Shake-Table Testing of Construction Specialties DriftReady™ Stair System

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Appendix 1

1. SUMMARY

This document describes the results of a shake-table experimental test program conducted on a "seismically resilient" stair system developed by Construction Specialties, Inc. The stair system design allows relatively free movement between the stair tread assembly and the upper landing while ensuring vertical load carrying capacity via support arms and rigid links that restrain the total movement of the stairs. At the time of testing, the stair system design was known as *AP4* and is now marketed as DriftReady™ Stair System.

The testing program comprised shake-table testing of a full-scale stair system assembly at the University of Nevada, Reno. This report describes the details of the test specimen, the test facility and experimental setup, the loading protocols applied and the test results.

2. TEST FACILITY

Shake-table testing was conducted at the Earthquake Engineering Laboratory at the University of Nevada Reno on one of their bi-axial shake-tables. The test setup comprised a stiff upper landing attached to a reaction block on the shake table with the lower landing fixed to the laboratory strong floor, see Figure 2.1. In this configuration, movement of the table resulted in relative movement between the two landings to simulate interstory drift on the stair system. The stair system was tested with no added mass and with steel plates attached to the treads to simulate 50 psf live load.

Table 2.1 UNR Biaxial Shake Table Specifications

Component	Capacity
Longitudinal Force	165 kips
Transverse Force	165 kips
Longitudinal Displacement	+/- 12 in.
Transverse Displacement	+/- 12 in.
Longitudinal Velocity	+/- 50 in/sec
Transverse Velocity	+/- 50 in/sec

2.1 Test Setup Instrumentation

Displacement and Acceleration

Instrumentation to measure displacement and acceleration included two wire potentiometers at each of the top and bottom landings to measure longitudinal displacement and rotation of the stairs assembly as well as one wire potentiometers to measure displacement in the transverse direction at the top and bottom of the stair assembly. Tri-axial accelerometers were placed on the shake-table and at the top, mid-height and bottom of the stair assembly. Displacement of the shake-table was obtained directly from the shake-table control system. A schematic showing the general instrumentation layout is given in Figure 2.2.

