PRECAST DUCTILE END-DIAPHRAGM SYSTEM FOR ACCELERATED CONSTRUCTION OF SLAB-ON-GIRDER PRESTRESSED CONCRETE BRIDGES IN SEISMIC REGIONS

Quarterly Progress Report
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1 Background and Introduction

In recent years, public concern about road closures resulting from new construction, replacement, or retrofit of bridges has been on the rise. The consequences of these works could be economic losses, security concerns at the construction site, costs and delay time suffered by the users, and in general problems that worsen the public perception of transportation agencies. At the same time, due to current environmental awareness, there is a concern about unnecessary use of vehicles operating on fossil fuels, in this case due to detours or traffic congestion. To reduce the impacts on the driving public and the environment, accelerated bridge construction (ABC) techniques have been gaining popularity.

In ABC projects, bridge elements or entire systems are prefabricated and erected to expedite construction (Culmo, 2011). Examples of such prefabricated elements include deck panels (Garber and Shahrokhinasab, 2019) and columns (Shafieifar et al., 2020). Prefabrication of beams and girders has been an integral part of bridge construction in the U.S. for many years (Culmo, 2011). Precast prestressed concrete (PC) girder bridges comprise a large percentage of the National Bridge Inventory (NBI). In PC bridges, end diaphragms are used to transmit loads—mainly transverse in the case of earthquakes—from the bridge superstructure to the substructure. Typically, these end diaphragms are cast-in-place concrete. Culmo (2009) notes, "The time for forming and curing of [these] connections can be significant," motivating the need for prefabricated diaphragms for use in ABC projects. According to the investigators' knowledge and extensive literature review, both experimental work and seismic design provisions for end diaphragms on PC girder bridges are limited despite their abundance in practice. The 2010 Chile earthquake came to demonstrate the importance of end diaphragms and the need for developing and understanding a viable and clear seismic load path in bridges (Yen et al., 2010; Marsh et al., 2015). Furthermore, for regions located in high-risk seismic zones, great care must be taken in the way the connections between precast elements are made (Marsh et al., 2011; Culmo, 2009).

In the case of steel bridges, some important distress suffered by the superstructure and mainly by the substructure during the most significant earthquakes during the last three decades that occurred worldwide has been identified (Zahrai and Bruneau, 1999a). As a proposal to solve these problems through retrofit, Zahrai and Bruneau (1999a) developed a system of ductile end-diaphragms for slab-on-girders steel bridges. They tested three types of diaphragms based on three successful bracing frames systems for steel buildings (Zahrai and Bruneau, 1999b). Furthermore, they proposed a simplified design procedure based on analytical evidence from 2-D and 3-D computational models. The solution has evolved until it became the Type 2 Global Seismic Design Strategy (GSDS) of the AASHTO Guide Specifications for LRFD Seismic Bridge Design (2011) that applies only to steel superstructures, and likewise it forms part of other important seismic design and retrofit codes in the U.S. for bridges.

Therefore, following the concept proposed by Zahrai and Bruneau (1999a; 1999b) for steel bridges, it would be important to develop guidelines on the behavior and detailing of precast concrete ductile end-diaphragm elements for seismic resistance. With this regard, the use of concrete ductile diaphragms as fuses (Type 2 GSDS) should be explored for the seismic lateral resistance of slab-on-girder concrete bridges. This diaphragm system should be developed to be part of ABC solutions for design of new bridges, has potential as an ABC solution for retrofitting of old infrastructure, and even could be used for a combination of both, in the case of simply supported PC girder bridges located in high-risk seismic regions.

