NUMERICAL INVESTIGATION OF THE IMPACT OF VERTICAL GROUND MOTIONS ON ABC CONNECTIONS IN THE NEAR-FIELD

Quarterly Progress Report
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ABC-UTC
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1. Background and Introduction

State-of-the-art research on the incorporation of vertical ground-motion effects in the response assessment of ordinary highway bridges has revealed the potential for a significant increase of the demands at the girder-to-cap face, particularly in the near-field of major active faults.

While this is not of major concern for ordinary bridges whose moment capacity at the face of the bent cap is typically adequate to resist the increased demands due to vertical effects, the impact of vertical ground motions on ABC connections is yet to be thoroughly investigated.

2. Problem Statement

According to the current design practice, precast girder-to-cap connections should be modeled as pinned connections, as the result of the severe degradation they are expected to experience under strong seismic events. Such oversimplifying approaches in modeling critical components subject to horizontal and vertical motions are still pervasive in codes and standards, and drastically reduce the interest in utilizing precast connections, particularly in moderate-to-high seismic regions.

This research is conducting a systematic numerical investigation with the use of 3-D numerical models and three-directional motions to understand and quantify the effect of vertical motions on ABC girder-to-cap connections. A comprehensive comparison of the demand posed to the girder-to-cap connections as obtained from a statistically significant population of arrays of near-field records and state-of-the-art methods will be provided upon completion of the project. Such methods will include (i) modeling the vertical acceleration as a constant pseudo-static force applied upward or downward along the bridge superstructure; (ii) utilizing time-history analyses that incorporate horizontal ground motion data from actual earthquakes and the vertical acceleration assumed as two-thirds of the magnitude of the horizontal acceleration; and (iii) employing near-field ground motion acceleration data arrays for both horizontal and vertical component as recorded in actual earthquake events, which to date are available in a very limited number.

3. Objectives and Research Approach

This research is exclusively based on detailed numerical models and simulation of the nonlinear dynamic response of bridge structures that incorporate ABC connections. The structural modeling part has been addressed with a two-level approach.

In the first-level, a solid three-dimensional model of a prototype ABC connection has been developed with a commercial software (DIANA) that allows for a detailed representation of concrete and steel constitutive relationships in a three-dimensional stress space. Such relationships include concrete degradation, spalling, and steel buckling. This model has been subjected to a series of static and dynamic analyses finalized at fully characterizing the nonlinear behavior of the ABC connection under complex loading patterns.

The results of this portion of the study is being utilized in the second-level of modeling aimed at creating a reduced-order equivalent model of the ABC connection in OpenSees (v 3.3.0, 2019), consisting of an assembly springs capable of reproducing the global constitutive relationship of the ABC connection. A calibration study is being conducted to finalize the set of properties of the springs.

The reduced-order model of the ABC connection will be then incorporated into a full bridge model to execute a large number of nonlinear time-history analyses under all three components of ground motions.

This research will provide the basis for the development of guidelines for the incorporation of spatially varying vertical ground motions effects in the design of ABC girder-to-cap connections. Upon completion, this study will offer a statistical basis adequate for identifying systematic trends and suggesting simplified measures to advance current design methods in the framework of the capacity design. Future effort combining computational and experimental work can provide the essential basis for the validation of the evidence from this research.

4. Description of Research Project Tasks

The following is a description of tasks carried out to date.

Task 1 – Literature review

Work proposed: Conduct a comprehensive literature review on "bent cap-to-column" and "bent cap-to-superstructure" ABC connections currently utilized in low-to-moderate and high-seismicity areas.

Work performed: The literature review carried out in the first months of the project has led to the identification of a typical nonintegral emulative precast bent cap system and baseline bent and bridge model to utilize as a case study for the low-to-moderate seismicity case (the next baseline model will cover the case of high-seismicity areas). Specifically, a two-span bridge, a two-column bent, and a bent-to-column pocket connection were selected. Figure 1 provides a representation of the key components of the selected baseline model.

