Blast and Earthquake Resistant Bridge Pier Concept:

Retrofit and Alternative Design Options

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ABSTRACT

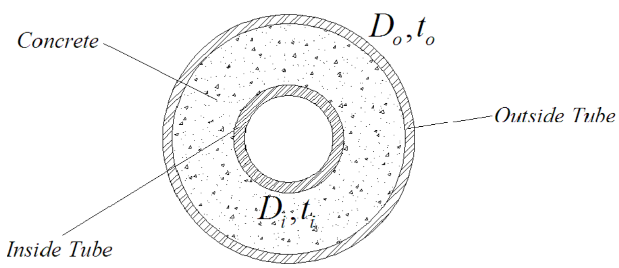
This paper summarizes a research program undertaken to develop cost-effective solutions aimed at protecting new and existing bridge column bents against multiple natural and manmade treats such as earthquakes and blast. Concrete-Filled Double Skin Tube (CFDST) column and Modified Steel Jacketed Column (MSJC) designs were proposed and tested for new bent construction and retrofit, respectively. While CFDSTs maintained their cross-section geometry in dissipating energy under cyclic loading, under severe blast loading, they deformed locally to dissipate the applied impulse and have enough residual strength to prevent collapse. MSJC, on the other hand, were developed to eliminate a deficiency observed in the form of direct shear failure near the top and/or the bottom of the jacket for steel jacketed column (SJC) subjected to blast loading. The proposed modification increases direct shear resistance in the shear-deficient areas and does not interfere with the ability of the jacketed columns to resist earthquake loading.

INTRODUCTION

There is a growing concern that bridges already prone to earthquakes actions may become targets for terrorists seeking to inflict psychological and economic woes on this nation. This concern is justified as threats have been received against bridges across the nation. In this context, highway bridges seem more accessible and vulnerable than landmark bridges which are closely monitored. In many instances, the destruction of a highway bridge can have profound effects on the economic circuit those infrastructures support. Protecting those critical components of the nation's infrastructure requires a new paradigm for the design of bridges exposed to natural and manmade hazards. One that relies on a system approach in which a single structural concept is used to provide protection against all credible hazards is proposed in this study. Such a concept should accommodate consistent demands imposed by the hazards and provide satisfactory performance for conflicting demands. Because of their inherent structural qualities, ranging from higher strength, substantial toughness and ductility and their applicability to situations requiring accelerated constructions or repairs, CFDST and MSJC are proposed as candidate concepts in that approach.

SYSTEMS DESCRIPTIONS AND FEATURES

CFDST is a steel-concrete-steel "sandwich" section formed by two concentric steel tubes separated by a concrete core as shown on Figure 1. That configuration seeks to draw upon the benefits in strength, toughness and stiffness derived for steel-sandwich construction by placing the steel at the periphery of a filler material (as described, for example, in Montague 1975). The outside skin at the periphery of the section provides strength and stiffness, the inside skin enhances ductility, and the concrete in between provides local and overall stability to the system. That synergy between the tubes and the core results in a more redundant section which completely fails only when all three layers of materials failed. In this section, concrete material failures such as spalling, breaching or scabbing under shock load are controlled. This helps preserve the stability of the section and guarantee enough (axial) residual strength for the section at ultimate conditions.



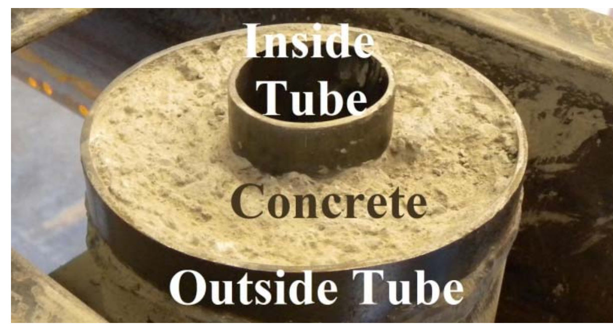


Figure 1. Concrete Filled Double Skin Tube

On the other hand, wrapping concrete column with a steel jacket is widely accepted as a cost effective retrofit technique for column of seismically deficient bridges. The merits of this technique do not translate however into improved blast performance for bridge column. Direct shear failure under blast load have been observed at the gaps between the jacket and the surrounding footing and cap beam when exposed to blast (Fujikura and Bruneau, 2008). By controlling this undesirable failure mode without hindering the initial role of the jacket, a multi-hazard resistant system is obtained. Structural steel collars placed around the gaps and tied to the adjacent elements with post-installed anchors can help increase the shear strength locally (Figure 2). A non-stick interface between the collar and the column can also be created to allow only smooth contact between the collar and the column thus increasing only shear strength while leaving flexural strength of the column virtually unchanged as initially intended.

