonstrations were summarized and recommendations were made along with batching sequences and mix designs for large scale mixing. A summary of construction practices and procedures was also included, followed by the results of full scale load testing on the completed ECC link slab demonstration bridge. The load tests concluded that the ECC link-slab functions as designed under bending loads.

The Michigan DOT incorporated link-slabs during deck replacements and deep resurfacing. Field performance assessment documented full-depth cracking of most of the link-slabs. These cracks allow surface water infiltration, which leads to accelerated deterioration. Ulku et al. (2009) conducted a study to address link-slab design and performance issues. The literature is inconsistent with the influence of design parameters on link-slab performance. The objective was to document the link-slab behavior of its design parameters, to propose a method to calculate the link-slab moment and axial force, and to propose recommendations for updating current design details and construction procedures. Single-girder, two-span, finite element assemblage models under various types and levels of loads in conjunction with the link-slab design parameters were used to evaluate the moments and axial forces developed in the link-slab. Analysis showed that support conditions underneath the link-slab greatly influence the link-slab moment and axial force. Use of moment interaction diagram is recommended for the design. A detailed analysis and design example is presented incorporating live load, temperature gradient load, and the support configurations.

Lepech and Li (2009) investigated the application of ECC in a bridge deck link-slab. The unique ultra-high tensile ductility and tight crack width of self-consolidating ECC was exploited in this application to improve bridge deck constructability, durability, and sustainability. Design guidelines and material specifications were developed for implementation of this ECC link-slab technology. A construction project implementing these guidelines and specifications was conducted in 2005 on an ECC-concrete bridge deck in southeast Michigan, USA. A full scale load test was conducted to explore the structural response of the constructed ECC link-slab. These load tests validated that the incorporation of an ECC link-slab in placement of a conventional expansion joint did not alter the simply supported nature of the bridge spans, and that ample strain capacity of the ECC is reserved for temperature induced straining as designed. Two years after this ECC link-slab was placed, the performance of this link-slab remains unchanged. With further long term performance monitoring and additional demonstration experience, ECC link-slab can be an effective replacement of conventional expansion joints resulting in significantly reduced bridge deck maintenance needs.

Georgia DOT

Snedeker et al. (2011) evaluated the performance history of continuous bridge decks in the State of Georgia, to determine why the current design detail works, to recommend a new design detail, and to recommend the maximum and/or optimum lengths of continuous bridge decks. The continuous bridge decks have continuous reinforcement over the junction of two edge beams with a construction joint for crack control. It was indicated that the current technical literature and current practices and design procedures were synthesized and summarized. GDOT maintenance reports were reviewed, and preliminary field evaluations were conducted to determine the performance of the continuous deck detail. The effects of bridge movement due to thermal strains, shrinkage, and live loads were considered in simplified analytical studies to better understand the demands placed on the GDOT continuous deck detail. A summary of the preliminary design and length recommendations were provided upon completion of Part 1 of the research.

Europe

In recent years, the so called jointless or integral bridge design has seen a significant rise in popularity in Europe. Whereas in the last decades, designers preferred clearly defined statical systems and only adopted jointless design principles for small structures, the new generation of engineers pushes for integral design wherever possible. This development is to some degree motivated by a paradigm shift towards life-cycle cost-orientated design. Integral bridge structures lack joints and bearings, which typically are the least durable elements and thus remove the need for costly inspections and replacements. However, the obvious advantage of reduced direct and indirect maintenance costs entails novel and complex design solutions, especially for the transition area between structure and soil body. Furthermore, their statically indeterminate nature leads to increased importance of the soil–structure interaction. Both aspects are associated with significant uncertainty.

Wendner and Strauss (2015) focused on the probabilistic performance assessment of an inclined approach slab solution for integral bridge structures of up to 150 m of total length. Findings are presented by the example of a recently constructed and ever since monitored 67-m-long prototype structure. Monitoring data recorded by a multisensor monitoring system during the first 30 months after construction serves as inputs for a probabilistic, extreme value-based assessment of critical design assumptions. In particular, (1) the modeling of boundary conditions, (2) the activated degree of earth pressure against the abutment wall, and (3) the strain distribution in the fiber-reinforced soil above the inclined approach slab were investigated. It was concluded that the combination of short and long extensometers represents a robust and cost-effective monitoring approach for relative and absolute abutment movements that has already been adopted by Austrian bridge owners. The obtained information can be used to investigate the soil–structure interaction in terms of actual boundary conditions and developing earth pressure, in case no other sensor system is available. Based on the observed linear relationship between temperature within the deck slab and recorded abutment movements, it was found that the recorded displacements account for only 42% of the expected displacements, assuming free thermal expansion. Hence, the assumption of free thermal expansion during the design of the dilatation area is highly conservative by itself. In the current engineering practice, the assumption of free thermal expansion compensates for the lack of experience regarding the actual performance of the approach slab that represents a hidden safety margin. The observed strain field is in agreement with the theoretical assumptions, showing a high strain concentration near the tip of the slab and indicating an inclined area of localized deformation going up to the surface.

Charuchaimontri et al. (2008) investigated the influence of lap reinforcement in link-slabs of highway bridges under four independent boundary conditions by using a three-dimensional nonlinear finite element code based on the microplane model. Numerical solutions for load–deflection relationships, internal force distribution and failure cracking planes are presented for link-slabs with different details of lap reinforcement. A full-scale test was performed on three reinforced concrete long span link-slabs with various lap reinforcement details subjected to mid-span loading. The comparison indicated a good agreement between the results from finite element analysis and the experiment. The model can be used to predict the effective moment of inertia of the link-slab under mid-span loading, end rotation and end translation for the development of design criteria for a link-slab.

