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Seismic performance modeling of concrete-filled steel tube bridges: Tools and case study

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ABSTRACT

Experimental research into concrete filled steel tube (CFST) bridge columns has demonstrated that they are an economical alternative to traditional RC columns used in high seismic regions for several reasons. They permit accelerated construction by eliminating internal reinforcement and formwork and incorporating the use of self-consolidating concrete. The placement of the steel is at the optimum location, thereby reducing the required diameter to meet flexural and shear strengths and stiffness; these properties reduce cost and material requirements. Finally, the initiation of tube buckling does not result in degradation of the load carrying capacity which is impacted only by tube tearing which develops in the event of continued cycling at large inelastic drift demands. This provides superior inelastic seismic performances in terms of bridge functionality and post-earthquake repair requirements. Prior work by the authors and others have developed new design expressions and construction techniques for CFST bridges; here the emphasis is on new tools for performance evaluation of CFST bridges, including nonlinear analysis and probabilistic damage assessment tool. These tools are intended to advance performance-based earthquake engineering of these systems. The nonlinear analysis tools for CFST are investigated and validated for use in line-element type models; both distributed plasticity and lumped plasticity formulations are investigated. In both cases, deformability of the connection is included. Structural damage states were identified and probabilistically related to engineering demand parameters. In combination, this set of tools links the response with the structural performance to quantify the likelihood of damage and required repair. A case study was conducted with these tools to explore and quantify the differences between RC and CFST bridges. Both tools, combined with incremental dynamic analyses, were used to evaluate damage and collapse potential. The results show that the CFST system is more resilient than the RC system for the selected case study structure.

1. Introduction

Highway bridges in seismic regions in the United States are commonly designed as moment-resisting frames. The preferred plastic mechanism is column hinging with an elastic superstructure. The connecting elements, including the cap beams and foundations, are capacity designed to resist the ultimate shear and flexure, in the cases of moment-resisting connections, resistance of the columns.

Reinforced concrete (RC) is commonly used in seismic regions, because of its stiffness, strength, and inelastic deformation capacity. However, RC bridges are susceptible to damage and deterioration of performance due to spalling and crushing of concrete. As such, the AASHTO Guide Specification [1] for RC bridges requires special detailing in regions of expected plastic hinging. Prior testing shows that this detailing is effective in preventing loss of lateral load carrying capacity when undergoing increasing or numerous inelastic drift cycles. However, these detailing requirements typically result in congested reinforcing which increases cost and the difficulty of construction.

Concrete filled steel tube (CFST) columns represent an alternative to RC construction. CFSTs are composite structural elements which are structurally efficient and facilitate constructability. In a CFST member, the steel tube acts as the longitudinal and transverse reinforcement to resist flexural and axial demands, provide superior shear resistance, and optimal confinement to increase the deformability of the concrete in compression. The structural efficiency of the member is derived from the location, strength, and ductility of the steel tube. The steel is at the optimal location for flexural resistance, thereby, for a given strength, the diameter of the CFST column is 20–40 percent less than an RC component, thus representing weight and materials savings [2–4]. The shear resistance is 2–3 times that of an RC section [5]. The circular