Figure 2. Steel Collar: Components (Left and Middle) and Construction (Right)

EXPERIMENTAL INVESTIGATIONS

Three CFDST column bents were tested under blast overpressures: two at the University at Buffalo's Experimental Campus for Large Infrastructure Protection, Sustainability and Enhancement (ECLIPSE) and one at the Engineering and Research Development Center (ERDC) of the US Army Corps of Engineers. A bent made of 4 MSJC columns was also tested at ERDC. Collars with height varying from 50mm to 100 mm were used to locally supplement the shear resistance of the retrofitted reinforced concrete columns. The test setup used for all blast tests is shown in Figure 3. The bents were laterally supported by a reaction frame that also serves to simulate the boundary condition and rigidity at the top of the beam that the deck of a full-scale bridge would have provided.

Five (5) other CFDST column specimens were submitted to cyclic pushover in the University at Buffalo's Structural Engineering and Earthquake Simulation Laboratory. The base of each specimen was a built up section made of steel channels and plates used to bolt the specimen to a strong beam. In Figure 4 a global view of the test setup and a close-up of the base showing partial instrumentation can be seen.

All components were designed in accordance with AISC341-10 Seismic Provisions. The resulting designs yield sections that combine inside and outside tubes ranging from moderately ductile (MD) to highly ductile (HD). All specimens were quarter scale but a range of properties were taken into account (see Table 1 and Table 2).

ASTM A513 steel tubes with a minimum yield of 290 MPa and self-consolidating concrete with a minimum strength of 34.5MPa were specified for the CFDST. The high workability of the self-placing concrete was deemed ideal to accelerate construction. The materials properties for the MSJC were the same as in Fujikura and Bruneau (2008). A 9.5mm A36 steel plate was used for the base of the collar, whereas the lip of the collar was cut from an A53 steel tube (216mm in diameter and 8mm-thick).

Table 1. Blast Test Specimens

	Specimen	Column Designation	H (mm)	D_i (mm)	D_o (mm)	t_i (mm)	t_o (mm)	Void Ratio	Ductility Inside Tube	Ductility Outside Tube
Bent 1	17_72_33	B1	1500	50.80	152.4	2.9464	2.1082	0.33	HD	MD
	16_70_25	B3	1500	50.80	203.2	3.1242	2.8956	0.25	HD	MD
	56_70_63	B7	1500	127	203.2	2.2860	2.8956	0.63	MD	MD
	26_48_33	B5	1500	50.80	152.4	1.9304	3.1750	0.33	HD	HD
Bent 2	20_73_42	B2	1500	63.50	152.4	3.1750	2.0828	0.42	HD	MD
	22_50_38	B4	1500	63.5	168.3	2.8956	3.3782	0.38	HD	HD
	33_94_50	B6	1500	101.6	203.2	3.0480	2.1590	0.50	HD	MD
		B8	1500	-	152.4	-	3.0480	0	-	HD
Bent 3	21_50_42	B9	1500	63.5	151.5	3.0480	3.0480	0.42	HD	HD
	21_51_38	B10	1500	63.5	165.3	3.0226	3.2512	0.38	HD	HD
	30_41_50	B11	1500	101.0	201.5	3.3528	4.9022	0.50	HD	HD
	40_42_62	B12	1500	124.6	201.4	3.1496	4.8006	0.62	HD	HD

Table 2. Cyclic Pushover Test Specimens

Specimen	Column Designation	H (mm)	D_i (mm)	D_o (mm)	t_i (mm)	t_o (mm)	Void Ratio	Ductility Inside Tube	Ductility Outside Tube
17_72_33	S1	2000	50.80	152.4	2.9464	2.1082	0.33	HD	MD
16_70_25	S2	2000	50.80	203.2	3.1242	2.8956	0.25	HD	MD
26_48_33	S3	2000	50.80	152.4	1.9304	3.1750	0.33	HD	HD
22_50_38	S4	2100	63.50	168.3	2.8956	3.3782	0.38	HD	HD
56_70_63	S5	2000	127.0	203.2	2.2860	2.8956	0.63	MD	MD