MTO

To address this problem of joints in bridges, the Ministry of Transportation of Ontario (MTO) has recently rehabilitated a number of bridge decks using a debonded link-slab system to replace the deck joints at the pier locations. MTO recently carried out an experimental research study of the long-term performance of the system on scale test models that were subjected to extensive cyclic loading in the laboratory. It also conducted a load test of a recently rehabilitated structure to study its structural behavior both before and after the link-slab was constructed. The test structure was instrumented with sensors that measured deflections and strains in the link-slab and girders.

Au et al. (2013) described the experimental research study on link-slab and the behavioral load tests that were carried out, and discusses the results obtained. The experimental study showed that the long-term performance of the link-slab was not affected by the extensive cyclic loading to which the model was subjected, and the load testing of the test structure showed that it satisfied the serviceability limit state requirements of the Canadian Highway Bridge Design Code, thus validating the design methodology of the system.

PCI

Details of jointless bridge superstructures are available in the PCI publication, “The State-of-the-Art of precast/Prestressed Integral Bridges,” authored by the Subcommittee on Integral Bridges of the Committee on Bridges.

THE USE OF FRC and FRP REBAR IN LINK-SLABS

Several researchers have investigated the use of Fiber-Reinforced Polymers (FRP) for bridge deck reinforcement (NCHRP – 2003) as alternatives to conventional steel reinforcement to provide corrosion resistant reinforcement that increases bridge service life and achieve economic and environmental benefits

FRC

Materials with high tensile strain capacity, such as fiber-reinforced concrete (FRC), can be used for application in the link-slab to improve the strength, durability, and cracking characteristics of the link-slab. Hong (2014) established a computational model of an existing bridge (Camlachie Road Underpass). It is found that the model and modelling approach in SAP2000 closely predicted the field test results obtained by the Ministry of Transportation of Ontario (MTO). Additionally, it is established that the horizontal stiffness of the elastomeric bearings is very low and therefore the supports are representative of roller supports. Therefore, axial forces are not generated when there are no horizontal restraints in the supports.

Hong (2014) examined the properties of FRC from experimental tests. Four-point bending tests are used to estimate the ultimate and service stresses of FRC using procedures from the fib Model Code (2010). It is found that the results from the fib Model Code are in agreement with the experimental beam tests by Cameron. Therefore, it is concluded that the fib Model Code procedures are valid for calculating the ultimate and service stresses in FRC, and are used in the computational and analytical models. Hong 2014 conducted a parametric study to provide a better understanding of link-slab bridge behavior to assess the impact of design decisions on the bridge response. It is found that the use of hooked steel fibres minimized the crack width of the link-slab, and a debonded length a 5% to 7.5% is found to be optimal based on cost and serviceability. Moreover, it is found that fibres are more effective when less steel reinforcements are used in the link-slab. Lastly, a parametric study is conducted on the computational model using non-linear analysis by including FRC in the computational model in the form of plastic hinges. It is concluded that the computational model has shown signs of cracking at the pier supports, which is consistent with the site observations during the MTO field test for the Camlachie Road Underpass. Hong 2014 developed an analytical model (i.e., design guideline) on the analysis and design of link-slab bridges with FRC. It is found that the proposed analytical model is able to closely represent the link-slab bridge behavior with very small difference (2-3%), whereas the current method of analysis using Caner and Zia's approach shows a larger prediction error (16%). For the link-slab design with FRC, it is found that fibres in reinforced concrete helped increase the bending moment capacity of the link-slab by more than 10% compared to normal reinforced concrete (without fibres). The use of polypropylene fibres and hooked steel fibers in the link-slab reduces the required steel reinforcement by 3.5% and 21%, respectively, and the crack width of the link-slab reduces by more than 3 times with the addition of fibres. Okeil et al. (2013) conducted a field study in Louisiana investigating the performance of a skewed prestressed concrete bulb-tee girder bridge made continuous. The study presented details of the monitoring system developed for this project, which has been in service for more than two years. Temperature, strain, rotation, and elongation readings are presented. It was concluded that positive moments develop in bridges employing the new continuity detail. They are caused by creep and thermal effects that cause upward camber at midspans, which leads to positive moments at continuous girder ends. Seasonal and daily temperature variations can induce large restraint moments in the bridge, especially temperature gradients. The level of restraint moment due to the combined seasonal and daily temperature effects is probably the most important factor in the design of this detail because the designer has no influence on the temperatures at the bridge site. The other positive-moment-inducing factor (girder creep caused by prestressing forces) can be greatly reduced by not establishing continuity until after a large portion of the creep takes place.