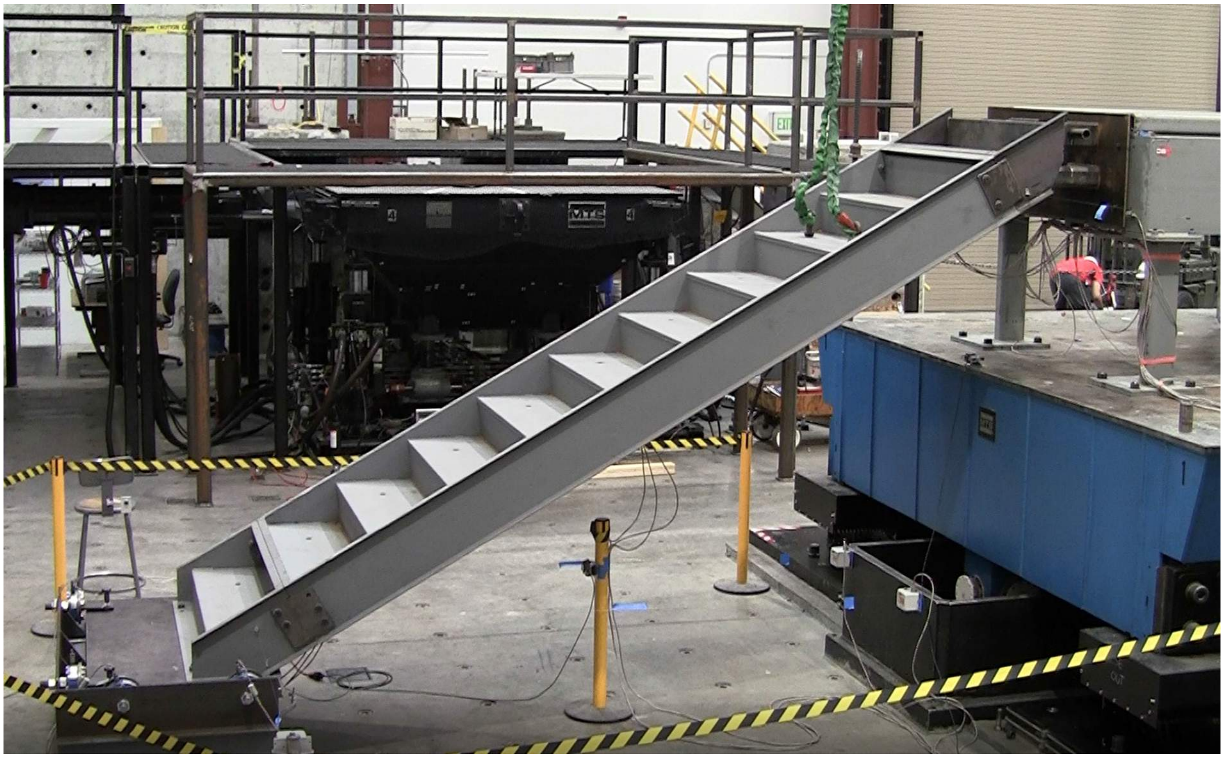

Figure 2.1 Testing Machine with Stair System Installed

<u>Force</u>

Force was measured directly by load cells in-line with the shake table actuators. The force output from the table includes both a friction component as well as table inertia. For that reason, force measured directly from the table is most informative for the quasi-static cases or viewed as a relative measure between different dynamic cases.

In addition to force measured by the shake-table load cells, four load cells were installed at the bottom landing, two in each direction as shown in Figure 2.3. The bottom landing rested on a greased High Density Polyethylene (HDPE) sliding surface. The load cells were connected to the bottom plate through holes slotted perpendicular to the axis of the load cell and reacted against support channels on two sides. Figure 2.4 shows a photo of the bottom plate and the load cells. When the bottom plate was not connected to the load cells it could be moved by hand relative to the HDPE plate. Therefore, it was reasonable to concluded that friction force at the bottom landing that was not measured by the load cells was relatively small.