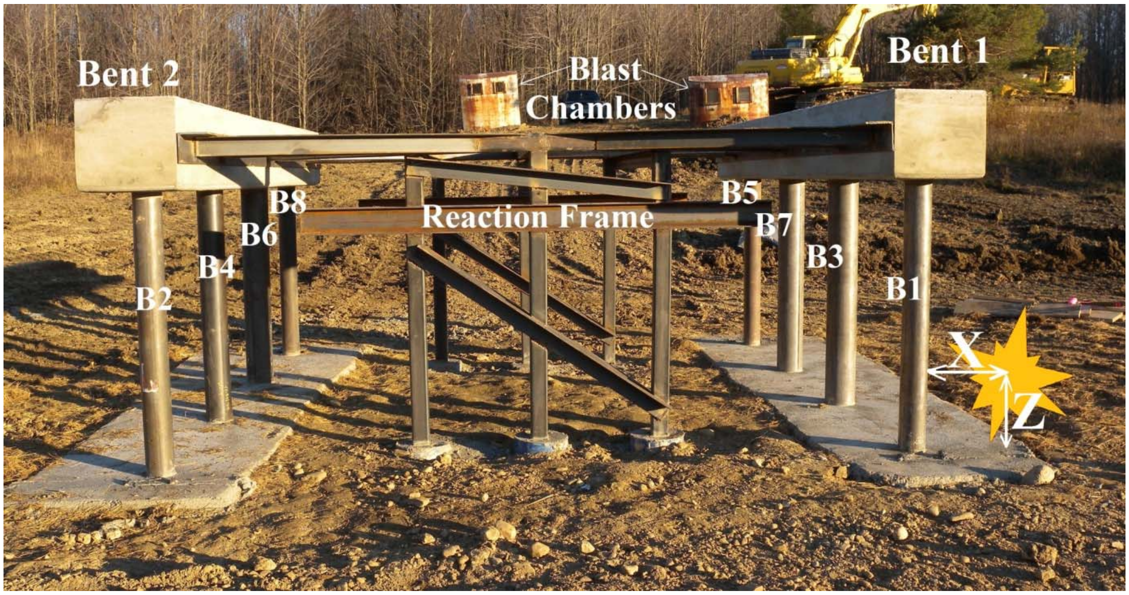


Figure 3. Test Setup for Blast Experiments

Test Procedures and Objectives

The blast tests were based on a scenario in which a Vehicle Borne Improvised Explosive Device (VBIED) is used to carry a terrorist attack. A charge weight consistent, at the scale of the experiment, with this scenario was chosen. Each column serves alternately as target for a charge center-detonated at a height of burst of 254 mm. Standoffs were varied to increase overpressure and impulse seen by a specimen depending on its strength. Table 3 below summarizes the experimental protocol. In this table the charge weight and the explosive locations are expressed in terms of W and x respectively the smallest charge weight and the smallest scaled distance of the tests.

In the cyclic pushover test, the loading was applied at the top of the specimen using an actuator. The loading protocol adopted is shown on Figure 5. Each test was carried using a displacement control approach and each specimen monitored to capture yielding, buckling and initiation of failure; no axial force was applied.

