# Seismic Behavior of Reinforced Concrete Hollow Bridge Piers Retrofit with ECC Jacket

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**Abstract.** A new design was proposed in which the Engineered Cementitious Composites (ECC) was used to improve the seismic behavior of the reinforced concrete hollow bridge piers. The ECC jacket was used both in and out of the cross section of the hollow bridge piers to improve the strength and ductility of the reinforced concrete hollow bridge piers. Also, the ECC would increase the anti-cracking behavior of hollow bridge piers, which would be of particular importance for the durability of the bridge piers. A numerical analysis model for the reinforced concrete hollow bridge piers retrofit with ECC was built, and the seismic behavior of the piers was studied. It is found that the strength and ductility of the piers could be increased by using ECC, which indicates effectiveness of the ECC jacket for seismic retrofit of hollow bridge piers.

## Introduction

Hollow bridge piers are widely used in bridges to maximum the structural efficiency in the strength/mass and stiffness/mass ratios and to reduce the mass contribution of a pier to seismic response. Hollow bridge piers play an important role for seismic safety of large bridges, and it is of particular importance to ensure the seismic safety of hollow bridge piers. However, during the 2008 Wenchuan earthquake, the hollow bridge piers of Miaoziping bridges cracked, and the maximum concrete cracking width reached as much as 0.8 mm. With such a width cracking, the hollow bridge piers under the water have to be retrofitted to protect the piers from corrosion attacking. The cost for the underwater construction of concrete was significant high. In engineering practice, many hollow bridge piers would be design and constructed under the water. In order to protect these bridge piers from corrosion attack, the concrete cracking damage of these hollow bridge piers should be restricted [1], more attention should be paid to the anti-cracking behavior of the underwater bridge piers.

Recently, a new kind of fiber reinforced cementitious composite, known as Engineered Cementitious Composite (ECC) has been developed. ECC exhibits tensile strain-hardening behavior with strain capacity in the range of 3-7%, with crack widths limited to below 100 μm, which is of particular importance for the durability of reinforced concrete structures [2-3]. The durability of ECC has been investigated by Li et al [4], and it is found that ECC could retain tensile ductility more than 200 times that of normal concrete or normal fiber reinforced concrete after exposure to an equivalent of 70 years or more of humid environmental conditions. Sahmaran et al [5] conducted an experimental investigation on the chloride transport properties of ECC under combined mechanical and environmental loads. And it has been found that ECC is effective in slowing the diffusion of chloride ion under combined mechanical and environmental (chloride exposure) loading, by virtue of its ability to achieve self-controlled tight crack width. Also, ECC has been demonstrated to enhance the performance of reinforced concrete structures in terms of damage tolerance, shear resistance, and energy absorption capacity.

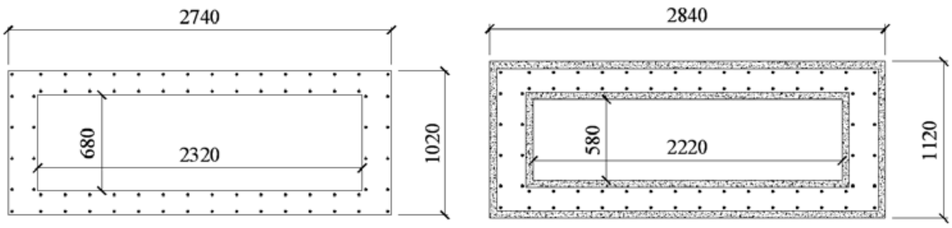
In the present study, a new design was proposed in which ECC was used to retrofit the reinforced concrete hollow bridge piers, and the seismic analysis models for the reinforced concrete hollow bridge piers and ECC retrofit hollow bridge piers were built. The hysteretic curves of retrofit hollow bridge piers were simulated and compared with test results of the original hollow pier specimens.