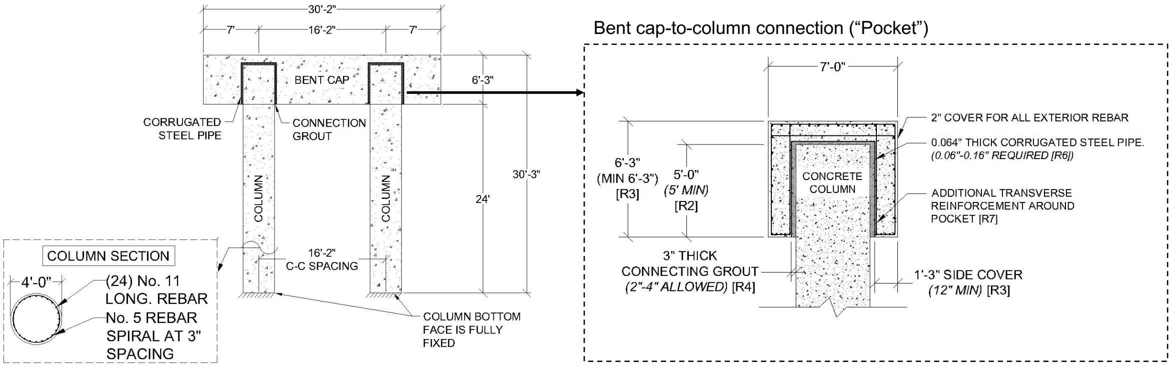
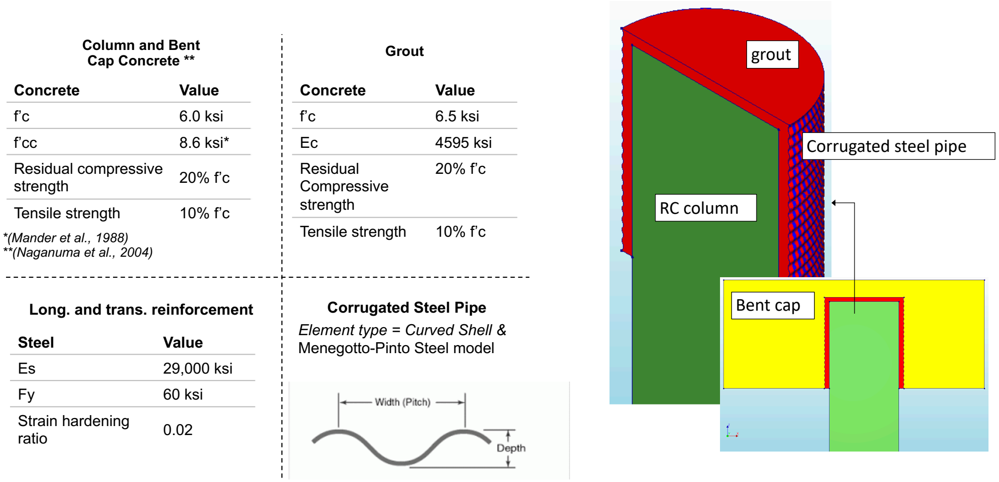


Figure 1. Baseline bent and bent cap-to-column model

Task 2 – Development and analysis of a solid element model of a typical ABC connection

Work proposed: Build a micro (solid elements) model of the ABC connection identified in Task 1 and conduct a series of static and dynamic tests under different load patterns to fully characterize the connection constitutive behavior.

Work performed: A detailed solid elements - (micro)model - of a single column and bent cap incorporating the pocket connection identified in task 1 was developed in DIANA. Figure 2 provides the material models and parameters assigned to each connection element (left) and a schematic representation of the connection components (right).



Column and Bent Cap Concrete **

Concrete	Value
f'c	6.0 ksi
f'cc	8.6 ksi*
Residual compressive strength	20% f'c
Tensile strength	10% f'c

*(Mander et al., 1988)
**(Naganuma et al., 2004)

Grout

Concrete	Value
f'c	6.5 ksi
Ec	4595 ksi
Residual Compressive strength	20% f'c
Tensile strength	10% f'c

Long. and trans. reinforcement

Steel	Value
Es	29,000 ksi
Fy	60 ksi
Strain hardening ratio	0.02

Corrugated Steel Pipe

Element type = Curved Shell &
Menegotto-Pinto Steel model

Figure 2. Micromodel of the ABC connection created in DIANA. Material properties (left), connection geometry (right)

This model was subjected to a series of static tests under different loading patterns. As an example, Figure 3 shows the lateral force versus lateral displacement curves obtained from monotonic (left) and cyclic (right) pushover analyses. These simulations served to gain understanding on the sequence of failures controlling softening and energy dissipation in the column-connection system and is informing the development of the reduced order model of the ABC connection as part of the activities of Task 3.

