SEISMIC DESIGN AND PERFORMANCE OF ULTRA-HIGH PERFORMANCE CONCRETE BRIDGE BENTS

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Abstract

This study aims at exploring the extended use of UHPC to entirely replace conventional concrete in a typical highway bridge multi-column bent. Four different UHPC mix designs of varying mechanical properties were considered to preliminarily design a two-column bent using current analytical tools (OpenSees) and following standard design guidelines. The objective of the design was to optimize UHPC cross-sections to reproduce similar column and bent cap beam capacities as obtained from conventional concrete. Sectional analysis was used for design optimization. Nonlinear lateral pushover and time history analyses were used to perform seismic capacity checks and compare the seismic performance of UHPC multi-column bents to conventional concrete structures. While UHPC bents are expected to have a better durability and longer service life, the results of this study show that UHPC bents can have much more compact cross-sections for a structural and seismic response comparable to conventional concrete bridge bents.

Résumé

Cette étude a pour but d'explorer l'utilisation étendue du BFUP pour remplacer totalement le béton ordinaire dans les appuis de pont courants comportant plusieurs fûts. Quatre types de BFUP avec des propriétés mécaniques différentes ont été étudiés pour la conception préliminaire d'une pile portique à deux colonnes en utilisant les outils analytiques habituels (OpenSees) et suivant les règles de calcul standard. L'objectif de la conception était d'optimiser les sections transversales en BFUP pour obtenir les mêmes performances des fûts de pile et du chevêtre qu'avec du béton ordinaire. L'optimisation s'est basée sur un calcul de section. Une analyse non linéaire en poussée progressive dans le sens transversal et une analyse dynamique temporelle ont été menées pour vérifier la capacité sismique et comparer les performances sismiques des palées en BFUP à plusieurs fûts et celles de leurs homologues en béton ordinaire. Tandis que les palées en BFUP sont censées avoir une meilleure durabilité et une plus longue durée de vie, les résultats de cette étude montrent que les palées en BFUP sont susceptibles d'avoir une section transversale beaucoup plus compacte pour une performance structurelle et une réponse au séisme comparables aux appuis de pont multi-fûts en béton ordinaire.

1. INTRODUCTION

Over the past few decades, ultra-high performance concrete (UHPC) has made major advances in structural applications like highway and pedestrian bridges. UHPC has garnered increased interest due to its high strength, ductile behavior, long-term durability, and compactness. Its particularly low porosity increases the uniformity of its mix components and allows the concrete to attain its extreme properties with a more uniform stress distribution [1, 2]. Another advantage to its low porosity is UHPC's superior freeze-thaw durability. When water freezes, it experiences an approximate 9 % increase in volume. When water penetrates the voids of normal strength concrete and freezes, the sudden increase in volume of water, once frozen, can rupture the voids causing the concrete to crack [3]. Water penetrating concrete can also become problematic as it can corrode the reinforcing steel. Accordingly, when UHPC is used in structural elements and harsh environments, it can significantly extend structures service life and reduce or eliminate the frequent need for maintenance. UHPC also utilizes steel fibers, which allow UHPC structural members to benefit from the significant increase in the tensile ductility and they transfer pre-cracking and post-cracking loads without succumbing to brittle failures. Due to the small diameter and spacing of the steel fibers, the steel is better distributed providing higher bonding capacity. Several studies that focused on tensile behavior of UHPC showed that UHPC features sustained tensile capacity and a tensile strain hardening response [e.g. 4]. Thus, UHPC can continue to carry significant tensile loads after cracking due to the uniformly distributed steel fibers. This unique property will allow an increase in ductility and energy dissipation capacity [1] throughout structural members, which naturally can provide a resilient solution for seismic design of structures.

The aforementioned features of UHPC render it as a very practical material for highway bridge designs in environmentally harsh and earthquake-prone environments. Many previous studies focused on UHPC mix design and material characterization [e.g. 5]. Several studies also focused on practical field applications of UHPC for accelerated bridge construction [e.g. 6]. However, and only recently, studies have started looking into expanding the use of UHPC to full structural components by investigating its structural performance under different loading conditions [e.g. 7] and its cost and environmental feasibility [8].

This study fills a knowledge gap by providing a pilot design case study where UHPC replaces conventional concrete of a typical highway bridge pier. A prototype bridge in California in the United States was selected for this study where seismic design and checks are required to further explore the capabilities of UHPC. Four alternative UHPC mixes from the literature with varying mechanical properties are selected and utilized to optimize the design of a two-column bridge bent. The seismic performance of the four designed bents is investigated using nonlinear pushover and time history analysis. Dedicated constitutive material models and analytical tools for UHPC are still under development [e.g. 9]. Thus, readily available constitutive material models in OpenSees [10] are calibrated in this study to capture the flexural behavior of UHPC columns under combined vertical and lateral seismic loads. The considered prototype bridge, modeling assumptions, design optimization, and nonlinear analysis results are discussed in the following sections.

