Nov 7th, 12:00 AM - Nov 8th, 12:00 AM

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Wei-Wen Yu International Specialty Conference on Cold-Formed Steel Structures
St. Louis, Missouri, U.S.A., November 7 & 8, 2018

Cyclic Performance and Behavior Characterization of Steel Deck Sidelap and Framing Connections

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Abstract

A wide variety of steel deck sidelaps and framing connections have been experimentally studied to characterize the cyclic performance required in seismic evaluation of steel deck diaphragms. This study intends to provide cyclic test results of common steel deck connections including screw nestable and top arc seam sidelaps; and powder actuated fasteners, arc spot weld, and arc seam weld framing connections. A total of 24 sidelap and 36 framing connection tests have been performed in the Thin-Walled Structures Laboratory at Johns Hopkins University by NBM Technologies. The connection test results have been used to parameterize a nonlinear hysteretic spring element (i.e. utilizing the Pinching04 material model) applicable to modeling of the connections in high fidelity steel deck diaphragms to evaluate the seismic behavior of the steel deck diaphragm in rigid wall flexible diaphragm buildings, where inelasticity and ductility of the building system are intended to be derived largely from the diaphragm and the connections. Finally, the test results have been compared to AISI 310 and DDM04 connection strength and stiffness predictions. This experimental program is a task within a larger effort, i.e. "Advancing Seismic Provisions for Steel Diaphragm in Rigid Wall - Flexible Diaphragm Buildings" by NBM Technologies. The object of the larger effort is to investigate alternative seismic design provisions for conventionally designed steel diaphragms in Rigid Wall -Flexible Diaphragm Buildings.

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Introduction

The objective of this paper is to provide cyclic connection test results essential to 3D building models required for performing P695 evaluation studies for Rigid Wall - Flexible Diaphragm (RWFD) Buildings. This experimental program is a task within a larger effort, i.e. "Advancing Seismic Provisions for Steel Diaphragm in Rigid Wall-Flexible Diaphragm Buildings". The object of the larger effort is to investigate alternative seismic design provisions for conventionally designed steel diaphragms in RWFD buildings.

Recently FEMA P-1026 (2015) developed an alternative design procedure that employed modifications to traditional equivalent lateral force procedures. Specifically, the proposed method employed the period of the flexible diaphragm, a new seismic force modification coefficient (R-factor) specific to the diaphragm, and introduced protected zones on the diaphragm perimeter that are designed for increased demands. The method was validated for wood structural panel diaphragms, but not for steel deck diaphragm systems.

FEMA P-1026 cited reasons for its exclusion of steel deck diaphragm systems and inadequacy and deficiencies in available cyclic diaphragm or connection test results featured prominently. This study intends to provide cyclic test results of common non-proprietary steel deck connections including screw nestable and top arc seam sidelaps; and powder actuated fasteners, arc spot weld, and arc seam weld framing connections.

To enable nonlinear high fidelity modeling of the RWFD buildings and perform P695 evaluation studies, the connection test results have been used to parameterize a nonlinear hysteretic spring element (i.e. utilizing the Pinching04 material model initially employed in OpenSees) applicable to modeling of the connections in high fidelity steel deck diaphragms.

A total of 24 sidelap and 36 frame (structural) connection tests have been performed in the Thin-Walled Structures Laboratory at Johns Hopkins University by NBM Technologies.

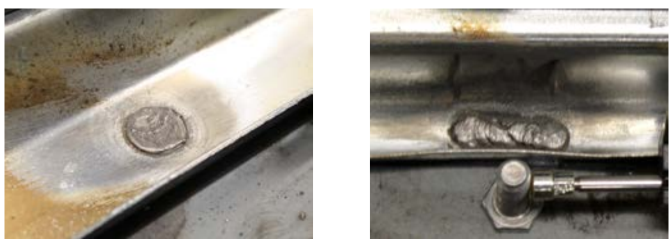
Test Matrix of the Connection Testing Program

The sidelap conditions considered in the testing program are summarized in Table 1 and shown in Fig. 1. As shown, three specimens have been tested cyclically and one monotonically for each condition.

