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# Experimental study of strand splice connections in UHPC for continuous precast prestressed concrete bridges

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ABSTRACT

Current infrastructure demands require bridging larger spans while maintaining construction and structural simplicity. The use of standard prestressed concrete girder elements which might be spliced *in situ* has been regarded as an appealing solution. This study investigated the performance of strand lap splices embedded in ultra high performance concrete (UHPC) and their further implementation in structural continuity connections for spliced girder bridges. The results of an initial experimental program suggested that the full development length of 12.7 mm and 15.2 mm diameter unstressed prestressing strands embedded in a steel fiber reinforced UHPC is approximately 510 and 610 mm (40 $d_s$), respectively. The implementation of the splice strand connection concept for girder spliced bridges was further developed and experimentally assessed. Two full scale box beam tandems were spliced and tested. It was demonstrated that large flexural capacity can be achieved with relatively short lap splice lengths. Approximately 90% of the ultimate flexural capacity estimated for the fully prestressed and continuous girder was reached by the spliced box beam tandem connected using a strand splice length of 762 mm (50 $d_s$). Additional detailing of the structural system and the reinforcing scheme is discussed to improve the performance of the system in general and the connection in particular.

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## 1. Introduction

Precast prestressed concrete bridges have been effectively used worldwide over the last 60 years. A large part of those bridges are built using full length simply supported precast prestressed girders in a structural solution that offers modularity, low life-cycle costs and adequate durability [1]. However, current infrastructure demands require bridging larger spans while maintaining construction and structural simplicity. Although the use of new materials, the integration of new girder sections, and advances in design methods have contributed to increase the span range of precast prestressed concrete girders over the years, the increase is relatively small and the use of beam splicing technologies is still the most promising development line to overcome span limitation [1,2]. Furthermore, size and weight limitations on girder shipping and handling make necessary the development of alternative solutions for connecting precast components *in situ* in order to achieve structural continuity while enlarging the span range for this structural typology. Structural continuity leads to more efficient structural systems, more favorable stress distribution within the superstructure and reduced demands on the substructure [1]. Besides the structural advantages, there are a number of durability, safety and economic benefits derived from the established continuity such as the elimination of the bridge deck joints and the reduced maintenance costs [3].

Girder splices can be located over the piers or in-span. In particular for on-pier connections, a large number of connection details have been developed over the last 50 years including the use of cast-in-place deck slabs and diaphragms, post-tensioned cables and bolts, welded plates, threaded rods, among others [1,4–6].

The National Cooperative Highway Research Program (NCHRP) Report 519 [7] presented a survey on the most commonly used negative and positive moment connections over the piers for prestressed girders. A total of six connection details using bent bars and bent strands were developed and tested. A minimum positive moment capacity of 1.2 times the cracking moment of the section was defined as the design goal to limit the crack width in the diaphragm and avoid significant loss of continuity. The connection details using bent bars over-performed the connection details using bent strands, however the former might be more difficult

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to implement on site. Further developments of the connection details, analytic tools and actual performance on site have been undertaken in other studies, which have considered the temperature and time-dependent effects on the connection performance [8,9].

However, a significant increase in the span range for precast prestressed concrete girder bridges might require the implementation of in-span girder splices. The NCHRP Report 517 [1] summarizes the main strategies adopted for extending the span range of this bridge typology. The concept of spliced girder bridges has a proven track record with some of the first spliced girder bridges being constructed as early as 1952. A span increase around 50% is typically achieved when using spliced girders, but increases up to 100% have been reported using haunched pier girder segments. The continuity of the structure can be achieved using a number of splicing details, which might include post-tensioning, pretensioning and conventional reinforcement strategies in single or combined solutions. The use of post-tensioning solutions is usual in the practice as they have the potential to provide superior long-term serviceability, however, they might also lead to complexity in forming and additional work for the post-tensioning and grouting tasks [1,2]. A significant number of spliced girder bridges have been constructed; most of them integrate combined pre- and post-tensioning, staged post-tensioning, or external post-tensioning solutions [1]. Although alternative solutions using conventional reinforcement strategies or additional splicing devices for in-span connections have been also reported in the literature, the information available is limited. Early studies by Lin [10] presented details for splices near the inflection points and indicated that non-post-tensioned connection details and even dry joints could be adequate solutions at those locations, although further research was regarded as necessary. Gutzwiller and Lee [11] also completed an early study on splicing details for in-span connections which considered three different solutions: post-tensioned, cast-in-place, and drop-in. The overall performance of the cast-in place splice was adequate and the solution was regarded as a feasible alternative under certain circumstances. The modifications suggested for the reinforcement detailing apply to the precast beams rather than to the splice itself.

