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Cyclic Testing of Composite Concrete on Metal Deck Diaphragms Undergoing Diagonal Tension Cracking

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ABSTRACT

While a considerable amount of testing has been performed on bare steel deck diaphragms, a limited amount of data exists on composite concrete on metal deck floor diaphragms subjected to cyclic loads. The few historical testing programs that have been conducted used some specimens that do not represent common floor assemblies in North America today. Therefore, more experimental data is required to understand the seismic performance of composite diaphragms that are typical of modern construction including the use of shear studs for shear transfer and concrete cover thicknesses that satisfy a two-hour fire rating.

As part of a larger diaphragm research project called the Steel Diaphragm Innovation Initiative (SDII), this testing program aims to supplement the existing data with a series of six cantilever diaphragm tests of which two have been completed to date. All specimens consist of a 5.2 m by 4.1 m composite slab with 0.91 mm steel deck, 27.6 MPa structural concrete fill, and 19 mm shear studs. One side of the diaphragm frame is fixed to reaction blocks that are anchored to a strong floor and the other side is restrained against out-of-plane movement with rollers while being subjected to in-plane racking displacements. The six specimens have varying depths of concrete cover (thinnest possible up to a thickness necessary to achieve a two-hour unprotected steel deck fire rated assembly), deck height (51 mm and 76 mm), perimeter stud anchor configuration, and concrete type (normal weight and light weight). Four specimens are designed to fail in concrete diagonal tension cracking, while two specimens are designed to fail the perimeter shear stud anchors without reaching the full strength of the concrete. A cyclic loading protocol based on FEMA 461 is used wherein two cycles are applied at each displacement level and the displacement levels increase exponentially. Preliminary results from these tests, in conjunction with past test data, support a modification to existing AISI equations for composite diaphragm strength. The resulting shear load vs. shear angle behavior is also providing important data sets for calibration of companion computational models.

Keywords: Seismic Performance, Composite Diaphragm, Large-Scale Testing, Concrete Shear, Floor Assembly

INTRODUCTION

Background and Motivation

The diaphragm is an integral part of a building's structure and the way buildings resist seismic loads. The majority of the seismic load originates at the diaphragm and the diaphragm acts to transfer these loads to the vertical elements of the lateral force resisting system (LFRS). While the diaphragm is arguably just as important in the load path as the vertical LFRS, the seismic demands and seismic behavior of diaphragms is not as well understood as the vertical LFRS. For example, it was only recently discovered that US code level forces significantly underpredict the loads in diaphragms and thus that diaphragms may be subject to inelasticity during design level earthquakes ([1],[2]). Full-scale testing of diaphragm assemblies is required to understand their cyclic behavior including strength, stiffness, ductility, strength degradation, hysteretic behavior, and failure modes.

A recent effort to assemble past diaphragm testing into a database found approximately 750 diaphragm test specimens, but only about 10% were concrete on metal deck and the majority of those were not representative of typical floor assemblies in North America [3]. An experimental program conducted by Luttrell [4] included nine specimens with insulating concrete, tested monotonically. Davies and Fisher [5] performed four cantilever diaphragm tests with structural concrete fill, but these tests were also monotonic and only failed the structural fasteners. A testing series conducted by ABK [6] included one specimen with structural concrete fill, but it was not loaded to failure. The most comprehensive experimental study on concrete-filled metal deck diaphragms was performed at Iowa State ([7]-[15]) and consisted of 32 cantilever diaphragm specimens subjected to cyclic loading. Of these specimens, only three used shear studs as the only means of perimeter fastening; the majority used arc welds as perimeter fastening.

A testing program is underway to fill some of the gaps in our understanding of composite diaphragm behavior. Six 5.2 m by 4.1 m specimens using headed shear studs for shear transfer will be tested with design variations including concrete cover thickness (51 mm to 114 mm), deck height (51 mm and 76 mm), perimeter stud anchor configuration, and concrete type (normal weight and light weight). Two out of six total planned specimens have been tested at the time of this writing. This paper describes the full testing program and results are presented for the two completed tests. Predictive equations for strength and stiffness are presented and compared to test data.