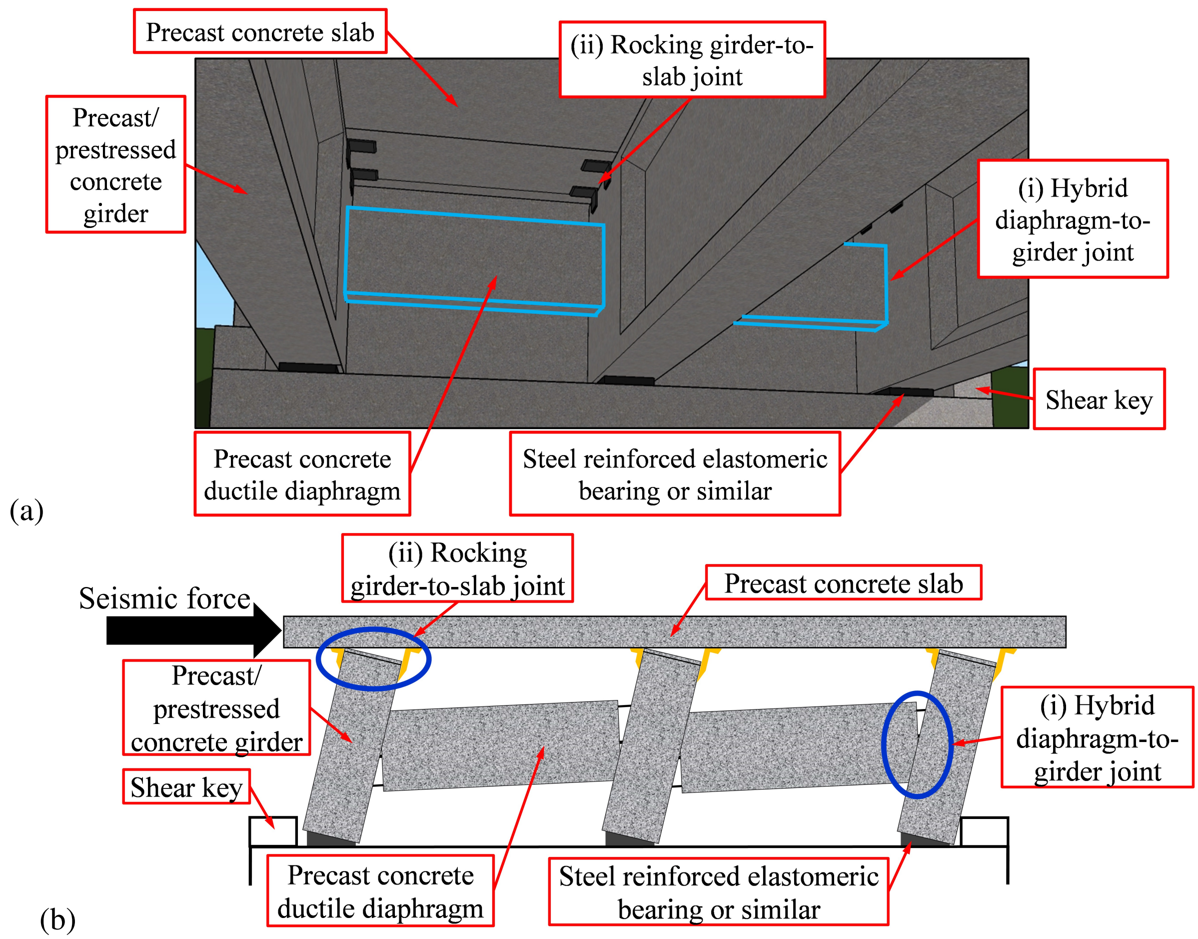

Figure 1: Proposed ductile precast end-diaphragm system: (a) General view of proposed system in a prototype bridge, (b) Schematic view of the expected rocking behavior of the system under lateral seismic load

In a preliminary study (Villalobos-Vega and Santana, 2022), the cyclic lateral load behavior of a ductile precast end-diaphragm system was proposed and modeled (see Fig. 1(a)). The system, whose intention is a global low damage behavior even under extreme events, is comprised of (i) diaphragm-to-girder connections based on the concept of the conventional hybrid system with unbonded post-tensioning and (ii) girder-to-slab connections with the use of steel angles for partially restricted (PR) or semi-rigid connections. In that study, a simplified method of design and step-by-step analysis was developed for both the components and the ductile end-diaphragm system, by means of which the force-drift relationship and the dynamic and seismic demand parameters of the bridge were obtained. To get the experimental behavior of the proposed concept, a length corresponding to 24 in. (0.60 m) of one of the ends of a prototype bridge was considered, and it was tested in real scale in the laboratory subjected to pseudo-static cyclic lateral loading (see Fig. 1(b)). The main objectives of the preliminary study were to propose the main characteristics and components of the system, determine the feasibility of its construction process, establish a first trial of its theoretical behavior, and test just a portion of the bridge to obtain a reasonable response of the system to have a parameter for comparison.

Overall, the above goals were met, but additional questions resulted. In particular, the experimental result of overstrength in one direction of load needs to be addressed, besides to determine if the connections' performance can be improved by using other known or novel cost-effective technologies adapted to the ABC market in the U.S. Additionally, it is necessary to improve and extend the analysis to the overall behavior of the bridge—not just at the ends—and at the same time parameterize variables such as the length, depth, and number of girders, to be able to better understand the interactions between the girders, ductile diaphragms, and deck under seismic actions. Finally, a second test is necessary to incorporate the improvements identified in the completed preliminary study and/or through modeling and verify experimentally its performance subjected to seismic demands. The project presented here aims to address these questions.