In the context of the present study, the potential use of ultra high performance concrete (UHPC) to develop simplified connection geometries where strands can be lap spliced together using short splice lengths has motivated revisiting the cast-in-place concept for spliced prestressed concrete girder bridges. UHPC is a class of cementitious composite material that exhibits exceptional mechanical and durability properties. These materials are characterized by compressive strength greater than 150 MPa and integrate relatively high volume fraction of fiber reinforcement, which allow for sustained postcracking tensile strength and increased toughness [12,13]. Those exceptional material properties allow for enhanced bonding of reinforcing bars and strands and thus significantly reduces their development lengths [14–17].

## 2. Strand development and splicing

Simplified details for splicing strands extending from the ends of precast prestressed concrete girders provide an economical solution not only for on-pier connection systems where they might allow for structural continuity for deck loads and future live loads but also for in-span connection solutions where they might allow for the elimination of post-tensioning and a potential increase of the span range. The anchorage of untensioned prestressing strands in concrete differs from that of reinforcing bars and tensioned prestressing strands [18]. The embedment length required to fully develop a prestressing strand depends on a number of factors including the mechanical properties of the concrete, the confinement provided by the concrete and the passive reinforcement, as well as the surface properties of the strand. The wedging effect that occurs near the ends of the strand when the strand is released and the prestress force is effectively transferred to the concrete element, which is referred to as Hoyer effect, is a significant resistance mechanisms that is not present when untensioned strands are cast in concrete. Relationships for predicting the development length of prestressing strands are provided in structural design guides and recommendations and they generally estimate development lengths of the order of 150 times the strand diameter ($d_s$) [19,20]. However, the development length of untensioned prestressing strands is normally expected to be longer than the one predicted for pretensioned strands in the guidelines.

The applicability of the predictive relationships provided in current design guidelines is limited to the range of the parameters considered in their validation, which in most cases do not specifically cover high performance materials. In particular, the description of the anchorage of bars and strands might require more comprehensive approaches considering main parameters including material properties, element typology, constructability and loading conditions. A comprehensive review of the transfer, development and splice length for strands in high strength concrete was presented in the NCHRP Report 603 [21], which aimed at broadening the applicability of the *AASHTO LRFD Bridge Design Specification* [19] for concretes with compressive strength up to 100 MPa. The reported results showed clear correlation between shortening of transfer and development lengths and increasing concrete strength. Likewise, the tensile strength and toughness of the concrete were also identified as parameters affecting the bond of the reinforcement. Furthermore, confining of the concrete that surrounds the embedded strands has proved to be effective in reducing the required development lengths. That passive confinement usually provided by mild steel reinforcing bars or fiber reinforcement is not explicitly taken into account within the predictive relationships for the strand embedment length.

### 2.1. Previous strand development tests

The development length of untensioned prestressing strands embedded in fiber reinforced concrete (FRC) and UHPC has not been extensively studied. Chao et al. [17] demonstrated that the confinement effect provided by fibers increases the bond strength between untensioned prestressing strands and the concrete matrix, likely leading to the decrease of the full development length. However, the results from the short embedded lengths used in the study might not be directly extrapolated to the full development length. Similar results were observed by Baran et al. [22], where the beneficial effects on the bond strength were evident even for low fiber volume fractions. Bertram and Hegger [16] studied the bond behavior of strands in a variety of UHPC formulations with fiber volume fractions ranging from 0.9 to 2.5%. The influence of the Hoyer effect and the concrete cover were investigated by pull-out tests in very short embedment lengths. Additional small scale beam tests were also completed in order to study the dimensions of the concrete section to avoid splitting cracks as well as the transfer length. The results of the study indicated that the bond stress varies from approximately 13 MPa when the Hoyer effect is not present to approximately 30 MPa when a significant Hoyer effect is present. Likewise, the results suggested that a concrete cover of at least 2.5 times the diameter of the strand might reduce significantly the likelihood of splitting failures. Previous studies completed at Ohio University [23] investigated the development length of 12.7 mm untensioned prestressing strands embedded in steel fiber reinforced UHPC.

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