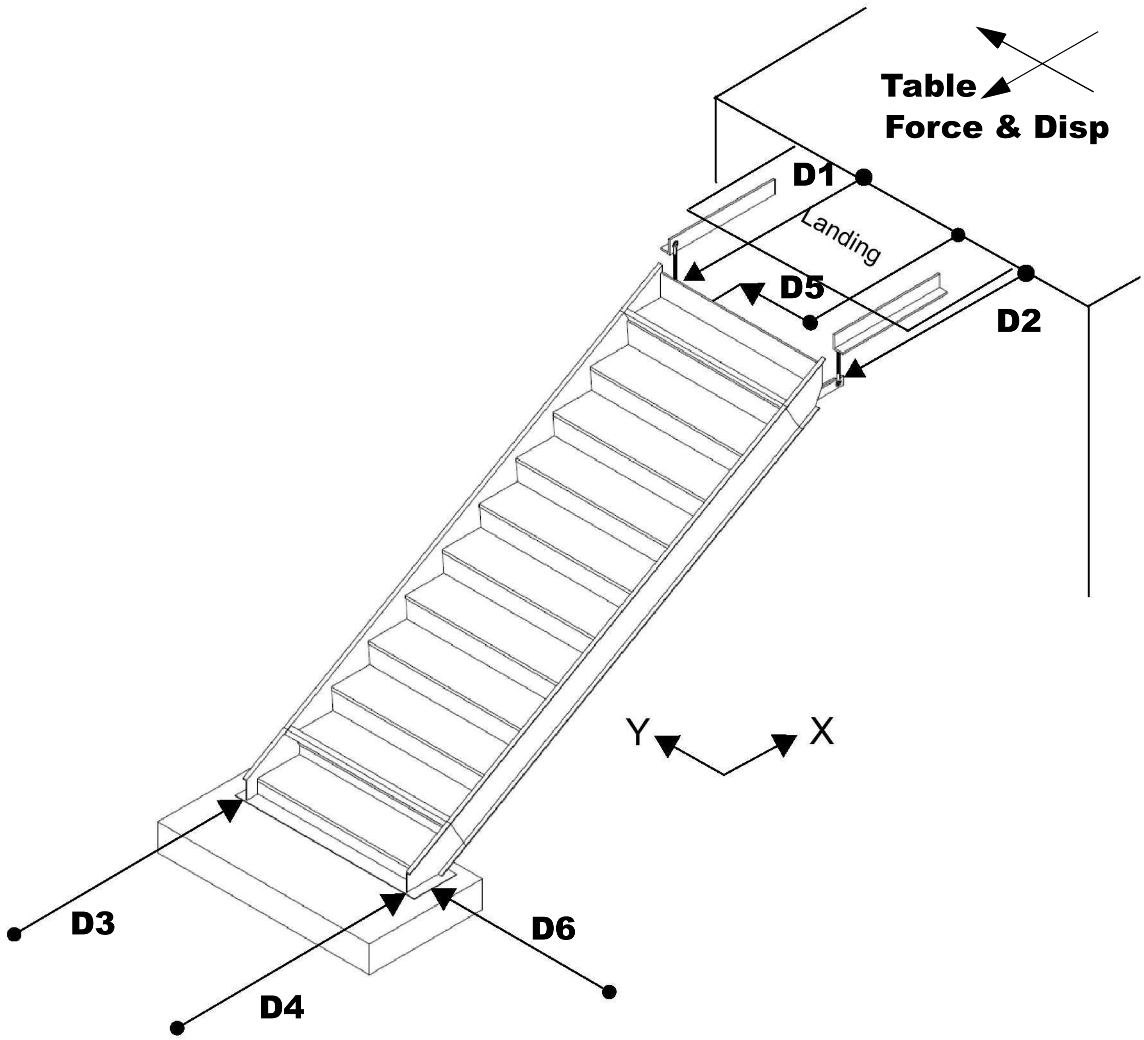

Figure 2.2 Testing Machine with Stair Specimen Installed

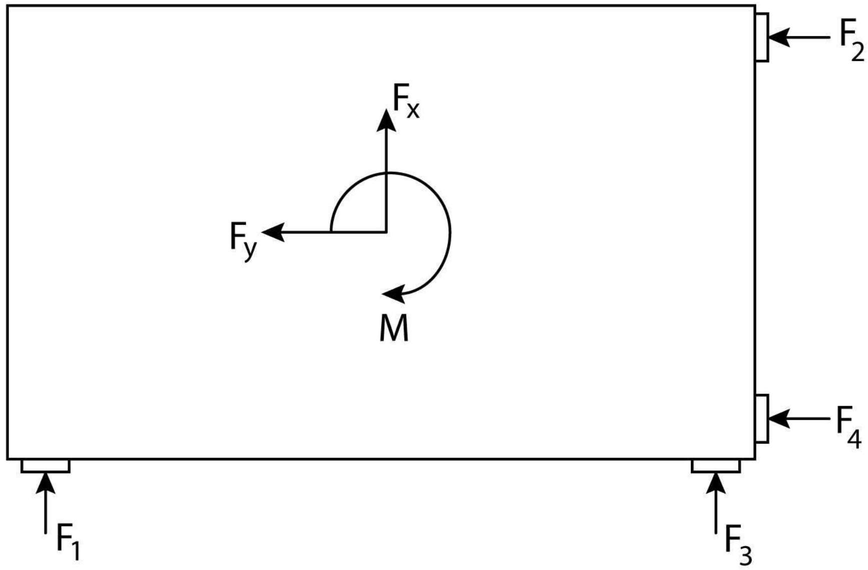

Figure 2.3 Schematic Showing Load Cells at the Bottom Landing

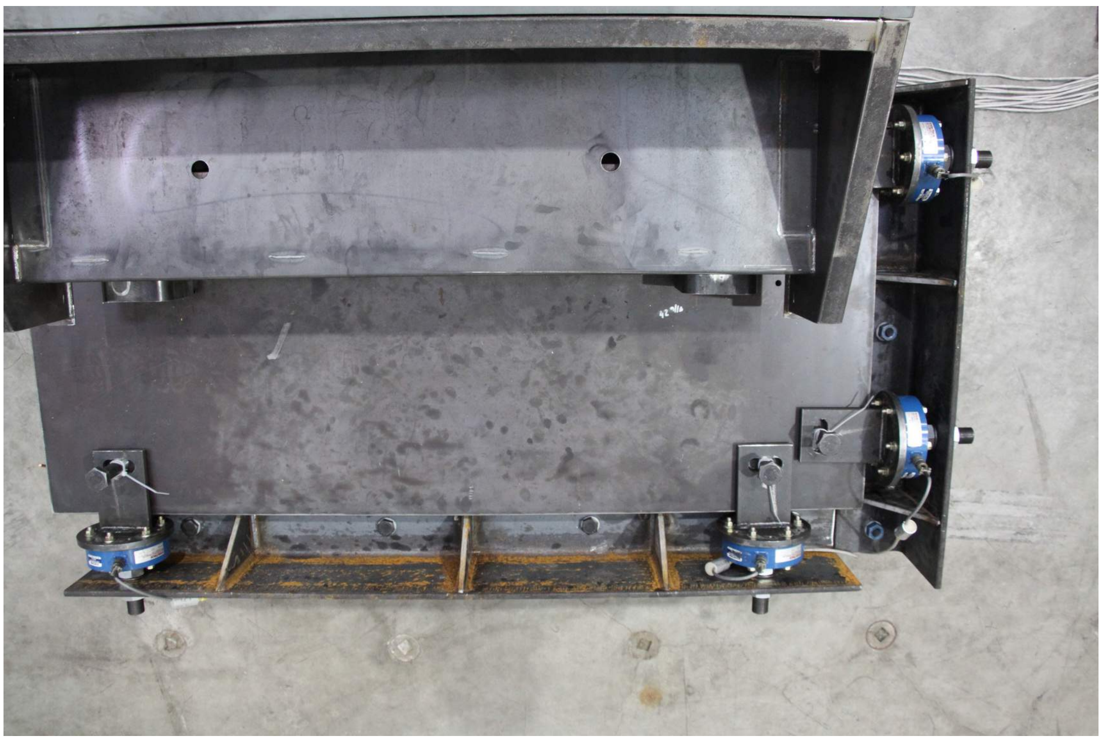

Figure 2.4 Photo of Load Cells at Bottom Landing (plan view)

3. TEST SPECIMEN

3.1 Description of Test Specimen

The AP4 stair system was fixed (bolted) at the bottom landing and supported vertically at the top landing by tube section cantilevers extending from the landing. In the longitudinal direction, rigid links restrained the top of the stairs from moving beyond the end of the cantilever support. In the transverse direction, the steel tubes are free to move through the brackets attached to the top landing. The length of the rigid links and the clearance between the rigid links and the support brackets are sized to allow movement in excess of the maximum expected displacement in either direction. Figure 2.5 shows the top assembly of the AP4 stair system.

Figure 2.5 View of Upper Connection of the DriftReady™ Stair System Tested

4. TEST PROGRAM

4.1 Input Motions

The loading protocol included quasi-static, dynamic and earthquake simulation tests over a range of different amplitudes. The design interstory drift (relative motion between the shake-table and the floor) was assumed to be 2.5% which corresponded to a drift amplitude of 2.5 in. The MCE drift was assumed to correspond to 4.0% interstory drift or 3.75 in. of shake table displacement.

Table 4.1 lists all tests performed on the AP4 stair system. The system was initially tested with no added mass and then re-tested with the equivalent of 50 psf distributed to the stair treads. Testing was initially conducted quasi-statically (0.25 in/s) in the longitudinal (X) direction followed by the transverse (Y) direction to confirm that the configuration functioned kinematically before conducting dynamic testing. The dynamic tests included three cycles in each direction at 0.5 in. and 2.5 in. amplitudes. Following the uni-directional tests, circular tests were conducted, again at 0.5 in. and 2.5 in. amplitudes. The test sequence was repeated dynamically (0.5 Hz) with the number of cycles increased to five at each amplitude. An additional dynamic circular test with an amplitude of 3.75 in. was conducted to represent an MCE drift demand condition.