Table 1: Sidelap connection test matrix

Specimen*	Thickness (gauge)	Connector	detail	Loading
S22#10	22	Screw** #10-16 ¾"	Minimum 1.5d edge distance	3 Cyclic -C1~3 1 Mono. -M1
S20#12	20	Screw*** #12-24 ¾"		
S18#12	18	Screw #12-24 ¾"		
S22AS	22	Top Arc Seam Weld	L_w=1.5 in.	3 Cyclic -C1~3 1 Mono. -M1
S20AS	20	Top Arc Seam Weld		
S18AS	18	Top Arc Seam Weld		

* All decks are 1.5 in WR
** Self-drilling screw S-MD 10-16 X 3/4 HWH3
***Self-drilling screw S-MD 12-24 X 7/8 HWH4



(a) (b)

Fig. 1. Non-proprietary steel deck framing welded connections. (a) Arc Spot Weld in nestable decks (b) Arc Seam Weld in interlocking decks

1.5 in. WR nestable sidelaps with screw fasteners are intended to represent common East Coast (United States) steel deck practice. The screw fastener size is selected and associated with the deck thickness. The Top Arc Seam Weld interlocking sidelaps are intended to represent non-proprietary West Coast (United States) deck performance. Per AISI S310-16 the length of the weld (L_w) is between 1 in. and 2.5 in. and a L_w of 1.5 in. has been selected herein. The steel deck specimens are all 3 ft long and connected at the sidelap by fasteners or welds. Deck material property is Class 1: 50 ksi (F_y) / 65 ksi (F_u).

The framing conditions considered in the testing program are summarized in Table 2 and shown in Fig. 2. Similar to sidelap connections, three specimens have been tested cyclically and one monotonically for each condition.

Table 2: Framing connection test matrix

Specimen	Ply1 (ga.)	Framing thickness	Connector	detail	Loading
F22SP	22	3/16 in.	Arc spot	Visible diameter=5/8”	3 Cyclic -C1~3 1 Mono. -M1
F20SP	20	3/16 in.	Arc spot		
F18SP	18	3/16 in.	Arc spot		
F22SP	22	3/16 in.	Arc seam	Visible length=1”, Visible width of the weld=3/8”	3 Cyclic -C1~3 1 Mono. -M1
F20SP	20	3/16 in.	Arc seam		
F18SP	18	3/16 in.	Arc seam		
F22PF	22	3/16 in.	PAF-Hilti	HILTI X-HSN 24 PAF	3 Cyclic -C1~3 1 Mono. -M1
F20PF	20	3/16 in.	PAF-Hilti		
F18PF	18	3/16 in.	PAF-Hilti		

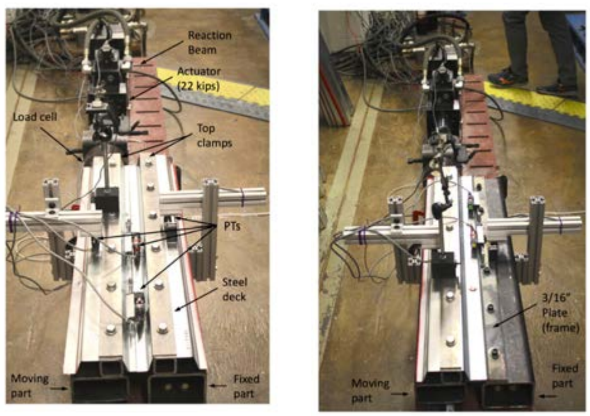
(a) (b)

Fig. 2. Non-proprietary steel deck framing welded connections. (a) Arc Spot Weld in nestable decks (b) Arc Seam Weld in interlocking decks; PAF: (c) HILTI X-HSN 24

1.5 in. WR nestable and Arc spot welds are intended to represent East Coast steel deck practice for nestable decks. The Arc seam weld is a non-proprietary detail assumed most consistent with West Coast practice. Hilti PAFs are today the most common mechanical connection in the West Coast. Frame element (substrate) thickness is based on common joists used in the West Coast. The steel deck specimens are all 3 ft long and connected to the substrate by fasteners or welds. Deck material property is Class 1: 50 ksi (F_y) / 65 ksi (F_u). The frame element is a flat plate with a width of 4 in., length of 36 in., and thickness of 3/16 in..

Test Setup and Instrumentation

The test setup is motivated from the lap-joint shear setup in AISI S905-13 and recent commercial testing. The test setup provides cyclic loading (displacement control). The testing rig is adjustable for both sidelap and framing connections with a 22 kip load capacity. The test rig is shown in Fig. 3.