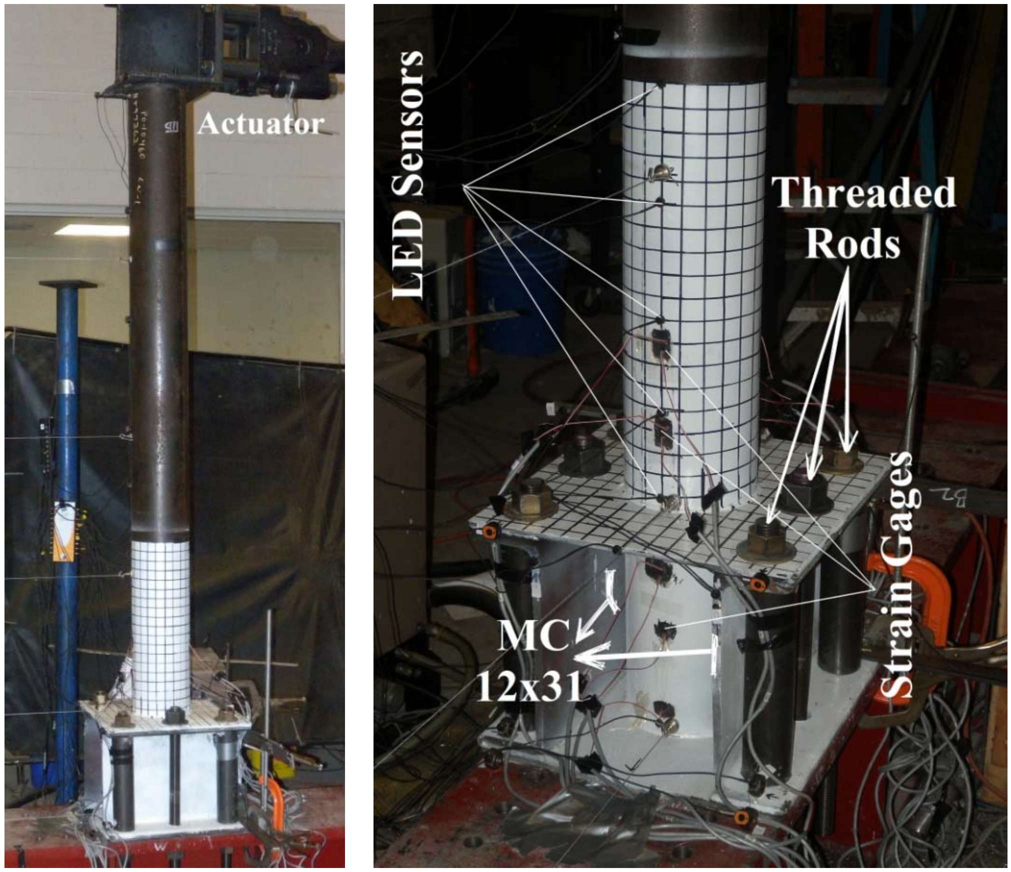


Figure 4. Cyclic Pushover Test Setup: Global View(Left) and Base Detail (Right)

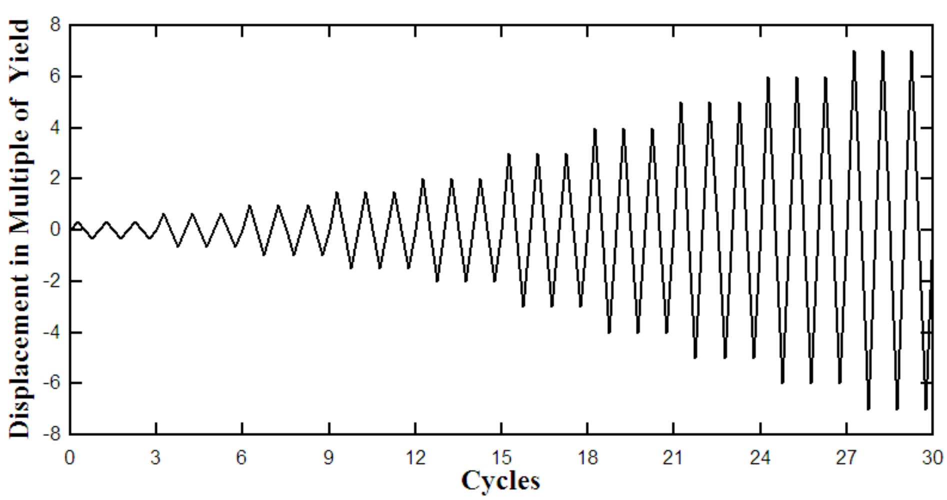


Figure 5. Cyclic Pushover Test Loading Protocol

Table 3. Blast Test Experimental Protocol

	Test	Charge	Scaled Distance $X/W^{1/3}$	Column Tested	Test Objective
ECLIPSE	1	W	$1.71\,x$	**B8**	**Plastic Deformation**
	2	W	$2.29\,x$	**B2**	
	3	W	$1.43\,x$	**B4**	
	4	W	$2.29\,x$	**B6**	
	5	W	$1.29\,x$	**B7**	**Maximum Feasible Deformation**
	6	W	$1.29\,x$	**B5**	
	7	W	$1.29\,x$	**B1**	
	8	W	$1.00\,x$	**B3**	
	9	W	$1.00\,x$	**B8**	**Fracture of the Outside Tube**
	10	W	$1.29\,x$	**B2**	
	11	W	$1.07\,x$	**B6**	
	12	W	$1.07\,x$	**B4**	
ERDC	13	W	$1.29\,x$	**B9**	**Plastic Deformation**
	14	W	$1.29\,x$	**B10**	
	16	W	$1.07\,x$	**B11**	
	17	W	$1.43\,x$	**B11**	
	18	W	$1.71\,x$	**B12**	

EXPERIMENTAL RESULTS AND GENERAL OBSERVATIONS

Blast Test Results

Measured plastic rotations after tests were well in excess of 2 degrees for CFDSTs and MSJC (Figure 6 and Figure 7). For structural members such as reinforced concrete plastic rotations of 2 to 4 degrees would lead to "moderate to heavy damage" (UFC, 2008) suggesting that repairs or complete replacement would be necessary. However, test results here for CFDSTs and MSJCs suggest that repair would be needed, only for aesthetical reasons, the deformed columns would indeed still be able to perform their functions. Plastic rotations in excess of 4 degrees were accompanied with moderate to important local denting of CFDST section and seam failure of MSJC's jacket. For near contact condition, fracture of the outside tube of CFDST occurred, however the inner tube prevented complete failure of the section.