Hawaii DOT

Reyes and N. Robertson (2011) in the report of the State of Hawaii Department of Transportation indicated that a cast-in-place link-slab has the advantage of providing good continuity at the ends of the FRCC section to the concrete or bridge deck, meaning it can be built to be flush with the bridge deck. However, because of the limitation of permanent strain in the link-slab, the effectiveness of the slab in compression is reduced. Therefore, a precracked link-slab would be more appropriate in most applications. The study also indicated that because HPFRCC concrete requires a long setting and curing time to reach its optimal strength, it may not be practical to cast-in-place especially when time is a construction consideration. The study also suggested that pre-cast slabs has the advantage of pre-cracking but are limited by the bond of the link-slab to the existing concrete. It suggested bonding through vertical dowels installed at an angle so that the slab is essentially pulled downward during tension loads, or a combination of vertical dowels and horizontal GFRP bars that would be more effective than either acting alone

TYPES OF BEAM CONTINUITY AT PIERS

There are several alternatives to create a link-slab and or jointless superstructure over the piers. AASHTO LRFD specifications (2009), Article 5.14.1.4 allows designers to use any one of the shown methods of design. Some examples of these jointless superstructure are listed as follows:

(a) Continuous deck slab or link-slabs supported by simple span beams

Most of the concrete beam bridges in Florida are currently built using continuous deck over the joint between beams/girders at a pier. A typical detail is shown in Fig. 14. The details do not include beam end diaphragms or debonding between the deck and beam. The absence of end diaphragms in these details significantly simplifies construction, but may not be feasible in states subjected to significant seismic activities. Some of the details include a saw-cut or tooled crack control joint in the deck over the pier that may be filled with sealant.

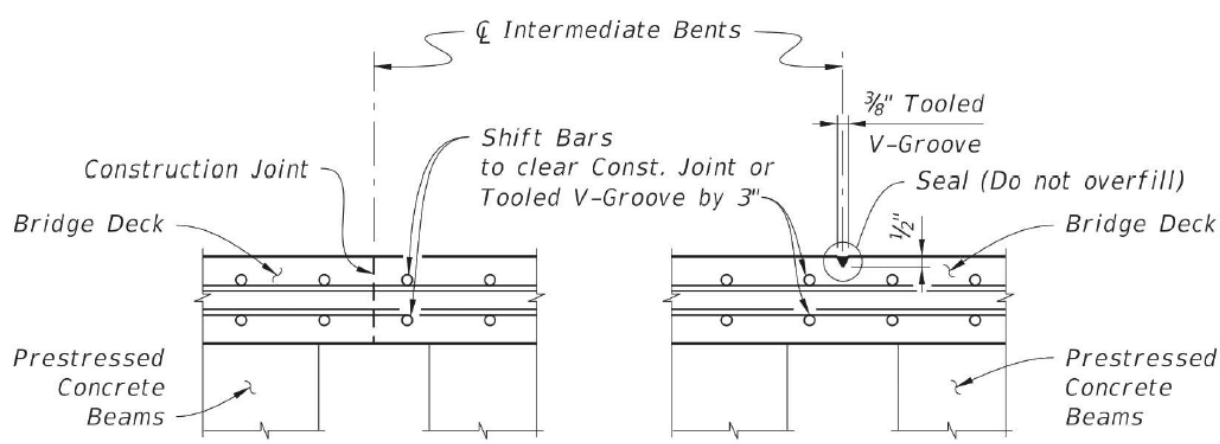


Fig. 14: Florida Department of Transportation details for continuous slab over joint between simple spans. Figure: Florida Department of Transportation Structures Detailing Manual

A similar method is also adopted using a link-slab to connect the simply-supported girders/beams with a continuous deck, while part of the slab is debonding from the girder ends at both sides of the joint. This detail of the link-slab with debonding results in a reduction in developed strains and cracking in the continuous deck slab since it distributes the deformations over a greater length. This method has a simpler construction than a fully continuous superstructure and is considered as a cost effective way of developing a jointless deck. To control cracking, a groove is formed, preinstalled or cut transversely in the deck at the pier centerline and may be filled with a sealant. Several researchers [ElSafty (1994); Zia et al. (1995)] provided early recommendations for design and construction of link-slabs. They recommend debonding the end 5% of the deck slab from the ends of the beams to reduce strains and control cracking in the link-slab region. Recommended analysis is to impose the end rotations of the beams on the slab. The resulting stress in the deck reinforcement should be limited to 40 ksi and cracking should be checked with current AASHTO LRFD specifications crack control provisions.

Virginia DOT

An example of a link-slab system used to remove expansion joints when rehabilitating bridges in Virginia is shown in Fig. 15. In this detail, which is used for relatively short spans, the debonded length is a constant 2 ft (VDOT 2013).