2 Problem Statement

Diaphragms connect parallel girder elements and assist with lateral distribution of load in bridge superstructures. Cast-in-place diaphragms are typically used with precast prestressed concrete girders, but time for forming and curing can be significant, which is not amenable to ABC. The present project explores the use of prefabricated diaphragms for ease and rapidity of construction, incorporating novel connection detailing for use in medium to high seismic regions to achieve ductile behavior.

The proposed precast concrete end-diaphragm system comprises unbonded post-tensioning diaphragm-to-beam connections and partially restricted beam-to-slab connections to achieve low damage behavior. The project extends previous work by the research team on this concept through computational modeling, experimental testing, and optimization of connection detailing, including the incorporation of ultra-high performance concrete (UHPC) based on the Co-PI's expertise. High-fidelity finite element models of a prototype bridge equipped with the proposed diaphragm system will inform the optimization of the connection detailing.

The resulting connection detailing will be tested experimentally to validate the performance, calibrate and validate the computational model, and determine its feasibility in an ABC context. The primary output of the project will be a guide for modeling and designing the proposed prefabricated ductile concrete end-diaphragm system, promoting its uptake in ABC projects.

3 Research Approach and Method

The objectives of the research project are: (a) calibrate and validate computational models for the behavior of the proposed precast concrete ductile end-diaphragm elements and rocking girder-to-slab connections, (b) synthesize analytical evidence of the enhanced seismic performance of these prefabricated ABC elements through computational modeling, and (c) develop guidelines for computationally modeling the proposed prefabricated ABC elements for use by practitioners and researchers.

4 Description of Research Project Tasks

The project plan follows an integrated program of computational modeling, experimental testing, and guideline development. The objectives described above are realized through the following research tasks: (1) Develop high-fidelity finite element model of a prototype slab-on-girder bridge equipped with the proposed precast ductile end-diaphragm system. (2) Optimize the design of the precast ductile end-diaphragm system and connections to enhance seismic performance. (3) Construct and test a scale, 3-girder bridge superstructure segment to demonstrate the system's performance. (4) Prepare guidelines for modeling and designing prefabricated ductile precast concrete end-diaphragm systems for use in accelerated construction

The proposed timeline is presented in Section 7. The main research tasks shown in Table 1 are described here. The key objectives related to each task are also listed.

4.1 Task 1 – Computational Modeling

Objective: *To model the holistic behavior of a bridge equipped with the proposed ABC system.*

The first task of this project is to develop a high-fidelity finite element (FE) model of a typical bridge from a seismic area of the U.S. equipped with the proposed ductile end-diaphragm system. A prototype bridge is currently being identified based upon a survey of the NBI database, focusing on high-seismic regions in the conterminous U.S., as well as a survey of Departments of Transportation (DOTs) across the country. This FE model will be used in Task 2 for the design optimization. Furthermore, the model will be updated throughout the project (see Table 1) based upon the optimized diaphragm design (Task 2; month 6) and the experimental behavior (Task 3; months 10–12). Furthermore, the computational modeling approach will be documented in Task 4.

4.2 Task 2 – Design Optimization

Objective: *To fine tune the detailing of the ductile diaphragm system and connections.*

The second task of this project is to refine the design of the ductile precast concrete end diaphragm and rocking girder-to-slab PR joint. The starting point will be the simplified design procedure developed in the preliminary study (Villalobos-Vega and Santana, 2022). Insights from that study will be used to refine the diaphragm and connection detailing. For example, the lack of better cementitious materials affected the results of the preliminary tests, so the use of (non-proprietary) ultra-high performance concrete (UHPC) or mortar, could significantly improve its behavior. Another example of areas of improvement that can be incorporated are the connections between elements, given that Villalobos-Vega and Santana (2022) used standard details. More state-of-the-art or novel ideas—identified through review of current ABC practice and the literature—could be incorporated to upgrade characteristics such as energy dissipation capacity, durability, ease of construction and replacement, economic competitiveness, among others. To further optimize the design, the FE model developed in Task 1 will be used to run a suite of risk-targeted earthquake ground motions to assess each design's performance to determine the best design.