2. BACKGROUND

This section presents the prototype bridge considered in this study along with the selected UHPC mixes and the corresponding OpenSees material modeling assumptions.

2.1 Prototype bridge

This study focused on the design of the substructure two-column bent of a typical three span California highway bridge with a prestressed reinforced concrete box girder superstructure. The selected typical prototype bridge is the California Department of Transportation (Caltrans) Academy Bridge [11, 12], which was designed according to AASHTO [13] and Caltrans Seismic Design Criteria (SDC) [14]. The bridge has three spans of 126 ft (38.4 m), 168 ft (51.2 m), and 118 ft (36 m). The original design of the bridge bent assumed conventional concrete with nominal 28-days strength of 4000 psi (~27.6 MPa). The bent was redesigned with each UHPC mix, wherein the column diameter, bent cap width, and reinforcing steel volume parameters were optimized. The width and depth of the concrete box girder were assumed to remain the same. Each UHPC bent's seismic performance was compared to that of the original design.

2.2 UHPC mechanical properties

The full two-column bent with cap beam was considered for design using four different UHPC mixes with varying mechanical properties. The mechanical properties of the selected UHPC mixes from the published literature used to calibrate the material model parameters are summarized in Table 1 (f'_c equal to 119, 146, 199 and 251 MPa). The table shows the tested (actual) values of compressive strength, tensile strength, ultimate strain, strains at peak stress, and modulus of elasticity. The columns were designed using longitudinal and transverse steel reinforcement with an expected yield strength (f_{ye}) and expected tensile strength (f_{ue}) of 66 ksi (455 MPa) and 92 ksi (634 MPa), respectively. While some properties were not reported, conservative estimates from the literature were used as indicated in the table.

Table 1: Mechanical properties of the selected UHPC mixes (1 ksi = 6.895 MPa)

Property	Original	UHPC 1	UHPC 2	UHPC 3	UHPC 4
f'_c (psi)	4,000	17,260	21,147	28,900	36,360
f_t (psi)	-	1,300	1,500*	1,700	2,611
E (ksi)	4,372	6,070	6,092	7,460	8,847
Strain at Peak Stress	0.002	0.0035	0.004442	0.0046	0.0047
Ultimate Strain	0.005	0.009	0.0146	0.01	0.015*
Source	[11]	[15]	[16]	[15]	[17]

* *Minimum value estimated for analysis.*

2.3 Modeling in OpenSees

Three types of analyses were considered in this study and performed using OpenSees for the conventional concrete and all four UHPC bridge bent cases (Table 1). First, section analysis was performed to estimate cross-section capacities under combined axial loads and bending moments. Moreover, a 2D plane frame model was developed as schematically shown in Figure 1 and used for nonlinear lateral pushover and time history analysis. OpenSees is an open source platform that is widely used for performance-based seismic design and includes robust nonlinear simulation capabilities. Due to the lack of dedicated UHPC constitutive models, two of the existing uniaxial concrete models in OpenSees were modified and calibrated to represent the typical UHPC compressive and tensile behavior. The two concrete material models are *Concrete02* and *Concrete04* [18]. Besides the much higher strength values, compared to conventional concrete UHPC has a high ductility capacity at a sustained strength and has the ability to strain harden in tension. In this study, the ultimate flexural plastic hinge behavior of columns was assumed to be controlled by rupture in the reinforcing bars, which has been preliminary demonstrated in recent studies [19]. Thus, the concrete material models input parameters were modified to diminish or eliminate strain softening and allow for much larger strain values. Figure 1 illustrates the typical stress-strain relationship for the original *Concrete02* model and the expected modified relationship with UHPC-tailored input parameters. A similar approach was used for *Concrete04,* which represents a uniaxial Popovics concrete material model.