## The New Hollow Bridge Piers Retrofit with ECC

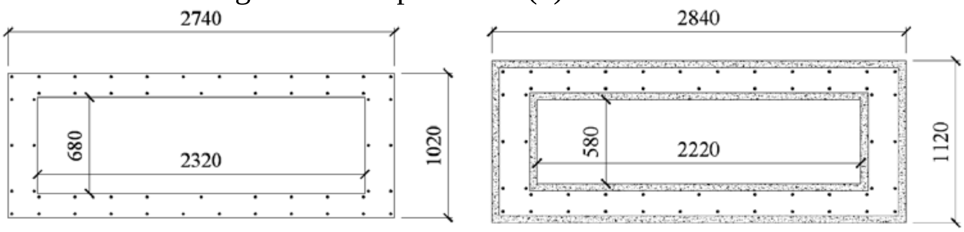
Taking the rectangular hollow bridge piers conducted by Pinto et al [6] as an example. A new hollow bridge pier retrofit with ECC was proposed. As shown in Fig. 1, two rectangular hollow bridge piers, labeled as TALL pier and SHORT pier, were designed and tested quasi-statically by Pinto et al [6]. Both of the original specimens had a rectangular hollow cross-section with external dimensions 2740×1020 mm. The widths of the flange and web were 210 mm and 170 mm, respectively. The height of the TALL pier was 14 m, resulting in an aspect ratio of 5.11. The height of the SHORT pier was 6.5 m, corresponding of an aspect ratio of 2.37.

Both piers presented several seismic deficiencies and consequently they showed poor hysteretic behavior and limited deformation capacity as well as undesirable failure modes that do not comply with the requirements of modern codes for seismic-resistant structures. More information about the test results could be found in reference [6].

In the present study, ECC was used to retrofit the hollow pier specimens. As shown in Fig. 1, 50 mm thick ECC was used both in and out of the cross section. As a result, the external dimensions of the retrofit piers changed to be 2840×1120 mm, and the internal dimensions changed to be 2220×580 mm. The compression and tension strengths of the ECC were designed as 70 and 2.5 MPa, respectively. Both of which were used in the seismic analysis model for the ECC retrofit hollow bridge piers.




(a) Cross section of original TALL pier (b) Cross section of retrofit TALL pier



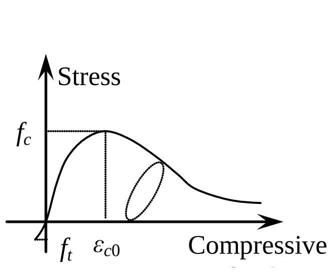

(c) Cross section of original SHORT pier (d) Cross section of retrofit SHORT pier

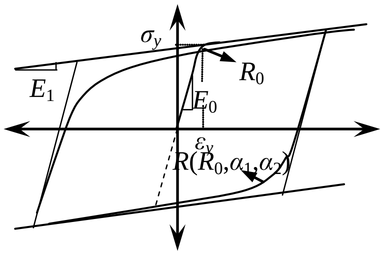
Fig. 1 Cross section for the original and retrofit hollow bridge piers

## Analysis Model

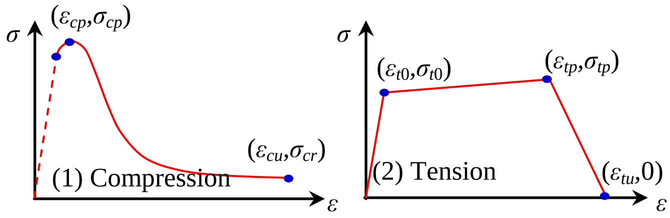
Seismic analysis models for the original and ECC retrofit hollow bridge piers were built by using the ZEUS NL software. ZEUS NL is a fiber-based finite element analysis software, specifically designed for earthquake engineering applications. It should be noted, by comparing the test results of the hysteretic curves of the original hollow piers with numerical results from a fiber model, Pinto et al [6] concluded that the numerical results were in good agreement with experimental results for the SHORT pier. For the TALL pier, the fiber model was unable to simulate the shear failure of the pier. For the ECC retrofit hollow bridge piers, as the ECC would significantly improve the shear strength of the retrofit hollow bridge piers, so it is feasible to model the hysteretic behavior of the ECC retrofit hollow bridge piers.