This testing program is part of a research project called the Steel Diaphragm Innovation Initiative (SDII) that is working to improve our understanding of steel diaphragm behavior and improve steel diaphragm design, particularly during earthquakes. The project considers both bare deck and concrete filled deck and includes a range of computational studies as well as experimental studies.

TEST SETUP

This testing program consists of six specimens with varying concrete cover, deck depth, and concrete type as given in Table 1. The first four specimens are designed to fail in diagonal tension cracking. This is to say that the failure mode will consist of the concrete slab cracking from the loading exceeding the shear capacity of the concrete. The last two specimens are designed to fail the perimeter shear stud anchors without reaching the full shear capacity of the concrete. All specimens consist of a 5.2 m by 4.1 m composite slab with 0.91 mm corrugated steel deck, structural concrete fill with specified 28-day strength of 27.6 MPa, and 19 mm diameter shear studs with nominal ultimate strength, F_u=448 MPa.

Table 1. Test Matrix of Cantilever Diaphragm Specimens

Status	Test Specimen	Compressive Strength*, f'_c (MPa)	Total Slab Depth (cm)	Deck Height, D_d (cm)	Concrete Type	Objective
Completed	3/6.25-4-L-NF-DT	26.9	15.9	7.6	LW	Typical 2 Hr Fire Rating for LW
	3/7.5-4-N-NF-DT	27.6	19.1	7.6	NW	Typical 2 Hr Fire Rating for NW
In Progress	2/4-4-N-NF-DT	27.6	10.2	5.1	NW	Thin assembly using NW
	2/4-4-L-NF-DT	27.6	10.2	5.1	LW	Thin assembly using LW
	3/6.25-4-L-NF-P	27.6	15.9	7.6	LW	Fail Studs with LW
	3/7.5-4-N-NF-P	27.6	19.1	7.6	NW	Fail Studs with NW

* Measured strength at time of testing for completed specimens, specified 28-day strength for others

Figure 1 illustrates the experimental setup which consists of a frame using W24x84 beams that are 4.6 m by 3.7 m center to center. Figure 3 shows a typical specimen before testing. The shear stud configuration for the first four specimens was designed to prevent a failure of the perimeter fasteners and included two studs per rib in the direction perpendicular to the deck and stud spacing of 305 mm in the direction parallel to the deck. Each test is accompanied by concrete cylinder tests to determine the compressive strength of the concrete.

The cyclic loading protocol was based on FEMA 461 [16] and includes six cycles before reaching the elastic limit. The elastic limit is calculated as a ratio of the predicted ultimate strength (Equation (1)) to the predicted stiffness (Equation (2)). The loading protocol includes two cycles for every displacement step with a 40% increase in amplitude between displacement steps. The loading is implemented using two actuators working in tandem. One actuator is displacement controlled while the force in the second is restrained to be equal but opposite the force in the master actuator. Because the load-deformation behavior of the specimens is to be used in the calibration of computational models capturing collapse, the inelastic behavior of these specimens is of special interest. Therefore, the tests are continued well past cracking up to the limits of the test setup.