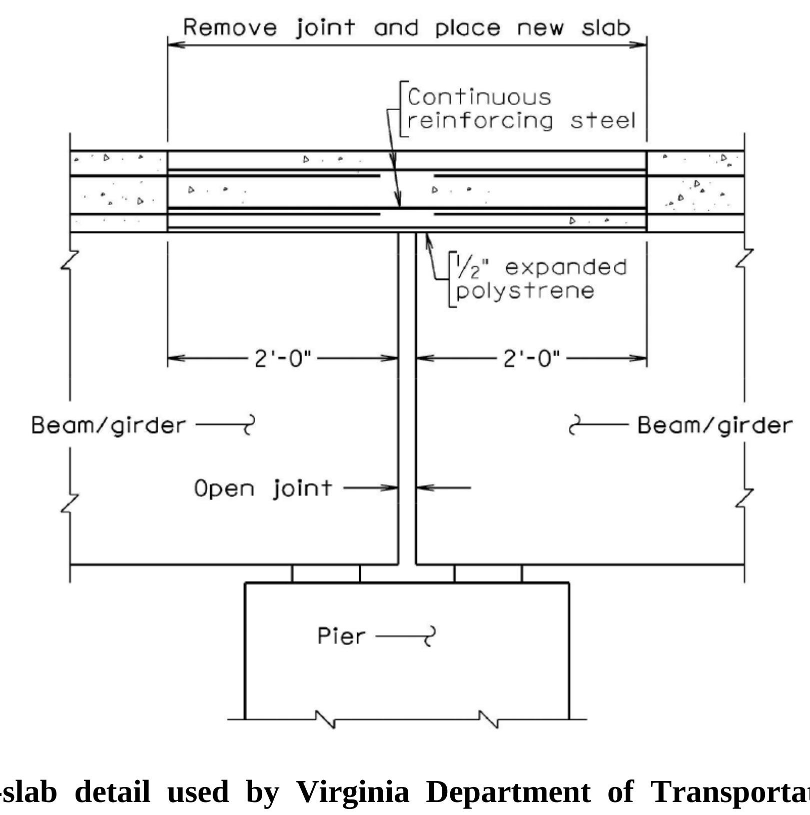


Fig. 15: Link-slab detail used by Virginia Department of Transportation to eliminate expansion joint in rehabilitation projects

(b) Continuous-for-Live-Load Beams

The prestressed concrete beams are set on bearings as simple spans and the diaphragm concrete may be placed partial height (Fig. 16). The deck concrete is then placed on the simple-span beams. Longitudinal deck reinforcement that extends over the pier region is designed to resist all subsequent loads, such as live load, as a continuous span composite superstructure. This system has been performing well for more than 40 years.

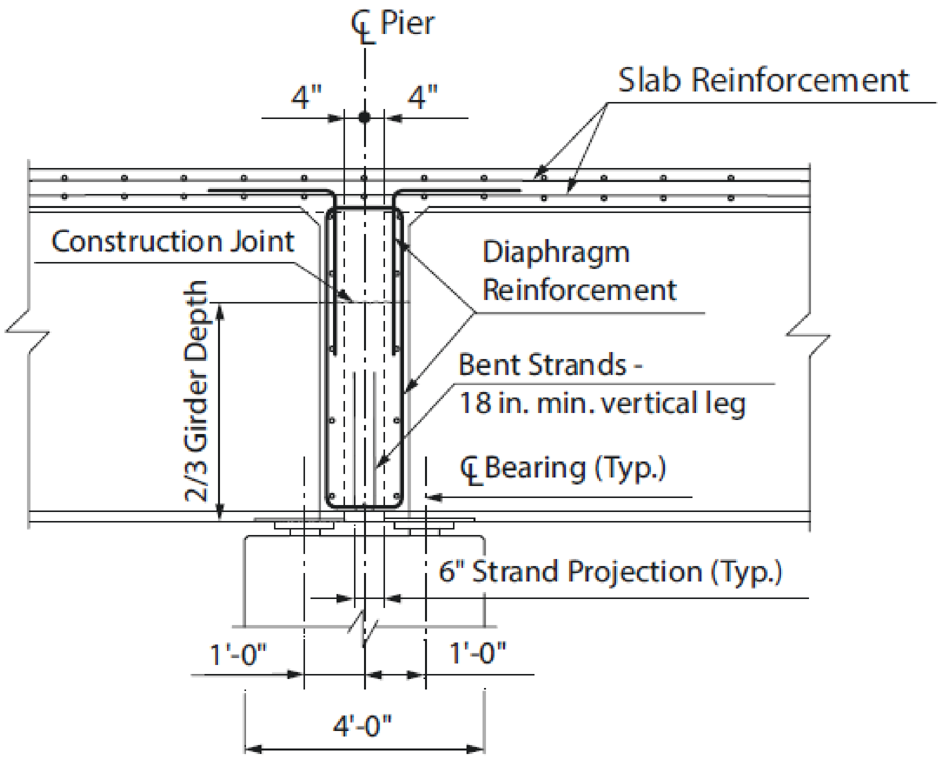


Fig. 16: Example of pier diaphragm details with either fixed or expansion bearings (Tadros 2016)

(c) Threaded Rod Continuity System

A method called threaded rod continuity was reported by Sun et al. (2016), where beams were made continuous using high-strength threaded rods placed on top of the beams in the negative moment zone over the piers. The rods were embedded in a concrete placement on the top flange of the beam that is constructed at the same time as the continuity diaphragm, as shown in Fig. 17. The result is a continuous beam for deck weight as well as all subsequent loads. This system, while slightly more complicated than the continuous-for-live-load system, allows for further optimization of the capacity of the beams. Also, as an additional benefit, the negative moment due to deck weight generally offsets the long-term positive restraint moment at the pier, eliminating the need for bars or strands extending from girders to provide a positive moment connection.

