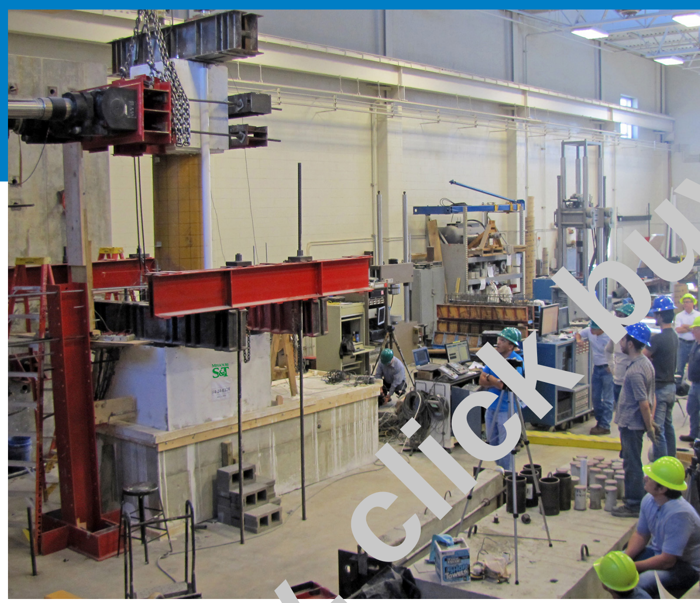
An ACI Technical Publication

SYMPOSIUM VOLUME



Structural Performance of Concrete Columns Incorporating Advanced Materials and Structural Systems

Editor:
Mohamed A. ElGawady

SP-341

American Concrete Institute
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Structural Performance of Concrete Columns Incorporating Advanced Materials and Structural Systems

Sponsored by
ACI Committees 441 – Reinforced Concrete Columns and 341A – Earthquake-Resistant Concrete Bridge Columns

The Concrete Convention and Exposition
October 14-18
Las Vegas, NV

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First printing, June 2020

Discussion is welcomed for all materials published in this issue and will appear ten months from this journal's date if the discussion is received within four months of the paper's print publication. Discussion of material received after specified dates will be considered individually for publication or private response. ACI Standards published in ACI Journals for public comment have discussion due dates printed with the Standard.

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Printed in the United States of America

Editorial production: Ryan M. Jay

ISBN-13: 978-1-64195-105-0

PREFACE

Columns are crucial structural elements in buildings and bridges. This Special Publication of the American Concrete Institute Committees 441 (Reinforced Concrete Columns) and 341A (Earthquake-Resistant Concrete Bridge Columns) presents the state-of-the-art on the structural performance of innovative bridge columns. The performance of columns incorporating high-performance materials such as ultra-high-performance concrete (UHPC), engineered cementitious composite (ECC), high-strength concrete, high-strength steel, and shape memory alloys is presented in this document. These materials are used in combination with conventional or advanced construction systems, such as using grouted rebar couplers, multi-hinge, and cross spirals. Such a combination improves the resiliency of reinforced concrete columns against natural and man-made disasters such as earthquakes and blast.

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Behavior of High-Strength Concrete and Normal-Strength Concrete Columns under Blast Loading

Amer Hammoud and Hassan Aoude

Synopsis: This paper presents the results from tests examining the performance of high-strength concrete (HSC) and normal-strength concrete (NSC) columns subjected to blast loading. As part of the study six columns built with varying concrete strengths were tested under simulated blast loads using a shock-tube. In addition to the effect of concrete strength, the effects of longitudinal steel ratio and transverse steel detailing were also investigated. The experimental results demonstrate that the HSC and NSC columns showed similar blast performance in terms of overall displacement response, blast capacity, damage and failure mode. However, when considering the results at equivalent blasts, doubling the concrete strength from 40 MPa to 80 MPa (6 to 12 ksi) resulted in 10%-20% reductions in maximum displacements. On the other hand, increasing the longitudinal steel ratio from ρ = 1.7% to 3.4% was found to increase blast capacity, while also reducing maximum displacements by 40-50%. The results also show that decreasing the tie spacing (from d/2 to d/4, where d is the section depth) improved blast performance by reducing peak displacements by 20-40% at equivalent blasts. The use of seismic ties also prevented bar buckling and reduced the extent of damage at failure. As part of the analytical study the response of the HSC columns was predicted using single-degree-of-freedom (SDOF) analysis. The resistance functions were developed using dynamic material properties, sectional analysis and a lumped inelasticity approach. The SDOF procedure was able to predict the blast response of HSC columns with reasonable accuracy, with an average error of 14%. A numerical parametric study examining the effects of concrete strength, steel ratio and tie spacing in larger-scale columns with 350 mm x 350 mm (14 in. x 14 in.) section was also conducted. The results of the numerical study confirm the conclusions from the experiments but indicate the need for further blast research on the effect of transverse steel detailing in larger-scale HSC columns.