In the present analysis, cubic elasto-plastic 3D beam-column element was used to model the nonlinear behavior of the original and retrofit hollow bridge piers. The concrete behavior was described by the nonlinear concrete model with or without constant active confinement modeling (con2). For the confined concrete, confinement factor was used to consider the confinement of the lateral reinforcement. The reinforcement steel behavior was modeled by the Menegotto-Pinto model with isotropic strain-hardening (stl3).




(a) concrete (b) steel




(c) ECC

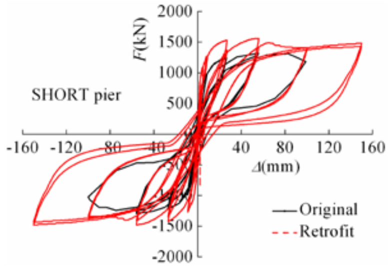
Fig. 2 Stress-strain models of the materials

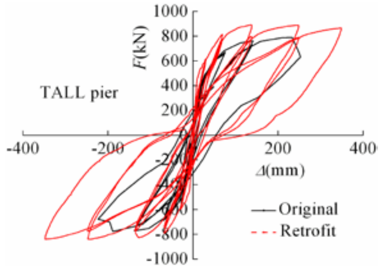
Nonlinear stress-strain model was used to simulate the nonlinear behavior of the ECC material (ecc). This model is developed by Gencturk and Elnashai [7], based on the response of the material at the stress-strain level under different loading regimes. Various features specific to ECC material such as the unloading and reloading characteristics, different backbone curves in tension and compression, and residual strains are taken into account in the model development. This model has been implemented into fiber based finite element analysis software ZEUS NL for structural simulation, and the accuracy of the model has been calibrated by comparing with ECC structures under cyclic and static time history loading [7].

The stress-strain relationship for concrete, steel and ECC is shown in Fig. 2. More detail information about ZEUS NL software and the ECC material model could be found in reference [7].

## Analysis Results

The hysteretic behavior of ECC retrofit hollow bridge piers was simulated by using ZEUS NL software. And the simulated hysteretic curves were compared with the test results for the original specimens. Fig. 3 shows the hysteretic curves of the original and ECC retrofit hollow bridge piers. It could be found that for the SHORT pier, the maximum lateral strength of the original pier Fo is about 1300 kN, while the maximum strength of the retrofit pier Fr reaches as much as about 1500 kN, which is about 1.15 times of the original one. As for the TALL pier, the maximum lateral strength of the original pier is about 800 kN, and the retrofit pier reaches 870 kN, which is about 1.1 times of the original one.




(a) SHORT pier (b) TALL pier

Fig.3 Comparisons of the hysteretic curves between original and retrofit hollow bridge piers

As for the deformation capacity, for the SHORT pier, the maximum lateral displacement for the original pier Δo is about 82.5 mm. While for the retrofit pier, the lateral displacement Δr reaches as much as 150 mm without significant strength degradation. For the TALL pier, the maximum lateral displacement of the original pier is about 230 mm, while the retrofit one reaches 350 mm without strength degradation. The deformation capacities of the retrofit hollow piers are about 1.52-1.82 times of the original ones. Table 1 summarized the strength and ductility parameters of the original and retrofit hollow bridge piers. It could be found that both the retrofit specimens have a much larger lateral deformation capacity than the original ones.

## Conclusions

A new design was proposed in which ECC was used to increase the anti-cracking capacity of the hollow bridge piers. And the hysteretic behavior of the ECC retrofit hollow bridge piers was simulated by using ZEUS NL software. By comparing the hysteretic curves of the retrofit hollow bridge piers with the original pier specimens. The follows conclusions can be made:

(1) The maximum lateral strength of the retrofit hollow bridge piers are between 1.09-1.15 times of the original specimens, indicating than the strength of the retrofit hollow bridge piers would be improved.

(2) The maximum lateral displacement of the ECC retrofit hollow bridge piers are between 1.52-1.82 times of the original specimens. Which indicates that the ECC is effective in improving the deformation capacity of the hollow bridge piers.

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