Experimental Hybrid Testing of a Concrete Filled Steel Tube (CFST) Bridge Pier Subjected to Vertical and Horizontal Ground Motions

Ali, Al-Attraqchi\textsuperscript{1*}, Javad, Hashemi\textsuperscript{1}, and Riadh, Al-Mahaidi\textsuperscript{1}

\textsuperscript{1}: Swinburne University of Technology, Melbourne, Australia; *: corresponding author email: aalattraqchi@swin.edu.au

Abstract. Hybrid simulation is a form of advanced testing that combines both numerical and experimental techniques to achieve an economical seismic response assessment of structures. The technique utilises the best feature of computer simulations and combines these with experimental testing. This makes hybrid simulation a powerful platform for experimentally studying the seismic responses of structures to collapse. This paper presents an application of hybrid simulation for tracing the seismic responses of a concrete filled steel tube (CFST) column subjected to combined horizontal and vertical ground accelerations. A state-of-the-art testing facility, known as the multi axis substructure testing (MAST) system, was used to impose complex boundary effects on the physical specimen using mixed load and deformation modes. The column was subjected to five increasing ground motion levels. During the test, the column experienced large axial force variations of up to 2.2 MN and reached a maximum drift of 8.8\% without significant damage. The results demonstrate that this CFST column is thus capable of resisting large compression and tension forces, offering high levels of ductility without collapse.

Keywords: vertical ground motion; experimental hybrid testing; earthquake engineering; structural engineering.

1. Introduction

Earthquakes frequently cause significant damage to reinforced concrete (RC) piers in bridges, leading to failure of concrete columns in shear. Studies have shown that the vertical component of the ground motion leads to large variations of the axial capacity of the columns, which reduces the shear capacity, leading to failure, especially at sites near to faults. Papazoglou and Elnashai (1996) provided analytical and field evidence of several RC columns being damaged due to the vertical component, and ignoring the vertical component during seismic design may underestimate the collapse risk assessment of bridges.

This paper investigates whether the use of concrete filled steel tube (CFST) columns in bridges provides a robust solution for resisting horizontal and vertical ground motions effectively, as there is a lack of experimental research on the behaviour of such columns under combined horizontal and vertical ground accelerations. The CFST column was chosen due to its benefits over the RC columns: as its steel is furthest from the centroid, it provides the greatest contribution to the second moment of inertia, which makes it most effective in resisting bending moments; in addition, the concrete is perfectly situated in the centre to withstand gravity loading, and delays and often prevents local buckling of the steel and moderates strength degradation...
after local buckling; finally, the steel tube provides confinement for the core concrete, which increases its compressive strength and ductility, and reduces strength deterioration. These benefits allow the CFST column to have high ductility and high energy absorption, providing superior seismic performance. Gourley et al. (2008) and Han et al. (2014) made a comprehensive review of the behaviour of these columns, and more recently Stephens et al. (2018) showed how CFST columns outperformed reinforced concrete columns at resisting earthquakes.

Figure 1. Hybrid Simulation Architecture at Swinburne University of Technology.

2. Experimental Program
2.1. Hybrid Simulation and the MAST system
The MAST system at the Smart Structures Laboratory at Swinburne University of Technology allows the experimental simulation of complex boundary effects based on multi-axial capabilities. Hybrid simulation is one of the most practical modern experimental techniques due to its ability to provide a safe and economical method of evaluating the dynamic responses of structures for the whole seismic response range, from linear all the way to inelastic levels approaching collapse (Nakashima et al., 1992). It simplifies the study of structures by using experimental techniques to evaluate only the critical portion of the structure, with the remaining parts of the structure simulated numerically on the computer. The Finite Element (FE) structural model is subjected to the desired ground motion acceleration and then computes the displacement demands and sends these to the actuator to be applied on the physical specimen, where the resisting forces are measured and fed back into the computation solver to calculate the displacements corresponding to the next time step. For further details of hybrid simulation at Swinburne, see Hashemi (2015). The hybrid simulation control system at Swinburne uses xPC-Target, which consists of a three-loop architecture as depicted in Figure 1. The innermost servo-control loop contains the MTS FlexTest controller, which sends displacement/force commands to the actuators while receiving measured displacements/forces. The middle loop runs the Predictor-Corrector actuator command...
generator on the xPC-Target (MathWorks, 2005), a real-time digital signal processor (DSP), and delivers the displacement/force commands to the FlexTest controller in real-time through the shared memory SCRAMNet (Systran, 2004). Finally, the outer integrator loop runs on the xPC-Host and includes OpenSees (McKenna, 2011), MATLAB, and OpenFresco (Schellenberg, 2009), all of which communicate with the xPC-Target through the TCP/IP network.