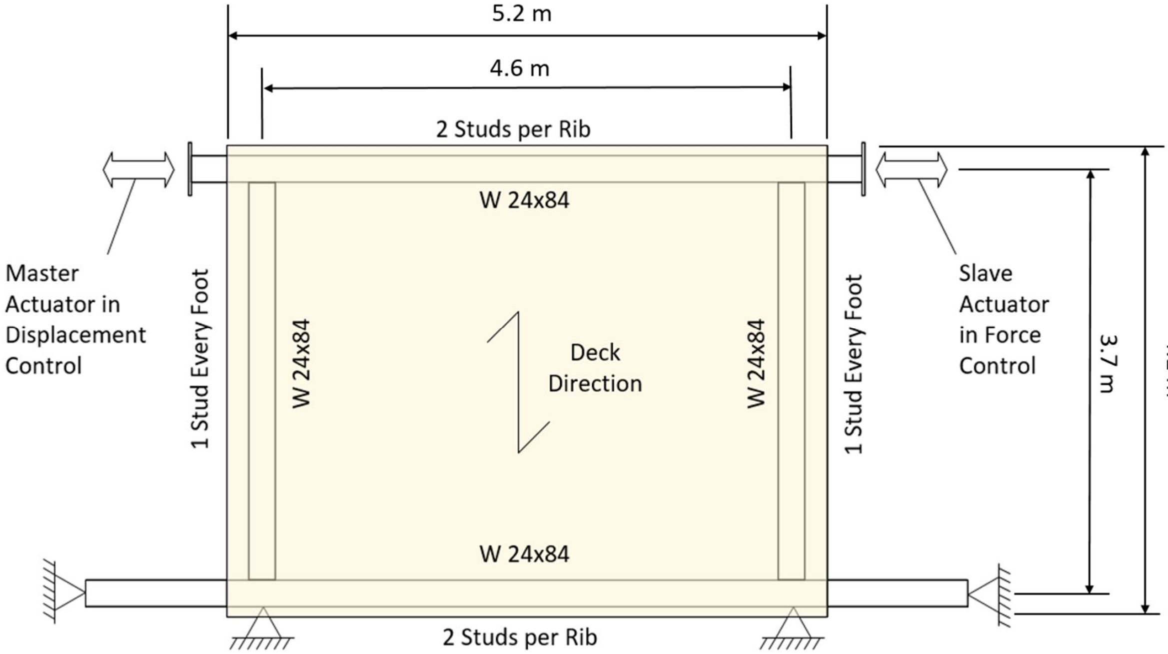

Figure 1. Experimental Setup for Cantilever Diaphragm Specimens

An array of string potentiometers (Figure 2(a)) is used to collect displacement data from the specimens. Shear angle is calculated per AISI S907-13 [17] using diagonal measurements of string potentiometers 1 and 5, as well as lateral displacement measurements from string potentiometer 2 with string potentiometers 3,4, and 7 to correct for rigid body rotation of the reaction frame. As shown in Figure 2(b), the diagonal measurements are taken at three different levels of the test setup: top, mid-level, and bottom. The three layers of instrumentation are meant to capture the flexibility of the steel frame to isolate the stiffness of the composite diaphragm specimen.