(a) (b)

Fig. 3. (a) Sidelap testing rig and (b) Frame testing rig at the Thin-Walled Structures Laboratory - Johns Hopkins University

The main test results are the applied force versus applied displacement on the specimen in shear. A load cell installed between the actuator and the moving part of the rig records the force response of the specimens and the rig displacements have been recorded through position transducers (PTs). The internal LVDT of the actuator provides the overall actuator displacements. Six other PTs are installed to measure relative displacement at different points on the testing rig, as shown in Fig. 4.

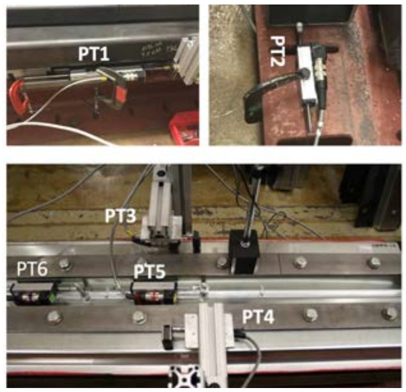


Fig. 4. Position Transducers (PTs)

Loading protocol

The FEMA 461 cyclic loading protocol has been adopted here. Notably, recent and extensive CFS-based cyclic fastener tests (Tao et al. 2016) also employed the FEMA 461 protocol.

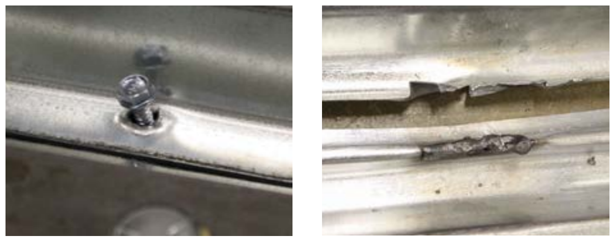
The loading rate in the testing program is assumed to be 0.01 in./sec throughout all cycles. However, the loading rate has been decreased to 0.0033 in./sec in the initial cycles (first 3 steps in the loading) to increase the displacement resolution for the small displacement amplitudes at the beginning of the testing.

Test Observations

Test observations throughout the tests are summarized here for all sidelap and frame connections.

The failure mode of all screw sidelaps is screw tilting and bearing as shown in Fig. 5(a). It should be noted that in large cyclic displacements, the screw started to back out of the hole to accommodate the large tilting angle and the back out was irreversible and ultimately ended up in a complete removal of the screw.

The typical failure mode of the Top Arc Seam sidelaps is shown in Fig. 5(b). In almost all cases, the failure was not visible from the top side of the specimen because the connection failure occurred at the edge of the “male” steel deck, which is welded to the “female” steel deck in the interlocking sidelap. Accordingly, the “male” ply tore and buckled underneath the top “female” plate and resulted in relatively sharp strength drop after the peak load. No failure was observed in the top arc seam welds.



(a) (b)

Fig. 5. (a) Screw nestable sidelap, Failure mode: screw tilting and bearing. (b) Interlocking sidelap, Failure mode: shear tearing at the edge of the “male” deck

Based on the test observations (see Fig. 6(a)), fracture of the steel deck all around the spot-weld in the Heat Affected Zone (HAZ) of the connected steel deck was the typical failure mode of the Arc-Spot Weld framing connections. The out-of-plane deformation of the thin deck due to buckling on the side of the weld in compression accelerated the fracture of the plate in the reverse cycle. Most of the connections failed within two subsequent cycles, where both sides of the weld experienced tension after the plate buckling.

The first degradation in the arc-seam weld connection strength happened after localized deformations of the steel deck around the weld and warping of the standing lip as shown in Fig. 6(b). The out-of-plane deformation of the thin deck where the ends of the welds were in compression accelerated the facture of the plate in the reverse cycle where the deformations were reversed and the load direction switched to tension. The longitudinal fracture of the weld happened along one side of the weld close to the web of the deck, but the other side of the weld connected to the standing lip did not fail until the end of the tests. In most of the tests, tension cracks were formed in the standing lip at the ends of the seam weld.

Typical failure mode for all PAF framing connections was shear tearing or bearing failure of the deck at the fastener location as shown in Fig. 6(c). Fastener failure was not observed in any PAF experiments.

(a) (b) (c)

Fig. 6. (a) Arc-Spot Weld framing connection, failure mode: fracture of the deck all around the weld in HAZ. (b) Arc-Seam Weld framing connection, failure mode: fracture of the deck all around the weld in HAZ and the standing lip. (c) PAF framing connection, failure mode: shear tearing/bearing of the deck against the fastener.