In order to investigate the response of the stairs to motion more representative of earthquake shaking, two simulated inter-story drift displacement time-histories were developed. The "Newhall" motion was developed assuming a simple bilinear single degree of freedom building model with an elastic period of 0.35 second. The building yield strength was chosen so that there was moderate yielding (ductility of about 5) experienced in both directions of motion for several seconds of shaking. After investigating the response of a number of bi-directional earthquake motions, the Newhall record from the Northridge earthquake was chosen as the response that showed several desirable traits. Namely, the relatively strong shaking in both directions for 8-10 seconds, the good representation of cycles with the stairs moving in the same and opposite directions, several instances when there is a reversal in one direction without a corresponding reversal in the other and the fact that the pulse in the Newhall record created a relatively strong forward-and-back displacement pulse. The "Long Period" motion was developed to simulate interstory drift in a long-period structure. The interstory drift histories were scaled to give a maximum amplitude in the primary direction of 2.5 in. and 3.75 in. for the DBE and MCE

Table 4.1 Loading Protocol

Fixed - AP4 (4" Disp Capacity) - NO ADDED MASS							
	Test	Direction	Ampli. [in]	ISD [%]	Rate	No. of Cycles	Comments
Quasi Static Tests	a.	x	0.5	0.5	0.25 in/s	2	
	b.	x	2.5	2.5	"	"	
	c.	y	0.5	0.5	"	"	
	d.	y	2.5	2.5	"	"	
Dynamic Cyclic Tests	e.	x	0.5	0.5	0.5 Hz sine	5	
	f.	x	2.5	2.5	"	"	
	g.	y	0.5	0.5	"	"	
	h.	y	2.5	2.5	"	"	
	i.	x+y	0.5	0.5	"	"	
	j.	x+y	2.5	2.5	"	"	
	k.	x+y	3.75	3.75	"	"	
EQ Tests	l.	x+y	2.5 max				"LongPeriod DBE" - 0 deg Longitudinal
	m.	x+y	2.5 max				"LongPeriod DBE" - 0 deg Transverse
	n.	x+y	2.5 max				"Newhall DBE" - 0 deg Long
	o.	x+y	2.5 max				"Newhall DBE" - 0 deg Transverse
	p.	x+y	3.75 max				"Newhall MCE" - 0 deg Long
	q.	x+y	3.75 max				"Newhall MCE" - 0 deg Transverse

Fixed - AP4 (4" Disp Capacity) - ADDED MASS							
	Test	Direction	Ampli. [in]	ISD [%]	Rate	No. of Cycles	Comments
Quasi Static Tests	a.	x	0.5	0.5	0.25 in/s	2	Four load cells
	b.	x	2.5	2.5	"	"	Four load cells
	c.	y	0.5	0.5	"	"	Four load cells
	d.	y	2.5	2.5	"	"	Four load cells
Quasi Static Tests	a.	x	0.5	0.5	0.25 in/s	2	Three load cells for all remaining AP4
	b.	x	2.5	2.5	"	"	testing
	c.	y	0.5	0.5	"	"	
	d.	y	2.5	2.5	"	"	
Dynamic Cyclic Tests	e.	x	0.5	0.5	0.5 Hz sine	5	
	f.	x	2.5	2.5	"	"	
	g.	y	0.5	0.5	"	"	
	h.	y	2.5	2.5	"	"	
	i.	x+y	0.5	0.5	"	"	
	j.	x+y	2.5	2.5	"	"	
	k.	x+y	3.75	3.75	"	"	
EQ Tests	l.	x+y	2.5 max				"LongPeriod DBE" - 0 deg Longitudinal
	m.	x+y	2.5 max				"LongPeriod DBE" - 0 deg Transverse
	n.	x+y	2.5 max				"Newhall DBE" - 0 deg Long
	o.	x+y	2.5 max				"Newhall DBE" - 0 deg Transverse
	p.	x+y	3.75 max				"Newhall MCE" - 0 deg Long
	q.	x+y	3.75 max				"Newhall MCE" - 0 deg Transverse

motions, respectively. Each interstory drift history test was run twice, once with the primary motion in the X direction and again with the primary motion in the Y direction.

Testing of other stair configurations not reported here, necessitated that Load Cell 2 be removed to allow clearance between the bottom of the stairs and the edge of the bottom attachment plate. In order to establish a baseline comparison between the measurement configurations with three and four load cells, the first four tests of the Added Mass (AM) testing were repeated twice, once with four load cells and then repeated again with only three load cells. The remainder of the testing was conducted with three load cells.