Figure 2. The elevation and cross section view of the full-scale bridge structure used in hybrid simulation, with one column selected and tested under the MAST system in hybrid simulation.

2.2. Bridge Structure
The bridge structure in this report was previously used in another hybrid study conducted by Kim et al. (2011) that evaluated the effects of vertical ground motion on RC columns using hybrid simulation. Here, the same structure was simulated but with CFST columns are used instead of RC columns. The bridge structure is shown in Figure 2: it has a total span of 97.6 m and is composed of three spans of 30.5, 36.6, and 30.5 m in length. There are two columns per bent with a clear height of 6.0 m. The finite element model was developed using OpenSees. The deck is a cast-in-place concrete box girder, while the bents are integral with box girder and modelled as equivalent elastic beams. The columns were modelled using force beam-column elements with plastic hinges at both ends, named “beam-with hinges” in OpenSees. The mid-section of the column is modelled elastically, while the nonlinear behaviour is concentrated within a finite length plastic hinge zone at both ends of the column, following common modelling methods (Deierlein et al., 2010). The hinge behaviour was modelled based on a bilinear hysteresis response as in the Modified Ibarra-Medina-Krawinkler (IMK) flexure model (Ibarra et al., 2005). This plasticity model was chosen because it is capable of capturing the important modes of deterioration that participate in the side-sway collapse of structures. The columns were calibrated based on previous quasi-static cyclic experimental results, and the experimental and numerically calibrated column is shown in Figure 3. Finally, the abutments were modelled as rollers in the longitudinal direction.
2.3. Hybrid Simulation and Ground Motion Selection
The developed FE model was used to conduct a 1:3 scale hybrid simulation. The test was conducted to trace the seismic response of the CFST column to collapse. The selected square column was 2m long with a cross section of 200mm×200mm×8.0mm (d×b×t), giving a depth-to-thickness ratio (D/t) of 25. The steel had a yield strength of 350 MPa and was filled with 60 MPa concrete. The experimental substructure consisted of one CFST column with all other structural elements modelled numerically on the computer. The structure was subjected to horizontal (longitudinal) and vertical ground motion, which were the two components taken from the Northridge 1994 Sylamar Converter station with peak horizontal ground acceleration of 0.62g and vertical ground acceleration of 0.74g, which is often observed in natural earthquake records. Five intensity levels of the ground motion were used to consider the structural response from the linear-elastic range all the way to collapse by pushing the structure to 0.25% (elastic), 2%, 4%, 6% and 8% maximum drift ratios, respectively. These maximum drift ratios represent the maximum drift achieved at each intensity level of the ground motion time history.

Figure 3. The shear vs drift response from the quasi-static experimental result and the numerical IMK model calibrated to the experimental results.

Figure 4. Side view of the tested column at maximum drift of each of the four ground motion levels.
Table 1. The four levels of horizontal and vertical PGA applied to the bridge during the hybrid simulation.

|                   | 1st Intensity | 2nd Intensity | 3rd Intensity | 4th Intensity |
|-------------------|---------------|---------------|---------------|---------------|
| Horizontal PGA (g)| 0.30          | 0.49          | 0.65          | 1.14          |
| Vertical PGA (g)  | 0.36          | 0.57          | 0.77          | 1.37          |

3. Results

The peak ground acceleration (PGA) experienced by the structure for the four levels of horizontal and vertical components are reported in Table 1. The first level of ground motion was elastic, and it is not reported here. Figure 4 shows the column at the maximum drift of each of the four intensity levels. The results of the hybrid simulation are reported in Figure 5. Part (a) shows the displacement time history, which highlights the maximum measured drift at each ground motion level. The column was expected to collapse at 8% drift, but it in fact reached 8.78% drift with no sign of collapse.
Figure 5. Hybrid simulation results: (a) lateral displacement with annotated maximum drift at each sequence; (b) lateral force with annotated maximum force at last sequence; (c) axial force with annotated maximum force at each sequence; (d) hysteretic behaviour of the column showing the lateral force vs. lateral displacement, with a colour map showing the axial force level.