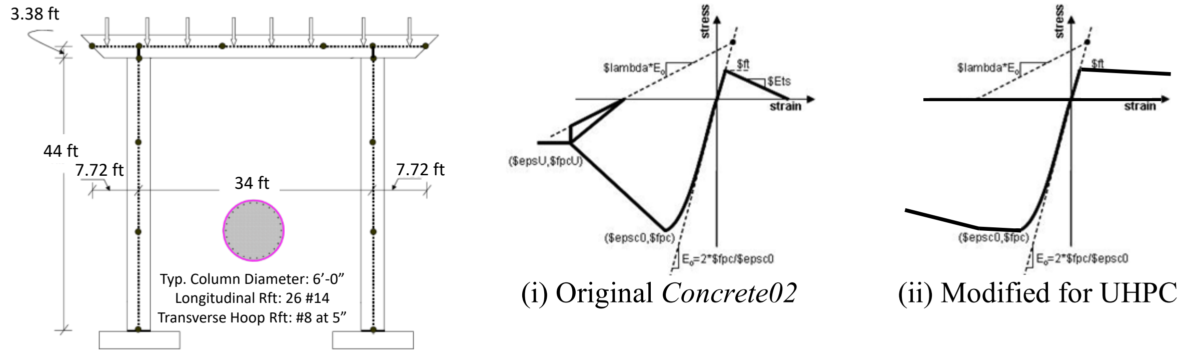

Figure 1: Bridge pier geometry and dimensions (left); and schematic representation of the original and modified stress-strain relationship for *Concrete02* in OpenSees (right).

3. UHPC BENT DESIGN

The study objective is to check whether the designs using UHPC can lead to a reduction in the cross-sections of the bridge bent columns and bent cap. The followed design procedure and UHPC design iterations and optimization are summarized here. It is noted that the design relied on OpenSees section analysis using both *Concrete02* and *Concrete04*.

3.1 Design procedure

A preliminary simplified design scheme was adopted in this study for each of the four UHPC mixes, which are outlined as follows:

- A preliminary UHPC column diameter was selected with ~1.5% reinforcement ratio (same as original design) to maintain a similar axial load ratio as conventional concrete;
- A cross-sectional analysis was performed for the UHPC column using *Concrete02* and *Concrete04* based on the given UHPC mechanical properties;
- The obtained UHPC column ultimate moment was compared with the ultimate moment capacity of the conventional concrete design;
- The column diameter was changed with increments of 2 in (5 cm) as needed to optimize the design with regard to the moment capacity;
- Different reinforcement ratios (~1.5%; ~2.0-2.5%; and 3.0-3.5%) were used and the section dimensions were optimized for each of the three cases. The aim was to investigate whether increasing the reinforcement ratio can better utilize the inherent UHPC strength.

It is noted that once the final column diameter was selected, the bent cap beam width was designed accordingly by adding 2 ft (~ 61 cm) to the column diameter as recommended by AASHTO and Caltrans SDC. The design procedure shown above was adopted for both *Concrete02* and *Concrete04* and the final optimized column designs as shown next.

3.2 Design optimization

The final optimized results of the sectional analysis for each UHPC mix design and for each varying longitudinal steel ratio (Concrete02 was used) is listed in Table 3. It is noted that Concrete04 was also used to define the UHPC concrete material model and to optimize the design cases for different UHPC mixes and reinforcement ratios, but only results from Concrete02 are shown here for brevity. Figure 2 illustrates the obtained moment-curvature relationships for all optimized UHPC sections compared to the original design that used a nominal 4,000 psi (27.6 MPa) concrete. Figure 2 also distinguishes between the three different ranges considered for the longitudinal steel reinforcement ratios. Note that the different UHPC mixes are identified in Figure 2 using their reported average 28-day strength. The results (Table 2) show that the original column diameter (6 ft ~ 1.8 m) can be reduced to 4 ft. 2 in. (~1.27 m) by using UHPC along with about 3.5% reinforcement ratio. Also, the higher reinforcement ratios result in more compact sections. UHPC is expected to provide strain compatibility up to higher strain levels than what is needed to rupture the reinforcing bars according to the current designs. Thus, higher reinforcement ratios or the potential use of high strength steel (e.g. Grade 80 or Grade 100) should be considered in future studies to further optimize the structural flexural design using UHPC.