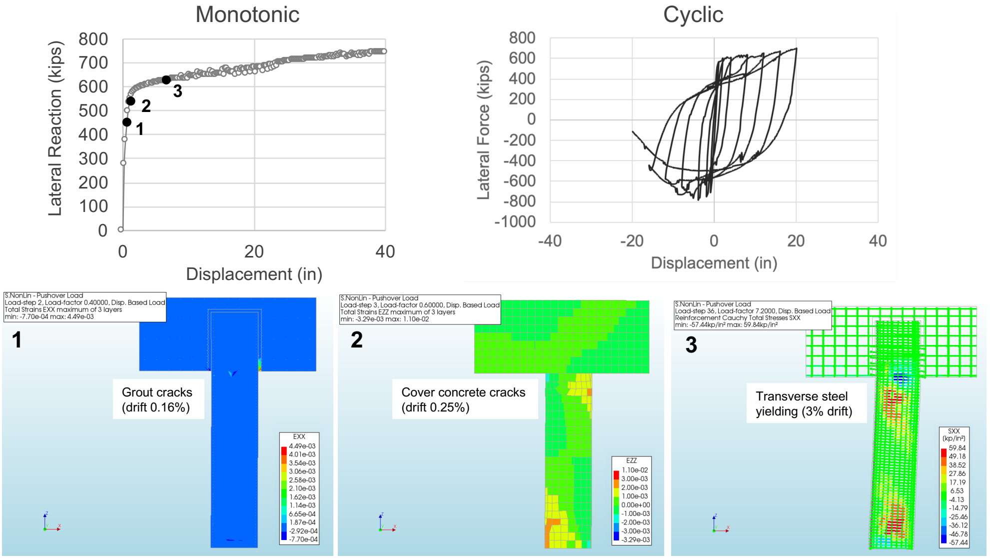


Figure 3. Top: Lateral force versus lateral displacement response as obtained from a monotonic (left) and cyclic (right) pushover analysis. Bottom: progression of the damage in the bent cap-to-column connection and column (DIANA).

Task 3 – Development of a reduced-order model of the ABC connection

Work proposed: Develop reduced-order models of the ABC connections in the OpenSees environment able to capture the main aspects of the global response as characterized in Task 2.

Work performed: This task is currently under development.

Task 4 – Build a reduced-order model of a full bridge

Work proposed: Build a reduced-order model of a full bridge with the use of OpenSees that incorporates the ABC connection models developed in Task 3.

Work performed: A simulation model of the full bridge has been developed in OpenSees. The model employs displacement-based beam elements with fiber sections for the columns and bent-cap, linear elastic beams for the deck, and assemblies of springs for abutments, foundation, and bent cap-to-column connections.

A sensitivity analysis was carried out to inform column model features and discretization. As an example, Figure 4 shows the differences in peak and post-peak response obtained from monotonic pushover analyses on the single nonlinear reinforced concrete column with different levels of discretization. The column model selected to model the full bridge adopts 7 elements.

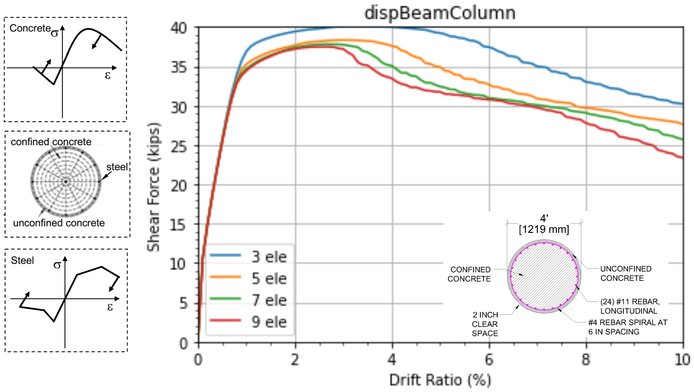


Figure 4. Peak and post-peak column response at varying of the column discretization

The column model so defined was utilize to perform a numerical 'blind prediction'. That is, two experimental columns from the literature (Calderone et al, 2001) were modeled with the selected material models and element discretization and subject to a monotonic pushover. The columns differ from each other for the shear reinforcement.