4.2 Observation and Inspection of Test Program

All tests were conducted and witnessed by representatives of the University of Nevada, Reno, SIE, Inc. and Construction Specialties.

5. RESULTS

5.1 Response Plots

Plots showing the response of the AP4 stair system for all tests are given in an Appendix 1 to this report. For each test, there are five pages of response plots:

Page 1) Shake-table displacement and force in the X and Y directions

Page 2) Shake-table displacement and force as an orbit plot

Page 3) Stair displacement in the X and Y directions and the rotation at both the top and bottom of the stairs

Page 4) Bottom landing load cell forces

Page 5) Bottom landing rotation and calculated moment

With reference to Figures 2.2 and 2.3, the response values are calculated as follows:

<u>Calculation of Deformation Values</u>

X Displacement (top) = (D1 + D2) / 2

X Displacement (bottom) = (D3 + D4) / 2

Y Displacement (top) = D5

Y Displacement (bottom) = D6

Tread Rotation (top) = (D2 - D1) / Separation Distance

Tread Rotation (bottom) = (D4 - D3) / Separation Distance

<u>Calculation of Force Values</u>

Fx = (F1 + F3)

Fy = (F2 + F4)

M = (F3 - F1) x d/2 + (F2 - F4) x b/2

where d is the distance between LC1 & LC3 and b is the distance between LC2 & LC4).

For the three load-cell configuration, the LC2 values in the above equations are zero.

5.2 Observations

General

The AP4 stair system accommodated the imposed drift in all tests. There was no damage of the stair assembly, supports or landings observed in any test.

Displacement

For movement (building interstory drift) in the longitudinal (X) direction, the displacement of the shake table was accommodated completely at the top landing (as expected). This can be seen in plots showing the table displacement and the relative motion between the top landing and the top tread, where these displacements are essentially identical.

Movement (building interstory drift) in the transverse (Y) direction was accommodated through a combination of lateral movement at the top of the stair assembly and rotation of the stairs over its height. From the response plots for a 2.5 in. drift (see Test H for example), approximately 1 in. is direct translation at the top and 1.5 in. of the drift is accommodated through rotation. Rotation of the system occurred through tolerance at the top landing between the tubes and the holes in the support brackets. At the bottom landing rotation was occurred through tolerance in the bolt holes connecting the stairs to the base plate and in the holes connecting the base plate to the load cells. It was not possible to determine the relative contribution of each to the rotation. The dimension between the displacement transducers is 45 in. Therefore, a tread rotation of 0.005 (which can be seen in many tests) corresponded to 0.225 in. relative motion between the stringers.

Force

Comparing the longitudinal (X) direction quasi-static tests A and B, it is seen that the force measured in the shake-table did not substantially increase when the displacement increased from 0.5 in. to 2.5 in. The measured force was the friction between the top of the landing and the cantilever supports and the friction in the shake-table itself. Comparing the plots for the No Added Mass (NAM) case and the Added Mass (AM) case, it is seen that the force amplitude increased by about 1 kip, from plus/minus 2.5 to 3.5 kips, a negligible change in system behavior for a change in mass from zero added mass to 50 psf.

The most accurate measurement of force was in the longitudinal (X) direction at the base of the stair assembly. In this direction, the load cells at either side of the plate resisted all the force at the base, with little to no rotation. For the NAM case the force was virtually zero, while for the AM case, the load was up to 1 kip, consistent with the load indicated by the shake-table load cells.

During the dynamic testing, high frequency spikes were seen in the measured force data. These spikes were a result of the through-bolts that connected the base plate to the load cell impacting on edge of the slot as the direction of loading reverses. No filtering of the data was done. Even with the impact spikes, the maximum force measured in the longitudinal (X) direction at the bottom landing was about 1 kip for the No Added Mass case and 2 kip for the Added Mass case.

The measurement of force in the transverse (Y) direction was more difficult as the imposed drift was accommodated through both translation and rotation. Furthermore, for the three load cell configuration, the load at the bottom landing was primarily resisted by a force-couple in the longitudinal (X) direction load cells. This can clearly be seen in Test D, for example. The force measured by the shake table did not increase appreciably between the NAM and AM cases. It is reasonable to conclude that the load in the transverse (Y) direction is less than the longitudinal (X) direction discussed above.