Cyclic Test results and Behavior Characterization

Cyclic test results along with the fitted hysteretic cyclic model, i.e. Pinching04 (P4) model, have been provided in Figs. 7-11. The Pinching04 hysteretic model is a pinching material model developed by Altoontash (2004) and Lowes et al. (2004) originally for simulating the earthquake response of reinforced concrete beam-column joints and later implemented in OpenSees (Mazzoni et al. 2006) as a hysteric material model. This hysteretic model has also be also been previously used to model steel-to-steel and sheathing-to-steel fastener response (Peterman et al. 2014; Tao et al. 2017).

For brevity, only one of the 20 gauge specimens of each type of connections is provided here. See Torabian and Schafer (2017) for the complete report of results.

In Figs. 7-11, the normalized per-cycle energy balance of the Pinching04 fit and the cyclic test, and the cumulative energy balance are provided. The total amount of energy dissipated by the Pinching04 model and the cyclic test are equilibrated at the end of the test. However, the dissipated energy of each cycle throughout the cyclic deformation is not necessarily the same in the P4 and testing results, but they are reasonably close. Since, cumulative cyclic energy of the P4 model is typically smaller than the test, the P4 fit can be assumed to be conservative. See Torabian and Schafer (2017) for all test results and Pinching04 parameters.