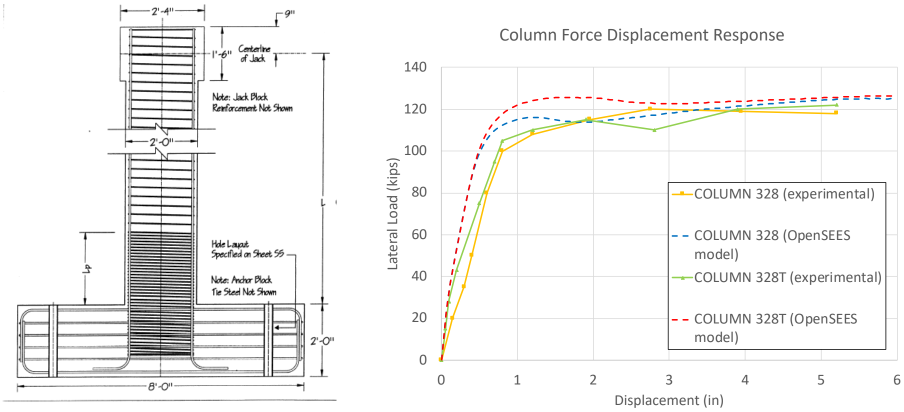


Figure 5. Reinforced concrete column in Calderone et al, 2001 (right), and experimental vs numerical force-displacement response (left)

In the OpenSees numerical model this was simulated by modifying the properties of confined concrete, following the relationships proposed by Mander (1988). Figure 5 shows the reinforced concrete column (left) and the lateral force versus lateral displacement (right) as obtained experimentally and numerically for the two columns. This numerical exercise allowed to gain confidence in the capability of the model to simulate the nonlinear behavior of typical bridge columns.

Such model was integrated into the full bridge model developed in OpenSees and represented in Figure 6. This model is currently being tested under some of the ground motions identified in Task 5.

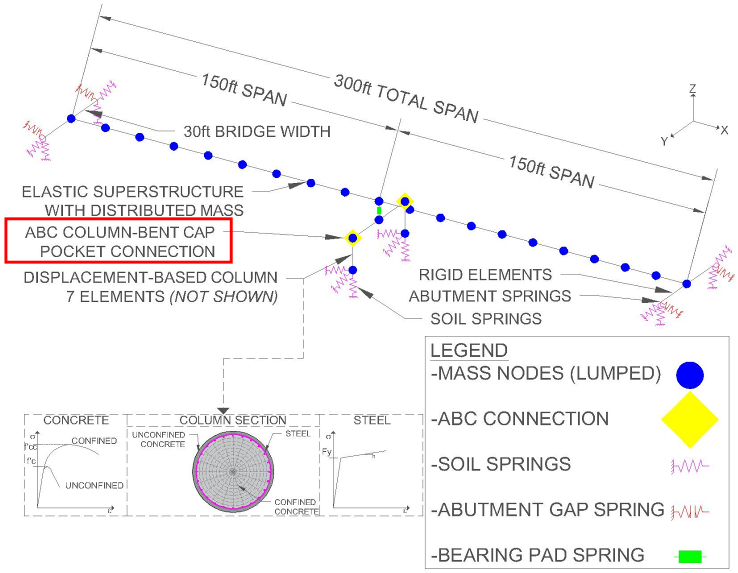


Figure 6. Model of the full bridge developed with the OpenSees software.

Task 5 – Establish a database of ground motions to utilize for the dynamic analyses

<u>Work proposed:</u> Identify a statistically significant suite of arrays of near-field motions (3 components) and perform nonlinear dynamic analyses by adopting a multi-support load pattern.

<u>Work performed:</u> This task is currently under development. It is planned to utilize a combination of real and simulated ground motions.

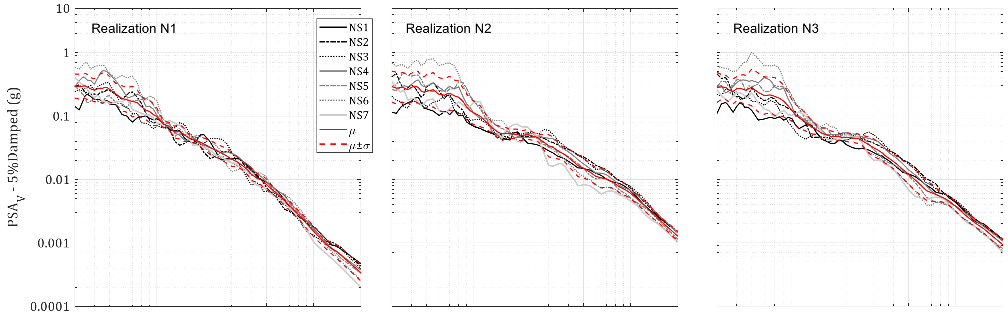


Figure 7. Pseudo-spectral acceleration of the vertical component of twenty-one near-field ground motions generated from three simulations of an M7 earthquake

Figure 7 represents the pseudo-spectral acceleration (PSA) of the vertical component of twenty-one near-field ground motions generated from three simulations of a Hayward Fault strike-slip earthquake. This is a preliminary set that has been selected to perform nonlinear time-history analyses with the full bridge model developed in OpenSees under three ground-motion components. The criteria utilized to select the motion include the identification of records with impulsive character in the vertical and/or horizontal direction, a significant between-events variability in the PSA at the spectral periods relevant to the response of the bridge components, and a range of V/H ratio values.