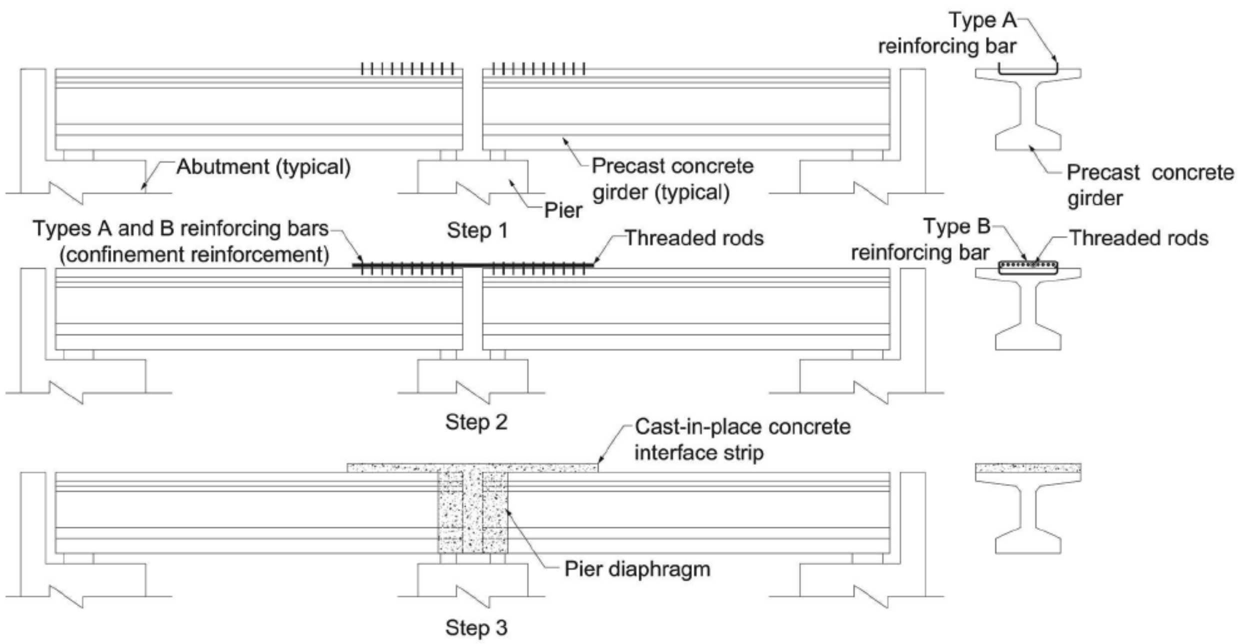


Fig. 17: Construction steps of implementing threaded rod continuity system prior to deck placement (Sun et al. 2016)

(d) New Link-slab System Details

Louisiana Transportation Research Center proposed a link-slab to be designed with enough FRP reinforcement to withstand the loads placed on the slab. Also, when possible, the link-slab was designed to be uncracked while under typical service loads. Design has been in accordance with the newest ACI 440 criterion. When creating the FRP link-slab, special measures should be considered to anchor the FRP reinforcement to the existing bridge deck during the installation of a link-slab in an existing deck. Using FRP grating or FRP bars for the creation of a link-slab in a new bridge or a complete bridge deck replacement was considered.

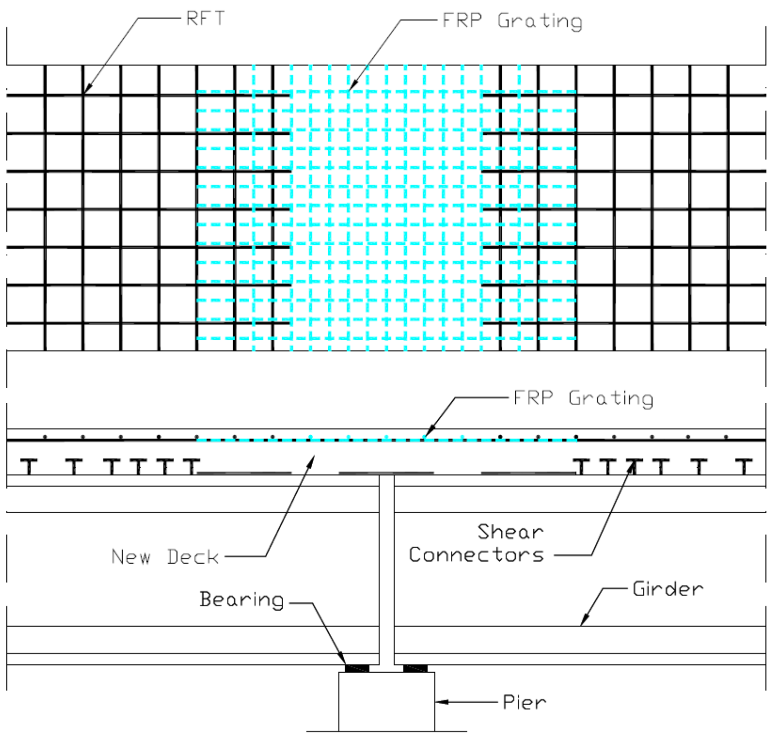


Fig. 18: FRP grating as reinforcement for new link-slab.