Table 2: Concrete02-based optimized column design and sectional analysis results

Property	**Original**	**UHPC 1**	**UHPC 2**	**UHPC 3**	**UHPC 4**
f'_c (psi)	4,000	17,260	21,147	28,900	36,360
f_t (psi)	-	1,300	1,500*	1,700	2,611
E (ksi)	4,372	6,070	6,092	7,460	8,847
$A_{st}\cong$1.5%					
Column diameter	6’-0”	5’-2”	5’-0”	4’-10”	4’-6”
Bent cap width	8’-0”	7’-2”	7’-0”	6’-10”	6’-6”
Column long. reinforcement	26 #14	28 #11	28 #11	28 #11	22 #11
Column trans. reinforcement	#8 at 5”	#5 at 5”	#5 at 5”	#5 at 5”	#5 at 5”
Actual steel ratio	1.44%	1.45%	1.54%	1.65%	1.50%
Ult. moment (kip-in)	176,911	178,136	177,013	178,473	177,536
Ult. curvature (1/in.)	0.001120	0.00016	0.00018	0.00018	0.00016
$A_{st}\cong$2.0-2.5%					
Column diameter	6’-0”	4’-10”	4’-8”	4’-8”	4’-4”
Bent cap width	8’-0”	6’-10”	6’-8”	6’-8”	6’-4”
Column long. reinforcement	26 #14	26 #14	28 #14	24 #14	22 #14
Column trans. reinforcement.	#8 at 5”	#5 at 5”	#5 at 5”	#5 at 5”	#5 at 5”
Actual steel ratio	1.44%	2.21%	2.56%	2.19%	2.33%
Ult. moment (kip-in)	176,911	182,065	179,394	179,508	180,684
Ult. curvature (1/in.)	0.001120	0.00024	0.00026	0.0002	0.0002
$A_{st}\cong$3.0-3.5%					
Column diameter	6’-0”	4’-8”	4’-6”	4’-4”	4’-2”
Bent cap width	8’-0”	6’-8”	6’-6”	6’-4”	6’-2”
Column long. reinforcement	26 #14	32 #14	32 #14	32 #14	30 #14
Column trans. reinforcement	#8 at 5”	#5 at 5”	#5 at 5”	#5 at 5”	#5 at 5”
Actual steel ratio	1.44%	2.92%	3.14%	3.39%	3.44%
Ult. moment (kip-in)	176,911	182,773	179,553	178,426	186,882
Ult. curvature (1/in.)	0.001120	0.00026	0.0003	0.00028	0.00024

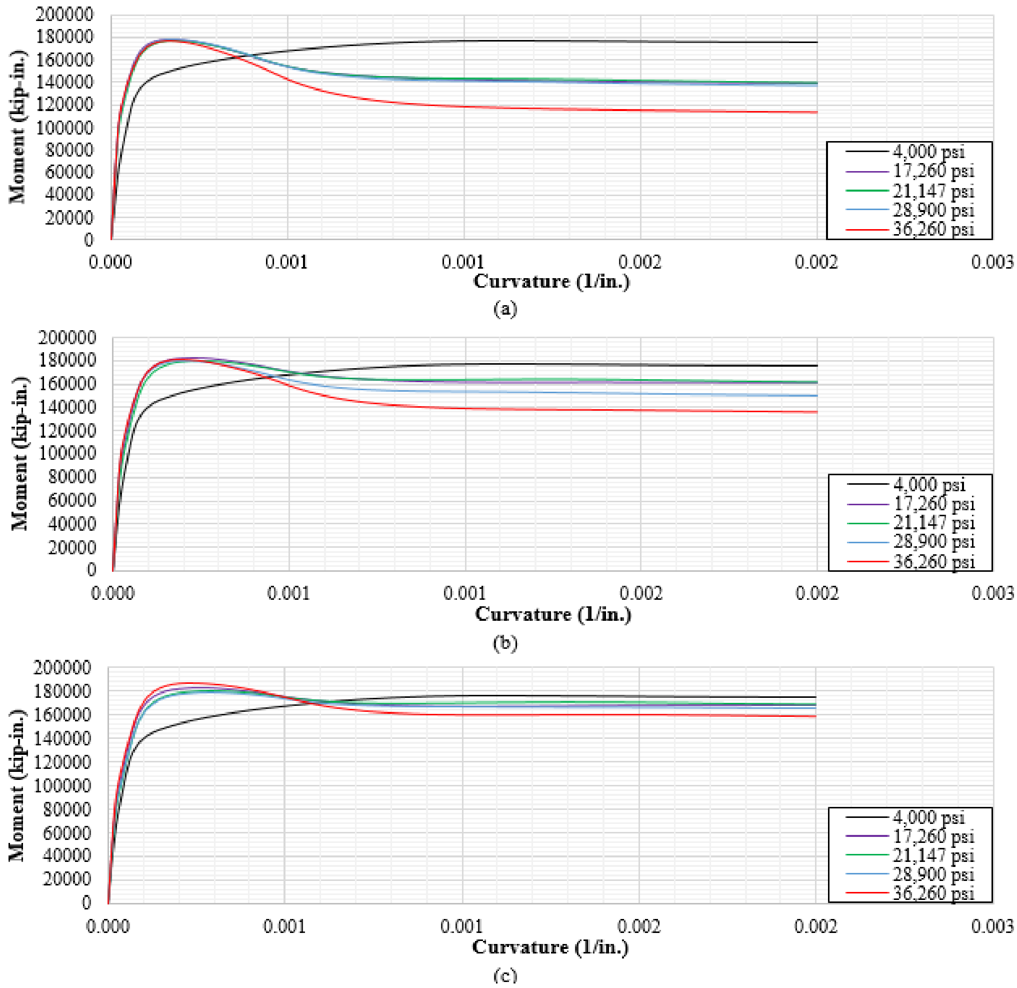

Figure 2: Concrete02-based moment curvature relationships for different UHPC and different longitudinal steel ratios: (a) $A_{st}\cong1.5\%$, (b) $A_{st}\cong2.0\text{-}2.5\%$, and (c) $A_{st}\cong3.0\text{-}3.5\%$.