Keywords: High-strength concrete, Columns, Blast, Shock Tube.

Combined use of UHPC and High-Performance Steel to Improve the Blast Performance of Columns with Square Cross-section

Sarah De Carufel and Hassan Aoude

Synopsis: This paper presents the results from tests examining the blast performance of columns constructed with ultra-high-performance concrete (UHPC) and high-performance reinforcement (high-strength steel or stainless steel). As part of the study six columns with square cross-sections were tested under simulated blast loads using a shock-tube at the University of Ottawa. Parameters investigated include the effects of concrete type, longitudinal reinforcement type and longitudinal reinforcement ratio. The results demonstrate that the use of UHPC increases the blast performance of reinforced concrete columns by increasing blast capacity and improving control of maximum and residual mid-span displacements by an average of 30% and 40%. Substitution of normal-strength bars with high-strength or stainless steel bars in the UHPC columns resulted in further reductions in displacements, which ranged between 18-43% for maximum deformations and 38-66% for residual deformations. The failure mode of all columns with low steel ratio of 1.24% (4 – No.3 bars) was tension bar rupture, regardless of steel type. Increasing the steel ratio from 1.24% to 1.84% (6 –No.3 bars) increased blast capacity and delayed failure. The use of increased amount of stainless steel bars was particularly effective, and transformed the failure mode from bar rupture to fiber pullout. The analytical study confirms that dynamic inelastic SDOF analysis can be used to reasonably predict the blast response of UHPC columns reinforced with varying steel types.

Keywords: UHPC, High-strength steel, Stainless steel, Columns, Blast, Shock Tube.

Parameters Affecting the Axial Load Response of Ultra High Performance Concrete (UHPC) Columns

Hyun-Oh Shin, Hassan Aoude and Denis Mitchell

Synopsis: Ultra-high-performance concrete (UHPC) is an innovative material that exhibits high compressive and tensile strength as well as excellent durability. The provision of fibers in UHPC results in improved ductility and increased toughness when compared to conventional high-strength concrete. These properties make UHPC well-adapted for use in the columns of high-rise buildings and heavily-loaded bridges. This paper summarizes the results from a database of tests examining the effects of various design parameters on the axial load performance of UHPC columns. Experimental results illustrating the effects of concrete type (UHPC vs. high-strength and ultra-high-strength concrete), UHPC compressive strength and transverse reinforcement detailing are presented. The results show that the use of UHPC in columns resulted in increased load carrying capacity and post peak ductility when compared to conventional high-strength or ultra-high-strength concrete due to the ability of steel fibers to delay cover spalling. However, greater amounts of confinement reinforcement were required to achieve the same level of axial load performance as the UHPC compressive strength was increased from 150 to 180 MPa. The results also showed that the amount, spacing, and configuration of transverse reinforcement, as well as their interaction significantly affected the axial load response of UHPC columns. However, increasing the amount of transverse reinforcement had the most pronounced effect on post-peak behavior. The effect of the confinement provisions in current codes (CSA A23.3-14 and ACI-318-14) on the ductility of the UHPC columns was also investigated. Based on the results, an alternative confinement expression for achieving ductile behavior in UHPC columns was proposed.

Keywords: UHPC; Fibers; Columns; Axial loading; Seismic detailing; Confinement

Comparative Structural Response of UHPC and Normal Strength Concrete Columns under Combined Axial and Lateral Cyclic Loading

Mahmoud Aboukifa, Mohamed A. Moustafa and Ahmad Itani

Synopsis: Ultra-High Performance Concrete (UHPC) is a versatile building material as it is characterized by very high compressive strengths reaching 30 ksi [200 MPa], ductile tensile characteristics, and energy absorption. Currently, UHPC is commonly used in limited structural applications, such as joints and connections between precast structural elements. To extend the use of UHPC in full structural elements, a better understanding of the structural behavior and failure mechanism of such elements is needed. One potential application of UHPC for structural elements is columns, which is the focus of this study. This paper presents an experimental investigation of the behavior of UHPC column subjected to combined axial and lateral loading. A large-scale UHPC column is tested under axial and quasi-static cyclic lateral loading at the Earthquake Engineering Laboratory at the University of Nevada, Reno. To establish a comparison with conventional columns, a normal strength concrete (NSC) column with same dimensions and design as the tested UHPC column is analytically modeled and analyzed under similar loading protocol using OpenSEES. The experimental response of the UHPC column is evaluated and compared to the analytical response of the NSC column. Both global and local behavior are presented and discussed to include damage progression, failure type, peak moment strength, stiffness degradation, and displacement and curvature ductility.