Task 6 – Simulation results summary and development of simplified measures to incorporate vertical ground motions into the design

Work proposed: Provide an extensive analysis of the simulation results to eventually propose simplified measures to advance current design methods in the framework of the capacity design.

Work performed: This task will be carried out once all the simulation results are available. However, a selection of the simulation outputs to utilize for the analysis of the simulation results has been performed. The current list includes shear demand at the bent cap to pocket connection interface, column ductility demand, column axial force, and deck midspan bending moment.

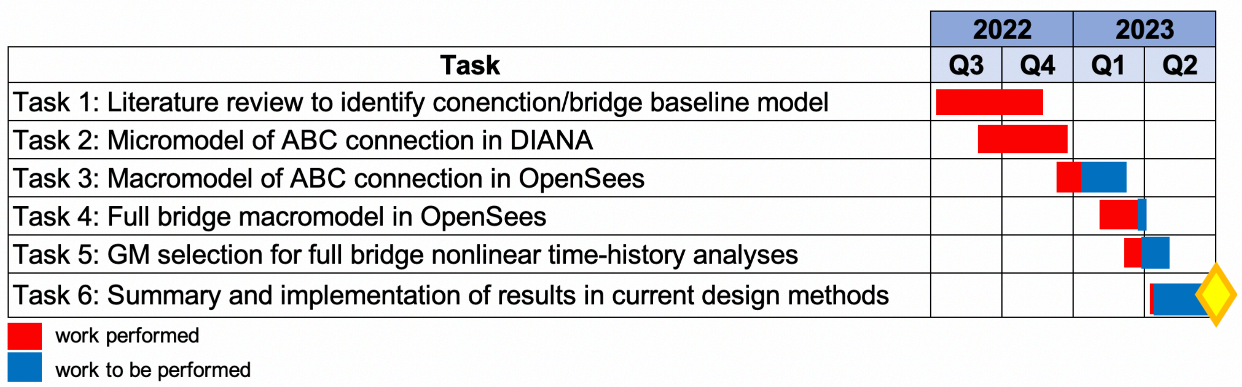
5. Expected Results and Specific Deliverables

It is anticipated that upon completion this research will provide (i) a detailed model and a reduced-order model of an ABC connection; (ii) a reduced-order model of a bridge that includes the proposed connection model; (iii) a critical review of how the demand obtained from the proposed analysis comperes with the ordinary methods proposed by codes and standards; (iv) suggestions on simplified measures that can be incorporated in current codes and standards for the inclusion of the vertical ground motions effects on girder-to-cap face connections.

The main deliverables will be a journal paper that summarizes the research findings, final report, data, guide, and 5-min video.

6. Schedule

The progress of tasks is shown in the table below.



	2022		2023	
Task	Q3	Q4	Q1	Q2
Task 1: Literature review to identify conenction/bridge baseline model	🟥	🟥		
Task 2: Micromodel of ABC connection in DIANA	🟥	🟥		
Task 3: Macromodel of ABC connection in OpenSees		🟥	🟥🟦	
Task 4: Full bridge macromodel in OpenSees			🟥🟦	
Task 5: GM selection for full bridge nonlinear time-history analyses			🟥	🟦
Task 6: Summary and implementation of results in current design methods				🟥🟦◆

🟥 work performed

🟦 work to be performed

7. References

1. OpenSees software, v 3.3.0, 2019.
2. Calderone, A. J., Lehman, D. E., & Moehle, J. P. (2001). *Behavior of Reinforced Concrete Bridge Columns Having Varying Aspect Ratios and Varying Lengths of Confinement* (No. 2000/08; p. 146). PEER.
3. Mander, J. B., Priestley, M.J.N., and Park, R., *Theoretical Stress-Strain Model for Confined Concrete*, J. Struct. Eng., 1988, 114(8): 1804-1826