Construction and Building Materials 190 (2018) 178–190

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental validation of optimized ultra-high-performance concrete shear key shape for precast pre-stressed adjacent box girder bridges

Husam H. Hussein [a,b,*], Shad M. Sargand [a], Fouad T. Al Rikabi [a], Eric P. Steinberg [a]

[a] Department of Civil Engineering, Ohio University, Stocker Center, Athens, OH 45701, United States
[b] Middle Technical University, Baghdad, Iraq

HIGHLIGHTS

- The enhanced material and mechanical properties of UHPC affect the load transfer mechanism between concrete members.
- The OPT-UHPC joint design has an ultimate load capacity 32% larger than the FHWA-UHPC design.
- The load capacity of a joint is substantially influenced by its configuration.

ARTICLE INFO

Article history:
Received 23 October 2017
Received in revised form 17 September 2018
Accepted 19 September 2018

Keywords:
Ultra-high performance concrete (UHPC)
Direct shear
Direct tension
Flexural
Bridge connections
Shape optimization

ABSTRACT

Recently, ultra-high-performance concrete (UHPC) material has been adopted as a grout material to fill connections between adjacent girders. Research to date has showed that using UHPC in the shear key connections of bridges improves the bridge superstructure performance. However, shear key configuration used in the most bridges are custom-designed and do not follow any specific design code. In a previous study by the authors, an optimized shape of the UHPC shear key (OPT-UHPC) was introduced in attempt to enhance load transfer and increase ultimate strength capacity. The optimization was conducted using three 3D finite element models simulating direct shear, flexural, and direct tension tests. The objective of the present study is to experimentally measure the performance and ultimate load capacity of the OPT-UHPC shear key by placing it between two high strength concrete (HSC) components and subjecting to direct shear, direct tension, and flexural tests. These results are then compared to the modeling predictions from the previous study. Two 45°-rectangular rosette strain gauges were placed on the surface of UHPC shear key and HSC components under direct shear load to obtain the strain in the shear key and the adjacent HSC components. The test results showed the OPT-UHPC design has an ultimate load capacity 32% larger than the FHWA-UHPC shear key, even though the cross-sectional areas are approximately equal, 19677 mm^2 for FHWA-UHPC and 20161 mm^2 for OPT-UHPC, a difference of about 2.5%. Also, the experimental results indicate the OPT-UHPC shear key enhanced the strain distribution between the concrete components and as result improved the load transfer. Thus, the load transfer mechanism is substantially influenced by the shear key configuration.

1. Introduction

In recent years, precast pre-stressed adjacent box girder bridges have become a preferred choice for constructing the bridges of short to intermediate spans in several states since these bridges have the advantages of ease of construction, simple structure, and low cost. In these bridges, the adjacent box girders are connected to each other using longitudinal shear keys along with transverse post-tensioning (TPT) ties to ensure the load is transferred between the girders. This load transfer system in the adjacent box girder design provides high longitudinal and transverse stiffness resulting in good superstructure performance. However, shear keys may experience longitudinal cracks after a large number of load and thermal cycles. The longitudinal cracks allow water and chemical agents to saturate the girder sides, causing spalling of the concrete and corrosion of the reinforcement, ultimately reducing in the service life of the bridge [1–8].

Several attempts to improve shear keys have been made by varying configurations, shapes and grout materials, and the performance investigated under flexural, direct shear, and direct tension

* Corresponding author at: Department of Civil Engineering, Ohio University, Stocker Center, Athens, OH 45701, United States.

E-mail address: hh236310@ohio.edu (H.H. Hussein).

https://doi.org/10.1016/j.conbuildmat.2018.09.122
0950-0618/

tests documented. Gulyas [9] and Gulyas and Champa [10] compared the performance of shear keys between adjacent box girders made from non-shrink grout material and magnesium ammonium phosphate mortar under vertical shear, direct tension, and direct longitudinal shear forces. The authors concluded that the use of these testing methods can be used to obtain the ultimate strength capacity and evaluate the performance of the shear key. Issa [11] utilized direct shear, flexural, and direct tension tests to evaluate the performance of the shear keys filled with four different grout materials: Set grout, Set grout 45 for normal temperature, Set grout 45 for hot weather, and polymer concrete. The researchers concluded that their test methods mentioned above were able to evaluate the performance of shear keys in terms of load capacity and bond strength. Porter [12] used the direct shear test to study the performance of the connections between adjacent precast panels with and without TPT force. In addition to the direct shear, direct tension, and flexural tests performed by past research, Miller [13] investigated mid-depth shear key performance connecting full scale box girders. Shear keys were filled with non-shrink grout and epoxy as grout materials. Those with epoxy had better load transfer than those filled with non-shrink grout material. Also, the shear keys filled with non-shrink grout material experienced cracks due to temperature changes before applying the cyclic load. However, due to the high difference in the coefficient of thermal expansion value between concrete and epoxy, shear keys filled with epoxy grout material may experience longitudinal cracks. The researchers recommended use of a new grout material having superior mechanical properties such as high bond and tensile strengths. Furthermore, testing a full-scale box girder is a time-consuming and costly procedure.