4. NONLINEAR PUSHOVER ANALYSIS

The finalized designs of the columns shown in the previous section were used to finalize the bent cap beam dimensions. A 2D plane frame model was developed in OpenSees using nonlinear beam-column elements for each of the obtained UHPC designs. The frame was first loaded using vertical loads that were calculated from the original bridge superstructure (dead weight of the concrete box girder, concrete barriers, wearing surfaces, and bent cap weight). Next, a displacement-control lateral pushover was applied and continued up to 50 inches (a high drift ratio that exceeds 10 % in this bridge configuration). A P-delta geometric transformation was considered for defining the column elements in OpenSees. The objective of the nonlinear pushover analysis was to finalize the cap beam design by verifying the capacity check and compare each UHPC bent response to the original conventional design. The seismic demands from the pushover analysis observed in both bent columns and the bent cap beam for each of the design cases are summarized in Table 3 for *Concrete02* based designs. Only designs with 3.0-3.5 % longitudinal reinforcement ratios are presented here, as they best utilized the mechanical properties of UHPC to optimize the column design. The UHPC bent cap beam capacities were also calculated using section analysis to perform the seismic capacity design. This check verifies that the bent cap remained essentially elastic when the column reached its over-strength moment (1.2 times the ultimate moment according to AASHTO and Caltrans SDC).

Figure 3 illustrates the pushover curves for UHPC designs using A_{st}≅3.0-3.5% compared to the original conventional concrete design. The figure demonstrates that peak and residual base shear capacity are comparable to the conventional RC bent design when using the optimized UHPC designs. Due to the over-turning moment effect, the two columns experience different axial loads during the lateral pushover. Figure 4 compares the moment-curvature relationship sampled from both columns along with that obtained from the section analysis. These figures show the section analysis results as an average estimate of the two columns as expected.

Table 3: Pushover analysis results using finalized cross-sections (*Concrete02*, A_{st}≅3.0-3.5%)

Property	Original	UHPC 1	UHPC 2	UHPC 3	UHPC 4
$f'_{c\ actual}$ (psi)	4,000	17,260	21,147	28,900	36,360
Column Diameter	6'-0"	4'-8"	4'-6"	4'-4"	4'-2"
Bent Cap Width	8'-0"	6'-8"	6'-6"	6'-4"	6'-2"
Column Section Analysis Results					
Ultimate Moment (kip-in)	176,900	182,800	179,600	178,400	186,900
Bent Cap Section Analysis Results					
Ultimate Moment (kip-in)	212,900	290,500	301,100	322,900	433,400
Pushover Analysis Results					
Pier Maximum Force (kip)	578	712	695	693	735
Equivalent Yield Deformation, Δ_y (in.)	6.8	7.6	8.1	7.9	7.2

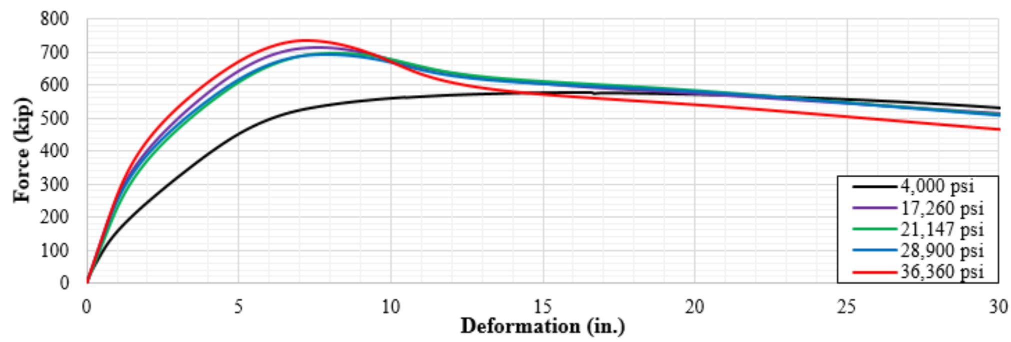

Figure 3: Pushover curve for UHPC bents at A_{st} ≅3.0-3.5% using Concrete02.