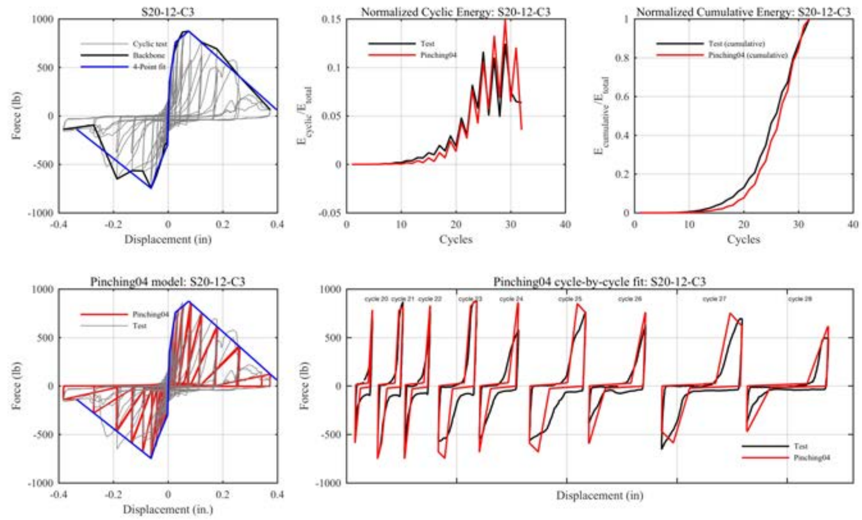


Fig. 7. Nestable Screw Sidelap, 20 gauge deck and #12 screw

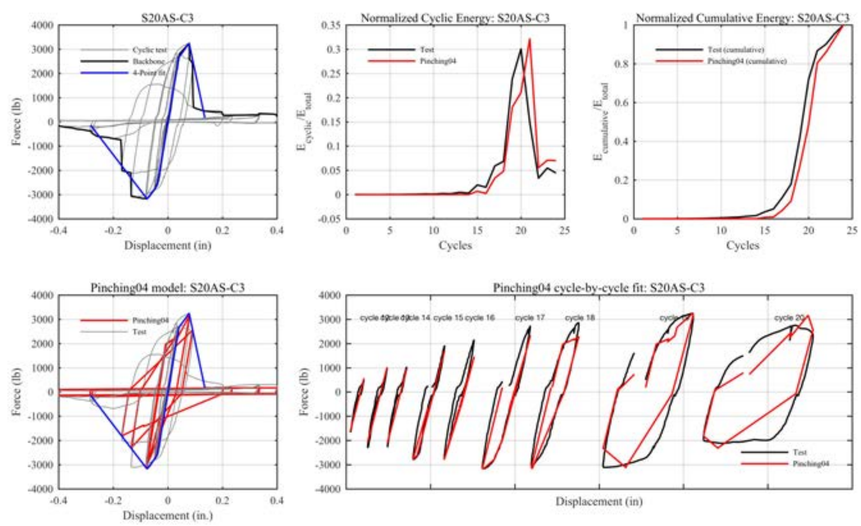


Fig. 8. Top Arc Seam Interlocking Sidelap, 20 gauge deck

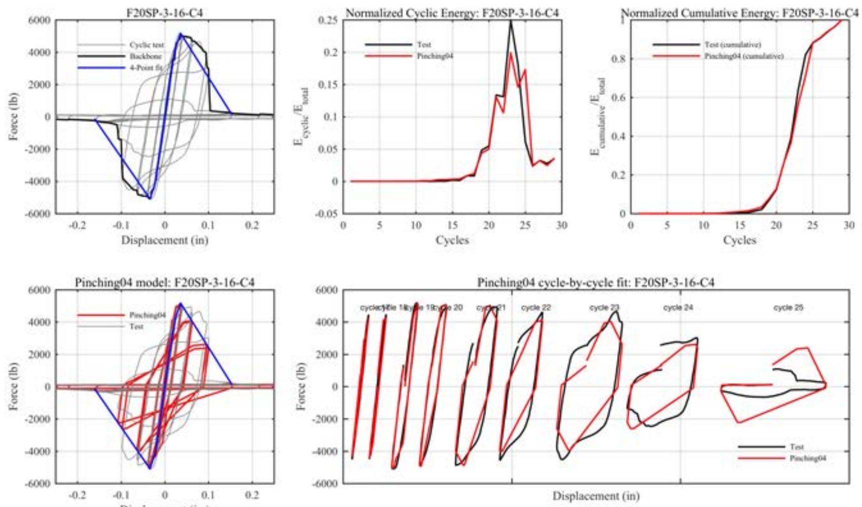


Fig. 9. Arc Spot Weld Framing Connection, 20 gauge deck

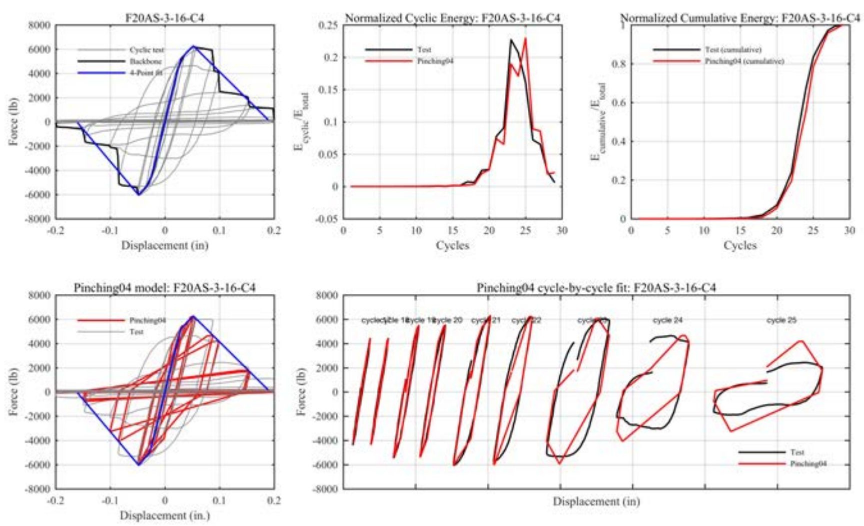


Fig. 10. Arc Seam Weld Framing Connection, 20 gauge deck

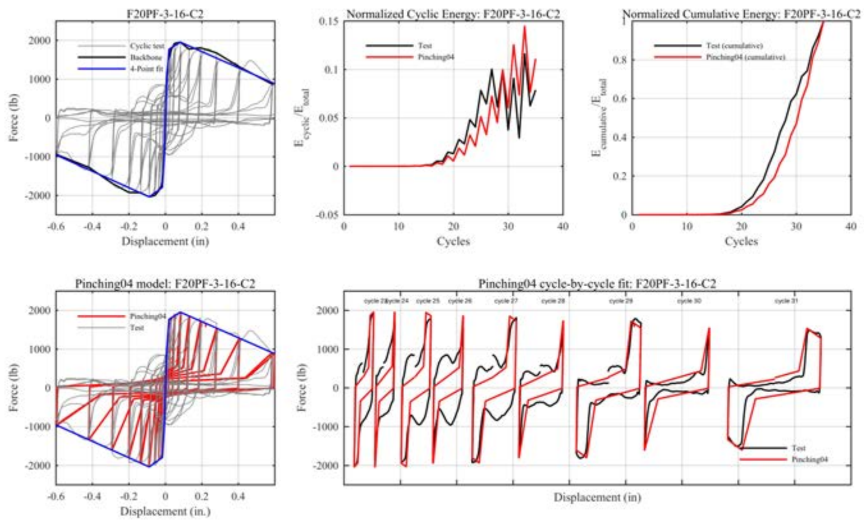


Fig. 11. PAF Framing Connection, 20 gauge deck

Comparison to DDM04 and AISI S310

The strength and stiffness of the tested connections are compared to AISI S310-16 (and DDM04) equations in Table 3 for the average of cyclic results. Since the tested specimens are intended to represent construction practice, the nominal capacities were calculated using the nominal fastener dimension and nominal weld and material properties (especially important for the welded connections).