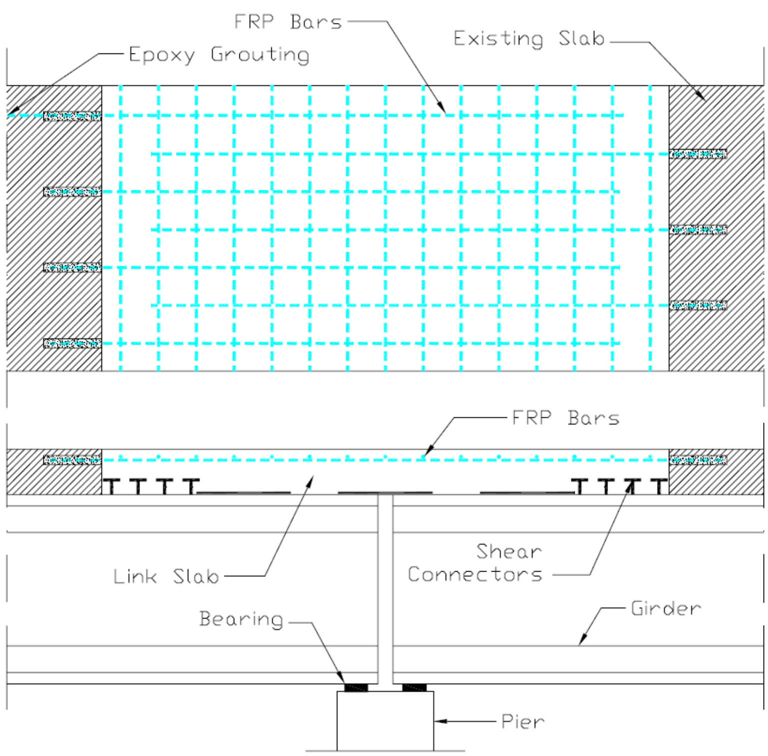


Fig.19: FRP rebars for use in link-slab installed in existing deck

INSTRUMENTATION OF THE LINK-SLAB

Researches have indicated that the link-slabs were instrumented using real-time strain inducers, thermocouples, and pH meters. Data was collected during field tests and service. The data logger has record when certain strains were reached in the FRP reinforcement.

Okeil, et al. (2013) investigated a precast prestressed-concrete simple-span girders that were made continuous by pouring a continuity diaphragm between the girders ends. Special reinforcement was extended from the girders' bottom flanges into the diaphragm to ensure continuity under positive moments that result from time-dependent effects such as creep, shrinkage, and temperature gradient. The bridge has been instrumented with embedded and surface-mounted sensors and was monitored for over 2 years to evaluate the performance of the new continuity detail. A live-load test was carried out to evaluate the response of the new detail under truck loads. A bridge segment was monitored that was a three-span continuous superstructure, 242 ft (73.8 m) long with a 45-degree skewed layout. American Association of State Highway and Transportation Officials (AASHTO) bulb-tee girders (BT-72) were used for the construction of this segment. Because of the bridge's symmetry, only one of the identical intermediate bents was monitored. A 96-channel monitoring system was designed to record essential performance measures for evaluating the continuity detail. Several sensor types were chosen to measure temperatures, strains, rotations, crack widths, and gaps. All sensors used the vibrating wire technology, which is known to be more suitable for long-term monitoring projects because they do not suffer from drifting. Embedded as well as surface-mounted sensors were employed.

Six types of sensors were used and the monitoring system included 66 active sensors. The sensors were strategically located at midspan and on both sides of the continuity diaphragm to capture the important measures that are most influenced by continuity, such as strains in hairpin bars and the gap between adjacent girder ends. The relative movement between the bottom flanges at the ends of the adjacent girders on both sides of the continuity diaphragm was investigated using the gapmeters installed at girders. Rotations on both sides of the continuity diaphragm were recorded. All measurements were corrected for temperature changes per recommendations of the gauge manufacturer. Figure 20 shows a schematic of the sensor locations. Okeil et al. (2013) provide more details about the instrumentation. Figure 21 shows instrumentation options and details.

Live load test on the monitored segment was conducted to assess the continuity detail's performance under truck loads. Dump trucks weighing 54.1 and 57.0 kip (24.5 and 25.9 tonnes) were used to load the bridge in nine static loading cases.

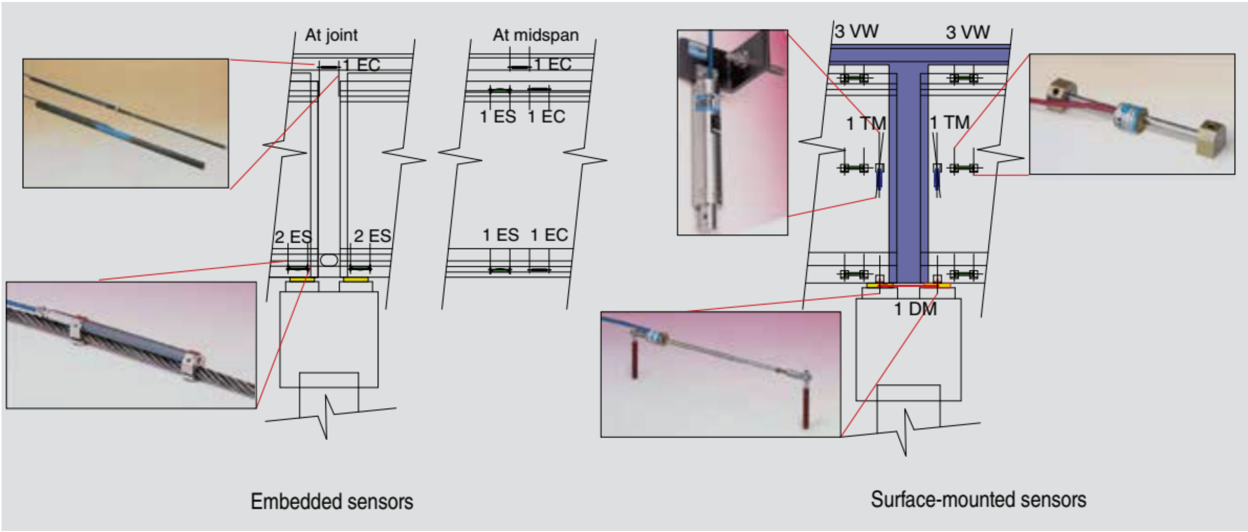
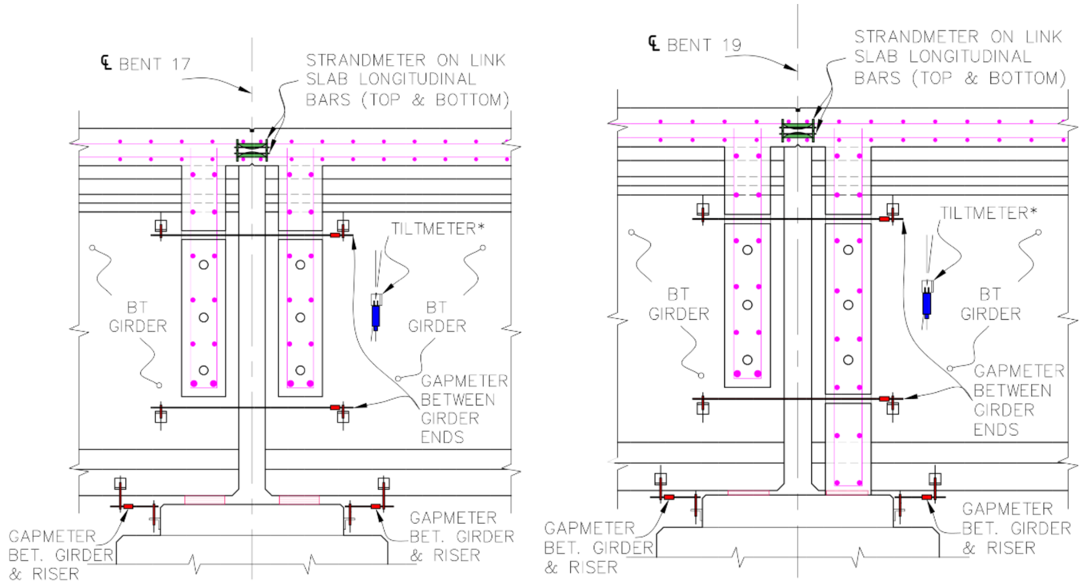