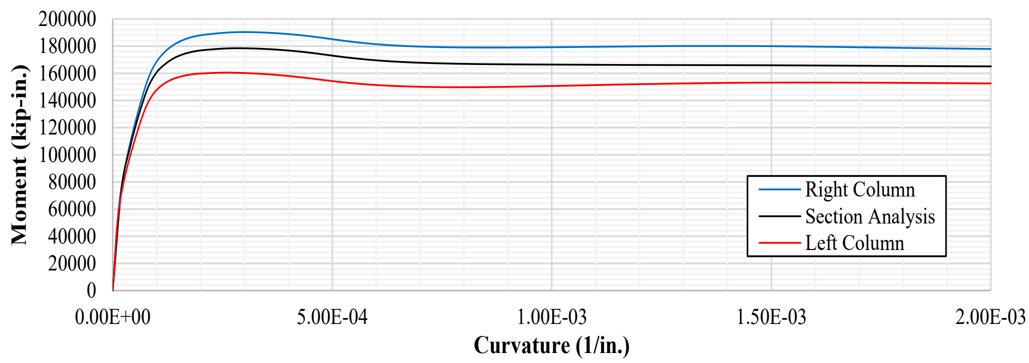

Figure 4: Sample moment curvature relationship for the two UHPC bent columns as obtained from pushover and sectional analysis [*Concrete02*; 28,900 psi; A_{st}≅3.0-3.5%].

5. NONLINEAR TIME HISTORY ANALYSIS

Selected UHPC design cases were utilized to perform nonlinear time history analysis to investigate the dynamic and seismic behavior of the UHPC bent under actual ground motions. The 1979 6.4 magnitude Imperial Valley earthquake, which represents a typical California crustal seismic scenario, was used for this analysis. Only the UHPC design cases that used *Concrete02* and $A_{st}\cong3.0$-3.5% were considered. Figure 5 shows the displacement history for the different UHPC mix designs as compared with the original conventional concrete. The figure illustrates that lower peak displacement values were obtained in the case of UHPC, which can be attributed to the stiffer, yet ductile, UHPC columns. Figure 6 shows the hysteretic force-deformation relationship for one sample UHPC design case (17,260 psi), where the overall stiffer behavior of UHPC can be observed. Moreover, Figure 7 shows the two bent columns moment-curvature relationships, which demonstrates a comparable seismic response in terms of moments and curvature demands for the UHPC cases as compared to the conventional concrete bents.