In general, mechanical fasteners such as screw in the sidelaps and PAFs in the framing connections are in relatively good agreement with the nominal design strength and stiffness. The screw test results are affected by the cyclic loading, but the change in capacity of the PAFs is not significant.

Compared with these results, AISI S310 (and DDM04) appears to over predict the sidelap cyclic strength, but is in good agreement with the monotonic test results. Tested strength has relatively high variation and sensitivity to screw installation location so drawing definitive conclusions on the accuracy of AISI S310 (and DDM04) is not possible with this data alone. Compared with these results, AISI S310 (and DDM04) under predicts the strength of the Arc Spot weld and Arc Seam weld framing connections. To account for expected variability it may be that some degree of over strength is embedded in the design equation for the welded framing connections. Cyclic loading resulted in about

5%-20% reduction in the strength of the Arc-Spot and Arc-Seam welds vs. the monotonic tests.

Table 3: Comparison of the cyclic test results to DDM04 and AISI S310

	Gauge	Substrate	Connector	Test Results (Cyclic)		DDM04/AISI-S310	
				Strength (lb)	Stiffness (kips/in)	Strength (lb)	Stiffness (kips/in)
Sidelap	22	-	#10	785	77	603	57
	20	-	#12	691	104	859	63
	18	-	#12	1320	124	1309	73
	22	-	Top Arc Seam	2496	43	2895	153
	20	-	Top Arc Seam	2994	58	3745	169
	18	-	Top Arc Seam	3902	107	5439	194
Framing	22	3/16"	PAF	1792	124	1489	137
	20	3/16"	PAF	2043	178	1795	152
	18	3/16"	PAF	2083	162	2347	175
	22	3/16"	Arc Spot	4005	180	2512	149
	20	3/16"	Arc Spot	4659	148	3016	165
	18	3/16"	Arc Spot	7369	205	3915	189
	22	3/16"	Arc Seam	4835	165	2788	149
	20	3/16"	Arc Seam	5374	186	3349	165
	18	3/16"	Arc Seam	9180	234	4348	189

Summary and Conclusions

The performance of the deck-to-deck (sidelap) and deck-to-structure (framing) connections is a key contributor to the complex nonlinear seismic response of steel deck diaphragms. This paper provided the testing and characterization of a series of 24 sidelap and 36 framing connections, tested in shear to the AISI S905 standard, and extended to cyclic response following the FEMA 461 protocol. The tests cover 18, 20, and 22 gauge WR nestable deck with sidelap connections consisting of fasteners, spot welds, and top arc seam welds; and framing connections to 3/16 in. plate consisting of PAFs, arc spot, and arc seam welds. A procedure is developed for idealizing the test results with a 1D phenomenological model (the Pinching04 model) that includes a symmetric multi-segment linear backbone as well as pinching, un- and re-loading parameters.

Acknowledgments

We would like to thank the industry associations that sponsored this testing, namely the: American Iron and Steel Institute, Steel Deck Institute, and Steel Joist Institute. We would like to thank their representatives who participated on the Industry Steering Group: Pat Bodwell, Ken Charles, Jim Fisher, Jay Larson, Bonnie Manley, Bob Paul, Dave Samuelson, and Tom Sputo. They provided expert advice and assistance throughout the work, and were particularly instrumental in developing the test matrix. We would like to thank the Laboratory Technician in the Department of Civil Engineering at Johns Hopkins University: Nick Logvinosky, for his assistance in completing the testing reported herein.

Disclaimers

Dr. Torabian's participation in this work was as a paid consultant for NBM Technologies. All opinions expressed and implied in this work are solely those of Dr. Torabian and do not represent or reflect the views of the Johns Hopkins University or the Johns Hopkins Health System. Dr. Schafer's participation in this work was as a paid consultant for NBM Technologies. All opinions expressed and implied in this work are solely those of Dr. Schafer and do not represent or reflect the views of the Johns Hopkins University or the Johns Hopkins Health System. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the sponsors.

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