Keywords: Ductility; large-scale testing; seismic behavior; UHPC column

Cyclic Behavior of a Reinforced Concrete Column with Unstressed Seven-Wire Steel Strands as Longitudinal Reinforcement

Yu-Chen Ou, Samuel Y.L.Yin, Yi-Qing Liu, and Jui-Chen Wang

Synopsis: The use of unstressed Grade 1860 (MPa) seven-wire steel strands as longitudinal reinforcement in columns has the advantage of reducing the cost of steel as compared with conventional Grade 420 (MPa) deformed steel bars. A preliminary experimental study was conducted to investigate the performance of a column with unstressed seven-wire strands as longitudinal reinforcement. Large-scale column specimens were designed and tested using double-curvature lateral cyclic loading under a constant axial load. Test results showed that the column with strands as longitudinal reinforcement (RH1) showed less and wider cracks and less energy dissipation than the column with deformed bars as longitudinal reinforcement (ORH1). Despite this, RH1 showed a slightly higher drift capacity than ORH1 even when the strands used in RH1 had a much lower ultimate strain than the deformed bars used in ORH1.

Keywords: columns, cyclic test, reinforced concrete, seven-wire strands

Analysis and Design of NiTi Superelastic SMA-Reinforced ECC Bridge Columns

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Synopsis: Current seismic codes prevent bridge collapse under strong earthquakes. For conventional reinforced concrete (RC) bridges, this performance objective is usually achieved through confinement of ductile members such as columns. When an RC bridge column undergoes large displacements, its reinforcement yield and sometimes buckle, the cover concrete spalls, and the core concrete sometimes fail. Damage of reinforcement and core concrete is not easy to repair. Advanced materials and new technologies are emerging to enhance the seismic performance of RC bridge columns by reducing damage, increasing displacement capacities, and/or reducing permanent lateral displacements. Two types of advanced materials, shape memory alloy (SMA) bars and engineered cementitious composite (ECC), are the focus of the present study. SMA bars are viable reinforcement for concrete structures since they resist large stresses with minimal residual strains. Furthermore, ECC, which is a type of fiber-reinforced concrete, shows significant tensile strain capacities with minimal damage. SMA-reinforced ECC bridge columns are ductile with minimal damage and insignificant residual displacements under extreme events. A displacement-based design method for NiTi superelastic SMA-reinforced ECC bridge columns is proposed based on large-scale experimental and extensive analytical studies. A summary of the proposed guidelines, background information, and supporting studies are presented for this novel column type to facilitate field deployment. Finally, the details of the world first SMA-reinforced ECC bridge constructed in Seattle, USA, is discussed.

Keywords: Advanced Material; Analysis; Design; ECC; Novel Column; RC Bridge, SMA

Seismic Fragility Assessment of Shape Memory Alloy Reinforced Concrete Bridge Piers under Long Duration and Near-Fault Ground Motions

Maher AL-Hawarneh, AHM Muntasir Billah, and M. Shahria Alam

Synopsis: In recent years, shape memory alloys (SMA) have drawn significant attention and interests among researchers and structural engineers for diverse civil engineering applications. Superelasticity, shape memory effect, and hysteretic damping are the three major characteristics of SMAs that make them appropriate for bridge engineering applications in high seismic zones. Recent earthquake events have shown the most devastating earthquake loading that structures could experience are the near-fault ground motions. On the other hand, the ground motion duration effect on structural response has attracted a lot of interest over the last decade. This study aims to evaluate the comparative seismic fragility of concrete bridge piers reinforced with SMA rebars and steel rebars in the plastic hinge region under long duration and near-fault earthquakes. The bridge pier is assumed to be part of a lifeline bridge located in Western Canada and has been designed following a performance-based design approach. Fragility analysis has been conducted considering uncertainty in the material properties and the seismic hazard of the site location. Fragility curves are developed using suits of long duration and near-fault motions where each suite contains 20 ground motions. The vulnerability of the SMA-RC bridge piers and steel-RC bridge piers has been evaluated in terms of maximum drift and residual drift as the demand parameters. The outcome of this study indicates how the performance of the SMA-RC bridge pier and steel-RC bridge pier are affected by the duration of ground motion and fault location.