Recently, ultra-high-performance concrete (UHPC) material has been adopted by Federal Highway Administration (FHWA) as a grout material to fill connections between adjacent girders [14]. Due to its superior properties, UHPC has ability to eliminate the longitudinal cracks in shear keys. UHPC has improved durability, strength, long-term stability compared to the conventional concrete and other grout materials. The UHPC components, including a lack of coarse aggregate, typical graded granular material, low water to cement ratio, and steel fiber volume of %2, play a big role in the enhancement of mechanical properties. UHPC shows superior mechanical properties such as compressive strength of 120–200 MPa, tensile cracking strength of 6–10 MPa, and modulus of elasticity of 40–70 GPa based on curing conditions, such as untreated, steam, tempered steam, and delayed steam curing regimes. UHPC also shows high tensile toughness, reduced permeability, and small long-term creep and shrinkage compared to the conventional concrete material [15]. UHPC constituents has a significant impact on the microstructure, which results in enhancements in the bond strength between fiber and matrix [16]. Also, unlike the conventional gout material, UHPC provides high adhesive strength for different types of roughness [17]. A comprehensive study regarding UHPC applications in highway bridges can be found in Russell and Graybeal [18].

There are limited studies investigating the performance of precast concrete bridges that have UHPC connections. Grace [19] tested an adjacent concrete decked bulb T-girder-bridge, which consisted of five girders connected by UHPC joints along with two unbonded TPT carbon fiber composite cable strands at four locations along the bridge length. The authors reported that the bridge failed due to concrete being crashed at the top of the flange, but the UHPC joints continued to endure the applied load without showing any sing of failure. On the other hand, eliminating the need for TPT ties without compromising the shear key strength and load transfer mechanism can be achieved by using UHPC as grout material [14]. To this end, a UHPC shear key (hereafter referred to as the FHWA-UHPC shear key) was developed by the FHWA Turner-Fairbank Highway Research Center (TFHRC) [14] and is shown in Fig. 1.

In later study by Yuan and Graybeal [20], a full-scale laboratory test of two adjacent box girders was performed to investigate the performance of the FHWA-UHPC connection. More than a million cycles of structural loading and ten cycles of thermal loading were applied to simulate traffic and thermal loads, respectively. The superior mechanical properties of UHPC material enhanced the connection capacity. Also, Hussein [21] tested the FHWA-UHPC shear key by conducting direct shear, direct tension, and flexural tests to obtain the ultimate strength capacity. The UHPC shear key showed a high shearer strength capacity than any combination of grout material and any shear key configuration previously studied.

UHPC shear keys used in bridges with T-section girders, deck panels, or adjacent box-girders, experience stresses due to the environmental traffic and loads. The type and level of these stresses depend on the joint configuration. It should be noted that due to high torsional rigidity and high span-to-depth ratio [22], the adjacent box girder sections do not have the same behavior of T-section girders and deck panels in terms of load transfer mechanism. All bridge connections transfer load via three mechanisms: (1) shear key configuration (joint interlock) (2), friction and cohesion/adhesion at the interface between concrete components (interface interlock), (3) and shear reinforcement bar action [23]. Hussein [24] and Saragand [25] investigated these three mechanisms using three different 3D finite element models: a direct tension model, a slant shear model, and a full-scale model of the two adjacent box girders connected by FHWA-UHPC shear key (see Fig. 1). These models were calibrated and validated at different levels of interface roughness against experimental data. When the joint between adjacent box girders constructed with indented faces are filled with UHPC material forming the shear key, mechanical interlock is served by the shear key. The resistance to the shear stresses in the shear key depends mainly on the strength of grout material and shear key configuration along with bond strength between shear keys and the girders. The authors reported that the UHPC shear key exhibited stiff behavior and no signs of cracking due to superior properties of UHPC material.

Research to date has showed that using UHPC in the shear key connections of bridges improves the bridge superstructure performance. However, no design code has been introduced for UHPC shear key and shear reinforcement bar spacing. Also, there are no design details for UHPC shear keys in the AASHTO LFRD bridge design specifications [23] nor in Graybeal [14]. Shear key configuration used in the most bridges are custom-designed and do not follow any specific design code [5,6]. In a recent study by Hussein [26], three 3D finite element models simulating direct shear, flexural, and direct tension tests were utilized to develop and design a new UHPC shear key. These models were calibrated and validated with experimental data reported by Hussein [21]. Hussein [26] compared these models with different shear key configurations from past research and existing design standards to study the effects of the shear key configuration on the load transfer mechanism. The researchers optimized the shape of the UHPC shear key in attempt to enhance load transfer mechanism and increase the ultimate strength capacity.

2. Objectives

The objective of the present study is to investigate the performance and ultimate load capacity of the optimized UHPC (OPT-UHPC) shear key between two high strength concrete (HSC) components using direct shear, direct tension, and flexural tests to demonstrate the suitability of the OPT-UHPC shear key in