Fig. 20: Distribution of sensors at each monitored location. Note: DM = gapmeter gauge; EC = sisterbar gauge; ES = strandmeter gauge; TM = tiltmeter gauge; VW = vibrating wire strain gauge.



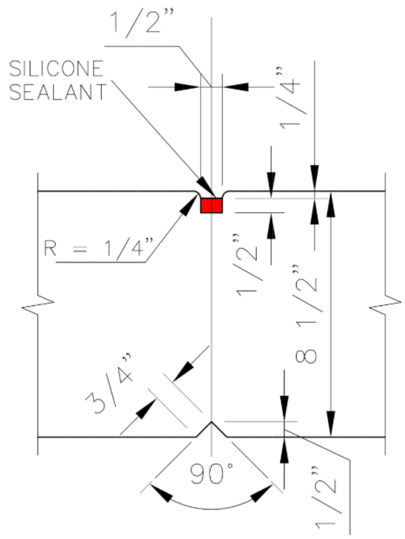


Fig. 21: Details of typical instrumentations

The monitoring of the tested bridge indicated that the continuity detail has the ability to transfer forces from one girder to the adjacent girder across the continuity diaphragm, as evidenced by the recorded data under long-term effects as well as live loads.

The authors concluded that seasonal and daily temperature variations can induce large restraint moments in the bridge, especially temperature gradients. The level of restraint moment due to the combined seasonal and daily temperature effects is probably the most important factor in the design of this detail because the designer has no influence on the temperatures at the bridge site. The other positive-moment-inducing factor, such as girder creep caused by prestressing forces, can be reduced by not establishing continuity until after a large portion of the creep takes place. The results from the instrumentation and monitoring also indicated that the live load test revealed that the continuity detail transferred negative and positive moments across the diaphragm. The strains from the live load test were lower than long-term effects. Even if the actual design load was to be applied (approximately twice the test live load), the strains would still be small. Therefore, the live load case should be considered in the design; however, it is not the most demanding action on the detail.

REFERENCES

- AASHTO. (2009). AASHTO LRFD bridge design guide specifications for GFRP-reinforced concrete bridge decks and traffic railings, 1st Ed., Washington, DC.
- Alampalli, S. and Yannotti, A. P. (1998) “In-Service Performance of Integral Bridges and Jointless Decks” Transportation Research Record Journal of the Transportation Research Board 1624(1):1-7
- Au, A., Lam, C., Au, J., and Tharmabala, B (2013) “Eliminating Deck Joints Using Debonded Link Slabs: Research and Field Tests in Ontario” J. Bridge Eng., ASCE, 2013, 18(8): 768-778.
- Caner, A., and Zia, P. “Behavior and Design of Link Slabs for Jointless Decks” PCI Journal, Vol. 43, No. 3, pp. 68-80, May-June 1998.
- Caner, A., and Zia, P. (1998) “Behavior and Design of Link Slabs for Jointless Bridge Decks” PCI Journal, Page 68-80.
- Charuchaimontri, T., Senjuntichai, T., Oˇzbolt, J., and Limsuwan, E., (2008) “Effect of lap reinforcement in link slabs of highway bridges” Engineering Structures 30 (2008) 546–560.
- El-Safty, A. K., ”Analysis of Jointless Bridge Decks with Partially Debonded Simple Span Beams,” Ph.D. Dissertation, North Carolina State University, Raleigh, NC, 1994.
- ElSafty, A., and Okeil, A. M., (2008). “Extending the Service Life of Bridges Using Continuous Decks, PCI Journal - Precast/Prestressed Concrete Institute.” PCI, Vol. 53, No. 6, pp. 96-111. 30.
- Gastal, A.L. and Zia, P. (1989). “Analysis of Bridge Beams with Jointless Decks.” In: International Symposium on Durability of Structures, LISBON, Conference Report, Zurich, IABSE, ETH Honggrberg.
- Groli, G., Caldentey, A.P., Soto, A.G., Marchetto, F., and Parrotta, J.E. (2014) “Simplified serviceability design of jointless structures. Experimental verification and application to typical bridge and building structures” Engineering Structures 59 (2014) 469–483.