Keywords*:* Seismic fragility, Shape memory alloy, Long duration motion, Maximum drift, Residual drift, Bridge pier.

Experimental Investigation on Mechanical Properties of Titanium Alloy Bars: Comparison with High-Strength Steel

Ruchin Khadka, Mustafa Mashal, and Jared Cantrell

Synopsis: Recently titanium alloy bars (TiABs) have been gaining popularity in civil engineering applications. They offer good deformation capacity, better fatigue performance, high-strength-to-weight ratio, lighter weight (60% that of steel), and excellent corrosion resistance. Recently, TiABs were used in the strengthening of two bridges in Oregon to increase the shear and flexural capacities of the concrete beams. The research in this paper quantifies some common mechanical properties of TiABs using experimental investigation. This is done to explore suitability of the material for wider applications in civil infrastructure. The four types of testing conducted in accordance with ASTM standards included tension, hardness, Charpy V-Notch, and galling tests. Samples of 150 ksi (1034 MPa) high strength steel were also tested for comparison. Test results showed good performance of TiABs. Analytical models are proposed for stress-strain and toughness-temperature relationships.

Keywords: analytical stress-strain relationship; Brinell hardness test; Charpy V-Notch impact test; galling test; high-strength steel; mechanical properties; novel materials; tension test; titanium alloy bars

Seismic Behavior of Bridge Precast Columns with Grouted Rebar Couplers

Arya Ebrahimpour and Barbara Earles

Synopsis: Accelerated Bridge Construction (ABC) technologies are being adopted by state transportation departments. One particular ABC technology is the use of precast concrete members joined with mechanical connectors. However, there are concerns about these connections in moderate-to-high seismic regions. A study was carried out for the Idaho Transportation Department (ITD) on the seismic performance of precast columns with grouted couplers versus the conventional cast-in-place columns. Experimental data provided the necessary input to model the grouted couplers. Using the OpenSees finite element analysis program, selected bridges were subjected to the seismic conditions of the most seismically active location in Idaho. Under seismic conditions considered, the stresses in both the longitudinal reinforcing bars and the grouted coupler regions are found to be well within acceptable ranges. The study resulted in recommendations on allowable column drifts, a list of approved grouted rebar couplers, and typical detail drawings for inclusion in the ITD's Bridge Manual.

Keywords: bridge; column; precast; cast-in-place; grouted couplers; seismic response.

Multi-"Hinge" Hierarchical Activation to Improve Structural Robustness of Post-tensioned Rocking Piers

Royce Liu and Alessandro Palermo

Synopsis: Structural redundancy and robustness are necessary to protect against beyond design seismic loads. In this paper, the idea of improving these properties is applied to single column bridge piers using the hybrid PRESSS/Dissipative Controlled Rocking (DCR) system through a novel technique called hierarchical activation. This technique involves the inclusion of more "hinges" (rocking interfaces) and or sets of dissipative devices in such a way that they are activated in a hierarchy with respect to the displacement of the structure. A 2/3 scale cantilever column designed to use this technique was tested. The specimen was capable of multiple configurations, two of which are focused on in this paper: conventional DCR; and segmented DCR (segDCR), which used hierarchical activation. Hierarchical activation was successfully achieved in the experiment; and despite the global response being similar, segDCR was found to be advantageous with respect to reducing the cyclic strain demand on the dissipaters.

Keywords: bridge pier; columns; post-tensioned; rocking; seismic; low damage; robustness; structural redundancy

Using Cross Spirals in Confining High Strength Concrete Columns for More Seismic Resiliency: A Review

Ahmed Ibrahim, Sabreena Nasrin, and Riyadh Hindi

Synopsis: The spiral reinforcement is a special detailing technique used for reinforcing columns in regions of high seismic activities because of its ability in energy absorption and ductility. In this paper, the results of the experimental testing on cross spiral confinement in reinforced concrete columns are presented. The experimental results were verified by nonlinear finite element analysis as well as an analytical model. The developed analytical model was based on the octahedral stress criterion and compared with other models available in the literature. In the Finite element model, the concrete damage plasticity and steel yielding criterion were used in the constitutive equations. The finite element showed very good prediction of the ultimate load and failure strain for various spiral reinforcement ratios. Analytical stress-strain models have been developed and compared to the experiment results in the literature and found work well in predicting the columns behavior under monotonic axial loads. The authors see that the proposed technique is a very good potential of industry implementation and provides a more seismic resiliency to structures.

Such detailing technique could be used as a mitigation system for columns in high seismic zones.

Keywords: Cross spiral, Reinforced Concrete, Ultra-High Strength Concrete, Seismic, Resilient