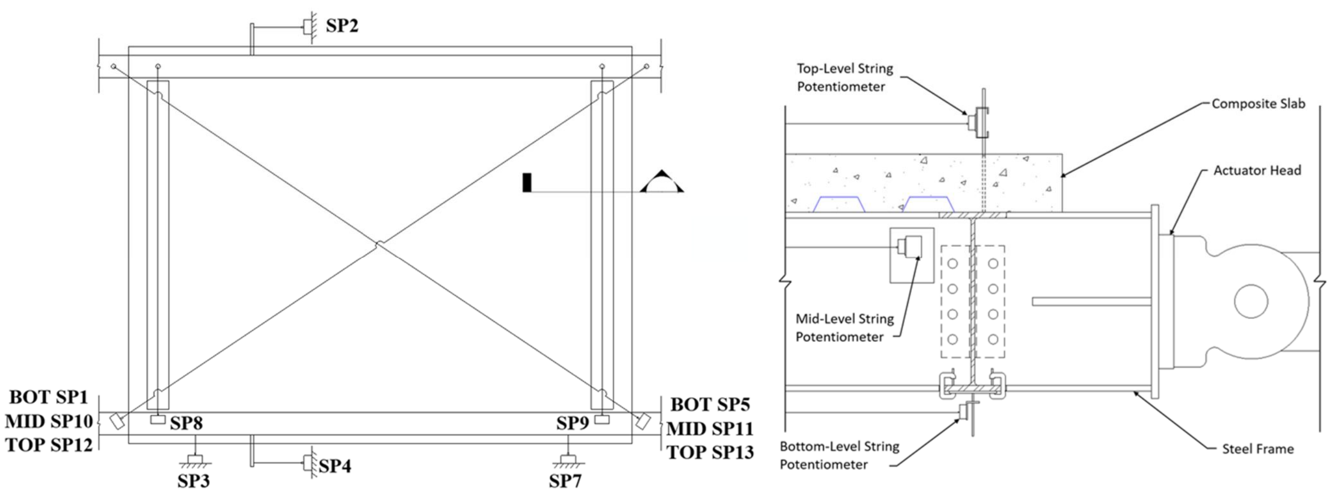

Figure 2. Instrumentation Setup for Cantilever Diaphragm Tests (a) Plan view. (b) Section.

Figure 3. Experimental Setup for Cantilever Diaphragm Tests

STRENGTH AND STIFFNESS PREDICTION

Equation (1) was used to predict the shear strength of the cantilever diaphragm specimens using measured concrete strength. This equation is obtained from [3] as a proposed modification to existing AISI equations for composite diaphragm strength. The specimens to be tested are intended to complement existing testing data to further validate the use of this proposed equation for predicting ultimate strength.

$$S_n = \lambda \cdot k \cdot t_e \cdot b \cdot (f_c')^{0.5} \quad \left(\frac{kN}{m}\ for\ SI, \frac{kip}{ft}\ for\ Imperial\right) \tag{1}$$

Where,

- λ = lightweight factor (1 for NW, 0.75 for LW)
- k= concrete strength factor, (2.66 for SI, 0.0032 for Imperial)
- t_e = equivalent total transformed concrete thickness, (cm for SI, inch for Imperial)
- b = unit width, (1 m for SI, 12 inch for Imperial)
- f_c' = Concrete Strength (MPa for SI, psi for Imperial)

Equation (2) is proposed for shear stiffness of composite diaphragms and was based on the equation from O'Brien [3]. The equation from O'Brien [3] was calibrated for normalweight concrete specimens, so a lightweight factor, λ_g, has been added to account for the difference in the modulus of elasticity of lightweight concrete. The predicted stiffnesses were calculated using the measured strengths given in Table 1.

$$G' = m \cdot \lambda_g \cdot t_e \cdot (f_c')^{0.5} \quad \left(\frac{kN}{cm} for\ SI, \frac{kip}{in} for\ Imperial\right) \tag{2}$$

Where,

- t_e = Effective concrete thickness, (cm for SI, inch for Imperial)
- m = 40 for SI, 4.8 for Imperial
- f_c' = Concrete Strength (MPa for SI, psi for Imperial)
- $\lambda_g = \frac{E_c}{E_{cNW}} = \left(\frac{w_c}{w_{cNW}}\right)^{1.5}$ (Lightweight factor)
  - = 1 for Normalweight (22.8 kN/m^3 for SI, 145 pcf for Imperial)
  - = 0.66 for lightweight (17.3 kN/m^3 for SI, 110 pcf for Imperial)

RESULTS

In this section, the behavior and results of the first two specimens will be described and then a preliminary evaluation of the results to date will be presented.

Specimen 3/6.25-4-L-NF-DT

The failure mode of interest for the cantilever diaphragm specimens is diagonal tension cracking. This failure mode occurs when the shear capacity of the concrete fill is exceeded. Figure 1 illustrates the progression of the diagonal tension cracking failure for the first tested specimen (3/6.25-4-L-NF-DT).

Before testing, some shrinkage cracking was detected (Figure 4(a)). When the shear capacity of the concrete was reached in the direction of loading, a diagonal tension crack was formed (Figure 4(b)). The same limit state was then reached in the opposite direction of loading (Figure 4(c)) forming a distinct “X” crack pattern. Loading continued with subsequent cracks forming in both directions until the test was stopped. The specimen showed debonding of the concrete slab from the steel deck along the edges of the diaphragm. Additionally, cracking occurred at the overhangs parallel to the deck ribs, with one of the overhangs eventually detaching from the specimen.