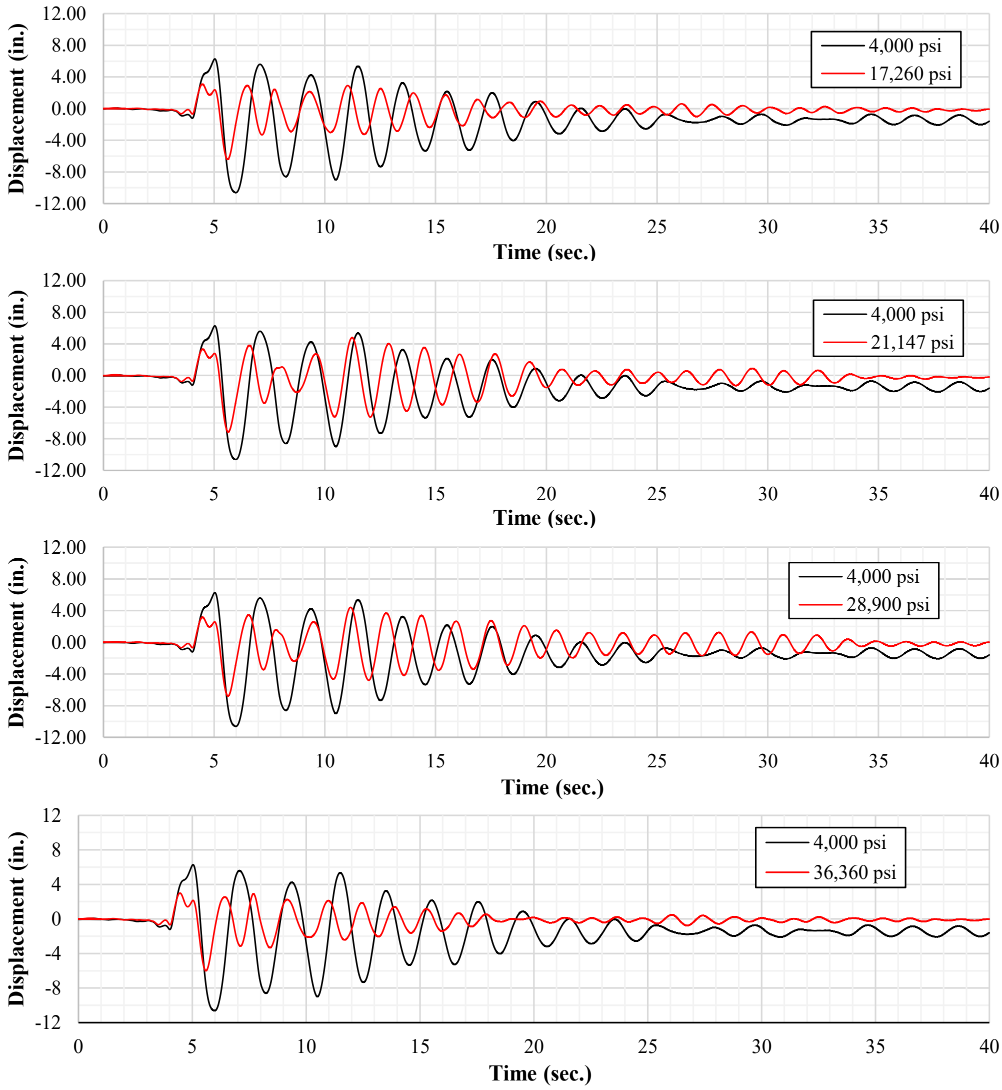

Figure 5: Displacement history for four different UHPC designs at $A_{st}\cong3.0$-3.5%.

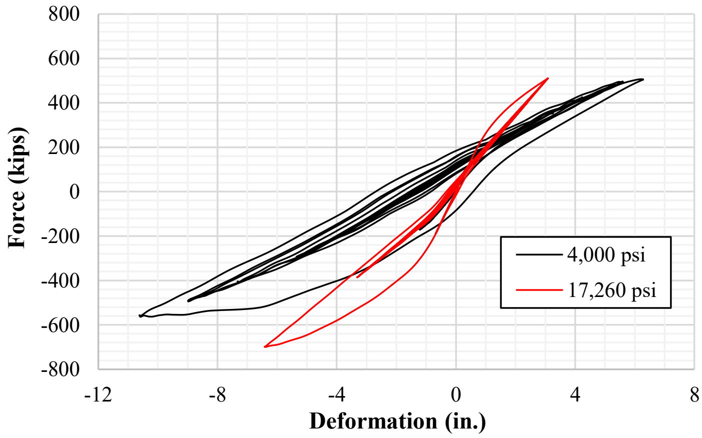

Figure 6: Comparison of the force-deformation relationship for one selected UHPC design case and the conventional concrete case for earthquake loading.

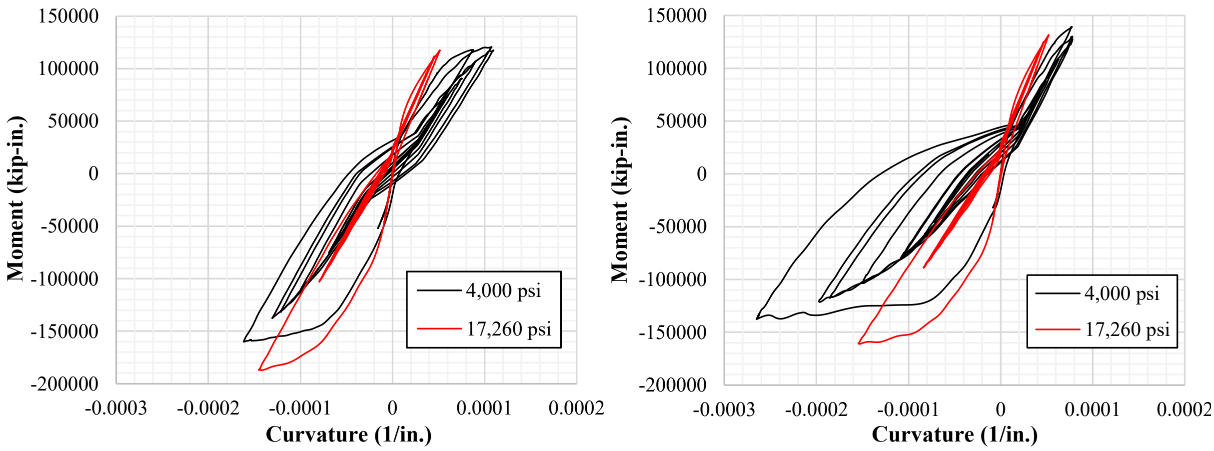

Figure 7: Comparison of the moment-curvature relationships for the two bent columns for a selected UHPC design case and the conventional concrete case under earthquake loading.