Part (b) shows the lateral force resisted by the column. The column did not experience any reduction in strength even at the last ground motion level where it achieved a maximum force of 269kN. Part (c) shows the axial force variation experienced by the column. During the first ground motion level, the column was in full compression; however, at the other three levels, it experienced both compression and tension. Furthermore, during the last level, the axial force variation was up to 2283kN (+723 in tension and -1560 in compression). The initial axial force due to dead load in the column was -415kN; however, the effects of the vertical component caused the axial force to increase to -1560kN, nearly 3.76 times the initial dead load. The column thus has tensile and compressive design capacities of 2,150kN and 3,670kN, respectively, according to ANSI/AISC 360-16 (2016). Part (d) shows the lateral force versus the lateral displacement, in addition to the axial force of the column, given by the colour map. The P-Delta effect on the lateral force can clearly be seen due to the fluctuations of the axial force. The results show that the column has high levels of ductility and was able to resist all four intensity levels of the applied horizontal and vertical ground motion.

4. Conclusion
Hybrid simulation was used as an advanced experimental method combining practical experiments with numerical analysis to investigate the seismic response of a CFST column with a low D/t ratio subjected to both horizontal and vertical ground motions. The column was subjected to five increasing levels of ground motion, and the results demonstrated that the CFST column was capable of resisting large axial force variations in both compression and tension, offering high levels of ductility without collapse.

References
ANSI/AISC 360-16. (2016) Specification for Structural Steel Buildings. American Institute of Steel Construction.
Deierlein GG, Reinhorn AM and Willford MR. (2010) Nonlinear structural analysis for seismic design. NEHRP seismic design technical brief 4: 1-36.
Gourley BC, Tort C, Denavit MD, et al. (2008) A synopsis of studies of the monotonic and cyclic behavior of concrete-filled steel tube members, connections, and frames. Newmark Structural Engineering Laboratory. University of Illinois at Urbana ....
Han L-H, Li W and Bjorhovde R. (2014) Developments and advanced applications of concrete-filled steel tubular (CFST) structures: Members. *Journal of Constructional Steel Research* 100: 211-228.

Hashemi MJ, Al-Mahaidi R, Kalfat R, et al. (2015) Development and validation of multi-axis substructure testing system for full-scale experiments. *Australian Journal of Structural Engineering* 16: 302-315.

Ibarra LF, Medina RA and Krawinkler H. (2005) Hysteretic models that incorporate strength and stiffness deterioration. *Earthquake Engineering & Structural Dynamics* 34: 1489-1511.

Kim SJ, Holub CJ and Elnashai AS. (2011) Experimental investigation of the behavior of RC bridge piers subjected to horizontal and vertical earthquake motion. *Engineering Structures* 33: 2221-2235.

MathWorks I. (2005) *MATLAB: The Language of Technical Computing. Getting started with MATLAB, version 7*. MathWorks, Incorporated.

McKenna F. (2011) OpenSees: a framework for earthquake engineering simulation. *Computing in Science & Engineering* 13: 58-66.

Nakashima M, Kato H and Takaoka E. (1992) Development of real-time pseudo dynamic testing. *Earthquake Engineering & Structural Dynamics* 21: 79-92.

Papazoglou A and Elnashai A. (1996) Analytical and field evidence of the damaging effect of vertical earthquake ground motion. *Earthquake engineering and structural dynamics* 25: 1109-1138.

Schellenberg AH, Mahin, S. A., and Fenves, G. L. (2009) Advanced Implementation of Hybrid Simulation. Pacific Earthquake Engineering Research Center: University of California, Berkeley, California.

Stephens MT, Lehman DE and Roeder CW. (2018) Seismic performance modeling of concrete-filled steel tube bridges: Tools and case study. *Engineering Structures* 165: 88-105.

Systran C. (2004) The SCRAMNet+ network (shared common RAM network). *Systran Corporation, Dayton, OH.*