4.3 Task 3 – Experimental Testing

Objective: *To calibrate the computational model and to validate the predicted load-drift behavior.*

The third task of this project is to experimentally test a scale model of a bridge superstructure equipped with the optimized end-diaphragm system found in Task 2. For these tests, three (3), 1/2-scale PC girders will be connected by precast concrete diaphragms based upon the proposed design (Task 2). Rocking girder-to-slab joints will be used to connect a precast deck slab for continuity across the top of the girders. A limited length (24in.) of the superstructure will be tested to focus on the end diaphragm system's behavior (see Fig. 2). Additional dead load will be applied across the top of the deck to account for the missing weight of the bridge span not physically present in the test setup. Quasi-static, cyclic, displacement-controlled loading will be used to characterize the load-drift behavior over a range of displacements. These lateral loads will be applied through the deck slab to simulate inertial loads due to an earthquake. These tests will leverage existing formwork at OU's Fears Structural Engineering Lab, previous research on UHPC slab connections

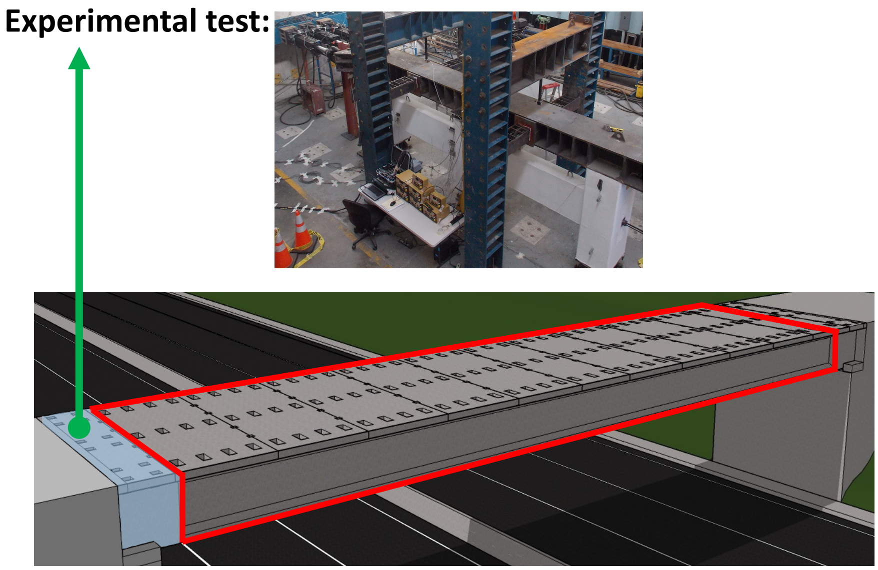

Figure 2: Schematic showing that from the entire bridge only the end regions are considered during the tests.

by the Co-PI (Looney et al. 2021), as well as the non-proprietary UHPC developed by the Co-PI's research group (Looney et al. 2019).

4.4 Task 4 – Guideline Preparation

Objective: *To promote the uptake of the proposed ABC system by providing guidance to the design and modeling of these systems.*

The fourth task of this project will be to prepare a *Guide for Modeling Ductile Concrete End-Diaphragm Systems* based upon the efforts in Tasks 1–3. This will include recommendations for modeling approaches for predicting the behavior of the proposed diaphragm system and guidance on the design of such systems.

5 Anticipated Research Results and Deliverables

Results from previous research by the student working on the project (Villalobos-Vega and Santana, 2022) will be extended to: (a) Improve understanding of the theoretical behavior of the subsystem and extend its applicability to behavior of the entire bridge; (b) Improve detailing, materials and technology used, both for components and for connections (e.g., using UHPC). Additionally, this project will develop guidelines for the modeling and design of a new type of ABC system, namely the precast ductile end-diaphragm system.

6 Applicability of Results to Practice

Results of the project have potential to extend the usage of the Type 2 GSDS of the AASHTO Guide (2011) for steel bridges to slab-on-girder concrete bridges, including its use as part of ABC solutions for design of new structures or seismic retrofit of in-service bridges.

7 Schedule

Progress on this project is shown in Table 1.

Table 1: Project schedule

Research Task	2023					2024					
	8	9	10	11	12	1	2	3	4	5	6
Contract Executed	■										
1. Computational Modeling	■	□	□		□			□	□	□	
2. Design Optimization			□	□	□						
3. Experimental Testing						□	□	□	□	□	□
4. Guideline Preparation										□	□

■ Work Performed □ Work to be Performed

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