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Nomenclature

A_s	area of steel tube in CFST
A_c	area of concrete fill in CFST
b	steel strain hardening ratio (E_p/E_s)
CMR	collapse/Replace margin ratio
D	CFST column diameter
DPM	distributed plasticity model
d1p	positive displacement at first point in envelop for *Hysteretic* material definition
d2p	positive displacement at second point in envelop for *Hysteretic* material definition
d3p	positive displacement at third point in envelop for *Hysteretic* material definition
d1n	negative displacement at first point in envelop for *Hysteretic* material definition
d2n	negative displacement at second point in envelop for *Hysteretic* material definition
d3n	negative displacement at third point in envelop for *Hysteretic* material definition
epsc0	concrete strain at compression strength for *Concrete01* material definition
epsU	concrete ultimate compression strain for *Concrete01* material definition
E_p	steel post yield tangent stiffness
E_s	steel modulus of elasticity
f'_c	unconfined concrete compression strength
f'_{cc}	confined concrete compression strength
f_l	lateral confining pressure on concrete fill in CFST
f_y	yield strength of steel tube
fpc	concrete compression strength for *Concrete01* material definition
fpcu	concrete ultimate compression strength for *Concrete01* material definition
IDA	incremental dynamic analysis
LPM	lumped plasticity model
l_p	plastic hinge length
l_b	buckled length
L_{col}	column length
L_e	embedment depth of steel tube into cap beam/foundation for ER CFST connection
M_{pcol}	column plastic moment strength
$M(d)_i^{exp}$	experimentally recorded moment at displacement increment d_i
$M(d)_i^{num}$	numerically recorded moment at displacement increment d_i
P	axial load
P_o	axial crushing capacity
PBEE	performance based earthquake engineering
pinchX	pinching factor for deformation during loading for *Hysteretic* material definition
pinchY	pinching factor for stress during loading for *Hysteretic* material definition
PRMR	partial replace margin ratio
RMR	repair margin ratio
S_{RT}	median spectral acceleration of the fitted cumulative distribution function for the repair limit state
S_{PRT}	median spectral acceleration of the fitted cumulative distribution function for the partial replace limit state
S_{CT}	median spectral acceleration of the fitted cumulative distribution function for the collapse/replace limit state
S_a	spectral acceleration
s1p	positive stress at first point in envelop for *Hysteretic* material definition
s2p	positive stress at second point in envelop for *Hysteretic* material definition
s3p	positive stress at third point in envelop for *Hysteretic* material definition
s1n	negative stress at first point in envelop for *Hysteretic* material definition
s2n	negative stress at second point in envelop for *Hysteretic* material definition
s3n	negative stress at third point in envelop for *Hysteretic* material definition
t	CFST steel tube thickness
V_n	nominal CFST column shear strength
α_θ	ratio of hoop stress to yield stress for calculating confinement of core concrete in CFST
α_1	constant which defines steel strain penetration length into the cap beam/foundation of ER CFST connection
α_2	constant which defines the post-buckling capacity of the steel tube in the CFST column
β_d	logarithmic standard deviation
ε_u	steel ultimate strain
ε_y	steel yield strain
ε'_{lb}	compression strain limit in the steel tube at buckling in CFST
θ_d	logarithmic mean
ρ	ratio of steel to concrete areas in CFST (A_s/A_c)

shape provides ideal confinement, while the concrete fill restrains local buckling of the steel tube through relatively large deformations. Internal reinforcement and formwork are not required, and this permits more economical and rapid placement of the concrete fill; in addition. As a result, CFSTs are a particularly attractive alternative to RC columns.

There are a number of reasons that CFSTs are not commonly used as pier elements. First, until the most recent code cycle, CFST expressions were not based on large-scale experiments and largely driven by the building codes. Next, common practice has led to the belief that that CFSTs must be internally reinforced, making them doubly reinforced relative to RC construction. In addition, many engineers and contractors' express concern about corrosion. Third, there is a feeling that retaining the casing in a pile or using a casing in a pier will drive up cost. Lastly, there were few verified connections that facilitated constructability and provided required structural performance in low and high seismic zones. Research over the past decade has dispelled each of these concerns, as demonstrated below.

Current AASHTO code provisions, which govern the design of highway bridges in the US, now include expressions for establishing the strength and stiffness of CFST columns [1], including CFST components as large as 762-mm (30-in.). Design expressions for the flexural strength of a CFST with internal reinforcement (commonly referred to as RCFST) indicates that the effectiveness of internal reinforcement is inversely related to D/t ratio, that is as the D/t ratio increases the effectiveness of the internal reinforcement decreases. Further, Moon [6] demonstrated that for typical levels of longitudinal reinforcement of 1–2%, there is only a marginal overstrength of 20% or less relative to the CFST alone, even for D/t of 80.

Concerns regarding corrosion can be mitigated through well-used techniques such as galvanization and through supplemental thickness [1], which can extend the life of the CFST well beyond the 50-year design life. Previous studies conducted on CFSTs which utilized galvanized steel tubes demonstrated that galvanization does not influence the stiffness, strength, or hysteretic response [2].

Finally, recent research by the authors has resulted in new,