Figure 6. Plastic Deformation of CFDST under Blast

Seismic Test Results

All specimen part of the seismic test program exhibited ductile behavior up to failure. In all cases, yielding preceded buckling of the outside tube. Yielding occur at drift level of about 1.5%, local buckling around at least 3% and failure well beyond 7.5%. Stiffness reduction was gradual, no substantial reduction in strength was observed until failure. In general, hysteretic loops for the specimens were stable up to failure and exhibited pinching proportional to the severity of local buckling, (Figure 8).

Figure 7: Global (Left) and Local Deformation (Right) of MSJC after Test

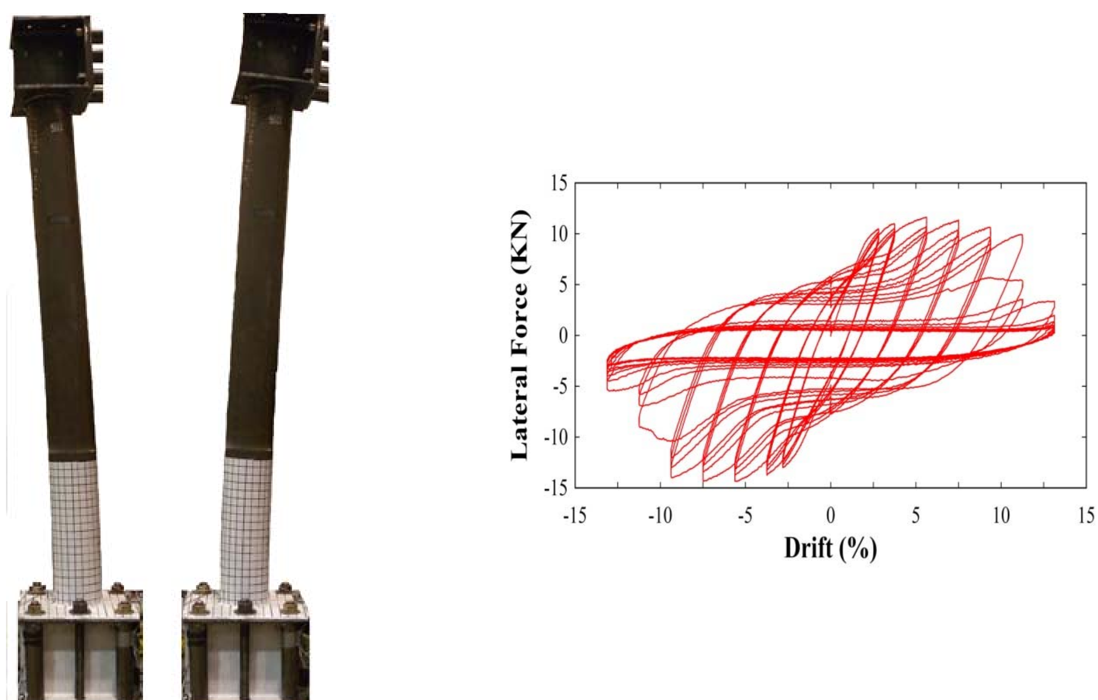


Figure 8: Specimen at Maximum Strength (Left) and Typical Hysteretic Loop (Right)

CONCLUSION

CFDST and MSJC were tested as candidate multi-hazard systems for bridge applications. For new bridge construction CFDST performance was deemed superior to reinforced concrete counterparts'. Satisfactory performance was also obtained even in near contact blast loading. MSJC sought to correct deficiencies in direct shear resistance of SJC without altering the intended flexural behavior of this retrofit. Test observations showed that the addition of an anchored collars around the top and the base of the jacket to be a cost-effective strategy. Large flexural deformations were achievable during blast test of the MSCJ while in previous studies on SJC direct shear failure was reported as a predominant failure mode. Further studies using analytical and advanced finite element methods undertaken to develop analytical and design tools for those systems are being validated.

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