- Ho E. and Lukashenko, J., (2011) "LINK SLAB DECK JOINTS" 2011 Annual Conference of the Transportation Association of Canada, Edmonton, Alberta.
- Hong, Y. (2014) "Analysis and Design of Link Slabs in Jointless Bridges with Fibre Reinforced Concrete" PhD. Thesis, University of Waterloo, ON, Canada.
- Kendall, A., Keoleian, G, A., and Helfand, G.E., (2008) "Integrated Life-Cycle Assessment and Life-Cycle Cost Analysis Model for Concrete Bridge Deck Applications" J. Infrastruct. Syst., ASCE, 14(3): 214-222.
- Kim, Y. Y., Fischer, G., and Li, V. C. "Performance of Bridge Deck Link Slabs Designed with Ductile Engineered Cementitious Composite", ACI Structural Journal, V. 101, No. 6, pp. 792-801, Nov-Dec 2004.
- Lepech., M. D. and Li. V.C. (2009) "Application of ECC for bridge deck link slabs" Materials and Structures, 42:1185–1195.
- Li, V. C., Fischer, V.C., Kim, G., Lepech, Y., Qian, M., Weimann, S., and Wang, S. (2003) "Durable Link Slabs for Jointless Bridge Decks Based on Strain-Hardening Cementitious Composites" Michigan Department of Transportation, Research Report RC-1438.
- Li, V.C., Lepech, M., and Li, M. (2005) "Field Demonstration of Durable Link Slabs for Jointless Bridge Decks Based on Strain-Hardening Cementitious Composites" Michigan Department of Transportation, Research Report RC- 1471.
- Mothe, R.N. (2006) "Partial continuity in prestressed concrete girder bridges with jointless decks" MSc. Thesis, Louisiana State University and Agricultural and Mechanical College.
- Okeil, A. M. and ElSafty, A. (2005). "Partial Continuity in Bridge Girders with Jointless Decks, Practice Periodical on Structural Design and Construction." ASCE Journal, Vol. 10, No. 4, pp 229-238, doi:10.1061/(ASCE)1084-0680(2005)10:4(229).
- Okeil, A. M., Hossain, X., and Cai, C. S. (2013) "Field monitoring of positive moment continuity detail in a skewed prestressed concrete bulb-tee girder bridge" Spring 2013, PCI Journal, Page 80-90.
- Reyes, J. and Robertson, I.N., (2011). "PRECAST LINK SLABS FOR JOINTLESS BRIDGE DECKS." Technical Report, Hawaii Department of Transportation

- Snedeker, K., White, D., and Kahn. L., (2011) “Evaluation of Performance and Maximum Length of Continuous Decks in Bridges – Part 1” GDOT Research Project No. 09-07, Task Order No. 02-64. Report, Page 130.
- Sun, C., N. Wang, and M. K. Tadros, M.K (2016). “Threaded Rod Continuity for Bridge Deck Weight.” PCI Journal, Precast/Prestressed Concrete Institute, Chicago, IL. V. 61, No. 3, pp. 47-67.
- Tadros, M.K. (2016), Eliminating Expansion Joints in Bridges, Concrete Bridge Technology, Aspire, pp. 32-35
- Thippeswamy, H.K., GangaRao, H.V.S., and Franco, J.M. (2002) “Performance Evaluation of Jointless Bridges” J. Bridge Eng., ASCE, 7(5): 276-289.
- Ulku, E., Attanayake, U., and Aktan, H., (2009) “Jointless Bridge Deck with Link Slabs Design for Durability” Transportation Research Record: Journal of the Transportation Research Board, No. 2131, Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 68–78.
- Virginia Department of Transportation (VDOT), Jeff Milton, (March 2013), 2013 Virginia Concrete Conference Joint Maintenance and Best Practices in Deck Joint Replacement
- Wendner, R. and Strauss, A. (2015) “Inclined Approach Slab Solution for Jointless Bridges: Performance Assessment of the Soil–Structure Interaction” J. Perform. Constr. Facil., ASCE, 29(2): 04014045.
- Wing, K. M. and Kowalsky, M. J. “Behaviour, Analysis, and Design of an Instrumented Link Slab Bridge” ASCE Journal of Bridge Engineering, Vol. 10, No. 3, pp. 331-344, May 2005.
- Xu, Z., Chen, B., Zhuang, Y., Tabatabai, H., and Huang, F. (2018) “Rehabilitation and Retrofitting of a Multispan Simply-Supported Adjacent Box Girder Bridge into a Jointless and Continuous Structure” J. Perform. Constr. Facil., ASCE, 32(1): 04017112.
- Zia, P., Caner, A., and ElSafty, A. (1995). “Jointless Bridge Decks.” Technical Report, FHWA/NC/95-006, North Carolina Department of Transportation (NCDOT).