6. CONCLUSIONS

This study aimed at exploring the extended use of UHPC to entirely replace conventional concrete in a typical bridge multi-column bent. Four UHPC mixes with different mechanical properties were used. The design was optimized for different reinforcement ratios, and OpenSees models were developed for the two-column UHPC bents to perform nonlinear pushover and time history analysis. The following conclusions can be drawn:

- Using UHPC for bridge bents can lead to much more compact sections with about 50 % reduction in column cross-section area. This is favorable for foundation footprint reduction and has potential environmental benefits with regard to the overall concrete reduction.
- The structural and seismic performance of the optimized UHPC bridge bents is comparable, and in some aspects superior, to conventional concrete structures with normal strength designs. This was quantified by evaluating and comparing moment and curvature demands along with peak deformations and residual displacements under earthquake loading.

- Using different longitudinal reinforcement ratios for optimizing the UHPC designs showed that the steel ratio might not affect the ultimate capacity of the section. However, higher steel ratios (~3.5 %) can result in higher residual force and moment capacity at the structural level. The 3.5 % is within the 1-4% Caltrans permitted ratio, but higher ratios outside this range (up to 6 %) are recommended to investigate in future studies to maximize the benefits of the superior UHPC strength and material ductility.

REFERENCES

[1] Hanson, K., "UHPC Offers Endless Possibilities." NPCA (2014).
[2] Russell, H.G. and Graybeal, B.A., "Ultra-High Performance Concrete: A State-of-the-Art Report for the Bridge Community." FHWA, U.S. Department of Transportation, Report No. FHWA-HRT-13-060 (2013).
[3] Graybeal, B., and Hartmann, J.L., "Strength and Durability of Ultra-High Performance Concrete." (2003).
[4] Graybeal, Benjamin A., "Tensile Mechanical Response of Ultra-High-Performance Concrete." Advances in Civil Engineering Materials 4, no. 2 (2014): 62-74.
[5] Yu, R., Spiesz, P., and Brouwers, H.J.H., "Mix Design and Properties Assessment of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC)." Elsevier, Cement and Concrete Research (2013).
[6] Young, Wade F., and Jasan Boparai., "Whiteman Creek Bridge: A synthesis of accelerated bridge construction, ultra-high-performance concrete, and fiber-reinforced polymer." PCI journal 58, no. 2 (2013).
[7] Aoude H., M. M. Hosinieh, W. Cook, D. Mitchell., "Effect of transverse reinforcement detailing on the axial load response of UHPC columns." 1st international interactive symposium in UHPC, Des Moines, 18-20 July, (2016).
[8] Joe, C.D. and Moustafa, M.A., "Cost and Ecological Feasibility of Using UHPC in Bridge Piers." 1st international interactive symposium in UHPC, Des Moines, 18-20 July, (2016).
[9] Xu M., K. Wille. "Three Dimensional Fracture Material Model for Ultra-high Performance Fiber Reinforced Concrete under Tensile Loading." 1st international interactive symposium in UHPC, Des Moines, 18-20 July, (2016).
[10] McKenna, F., G.L. Fenves, and M.H. Scott., "Open system for earthquake engineering simulation." University of California, Berkeley, CA (2000).
[11] Caltrans Bridge Design Academy, "LRFD Design Example B." (2006).
[12] Moustafa, M.A., K.M. Mosalam. "Seismic response of bent caps in as-built and retrofitted reinforced concrete box-girder bridges." Engineering Structures 98 (2015): 59-73.
[13] American Association of State Highway and Transportation Officials (ASSHTO), "AASHTO LRFD Bridge Design Specifications, 6th Edition", (2012).
[14] Caltrans, "Seismic Design Criteria Version 1.7." Sacramento, CA, (2014).
[15] Graybeal, B., "Material Property Characterization of Ultra-High Performance Concrete." FHWA, U.S. Department of Transportation, Report No. FHWA-HRT-06-103 (2006).
[16] Prabha, S.L., Dattatreya, J.K., Neelamegam, M., "Stress Strain Behavior of Ultra High Performance Concrete Under Uniaxial Compression." (2014).
[17] Wille, K., El-Tawil, S., and Naaman, A.E., "Properties of Strain Hardening Ultra High Performance Fiber Reinforced Concrete (UHP-FRC) Under Direct Tensile Loading." (2014).
[18] Mazzoni, S., F. McKenna, M.H. Scott, and G.L. Fenves., "OpenSees command language manual." Pacific Earthquake Engineering Research Center, (2006).
[19] Kim, J., S.H. Chao. "Formulating Constitutive Stress-Strain Relations for Flexural Design of Ultra High-Performance Fiber-Reinforced Concrete." 1st international interactive symposium in UHPC, Des Moines, 18-20 July, (2016).