Figure 5 shows the load-deformation behavior of specimen 3/6.25-4-L-NF-DT. After reaching diagonal tension cracking at a shear force of 618 kN, the strength of the diaphragm started decreasing and the stiffness degraded rapidly. The measured stiffness of 2828 kN/cm was calculated as the secant stiffness through a point at 40% of the peak shear load using the mid-level diagonal string potentiometers. To characterize the ductility of the specimen, the yield shear angle was calculated as the ratio of the peak shear strength divided by the measured stiffness and the ultimate shear angle was taken at 20% loss in strength compared to the peak shear force. The ductility of the specimen is then defined as the ratio of ultimate shear angle to yield shear angle. Using these parameters, ductility for Specimen 3/6.25-4-L-NF-DT was calculated to be μ=9.1.

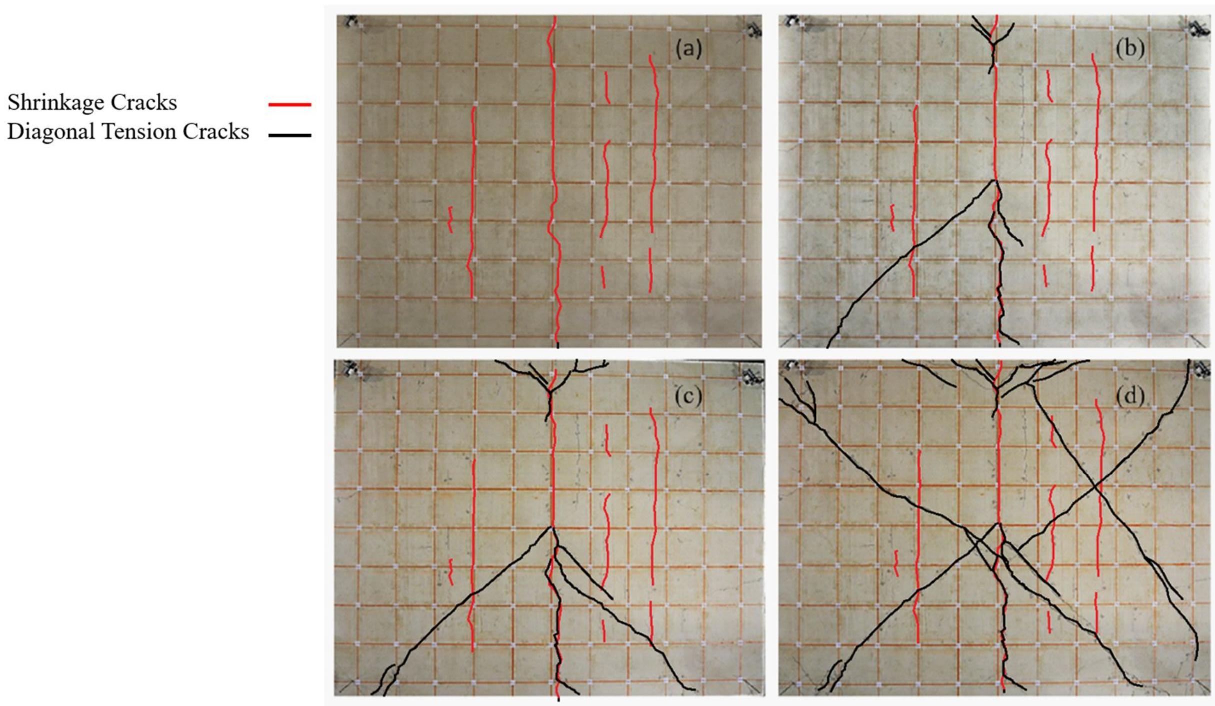

Figure 4. Progression of failure for specimen 3/6.25-4-L-NF-DT. (a) Before testing. (b) First appearance of diagonal tension cracking. (c) First appearance of diagonal tension cracking in opposite direction. (d) Crack pattern past failure

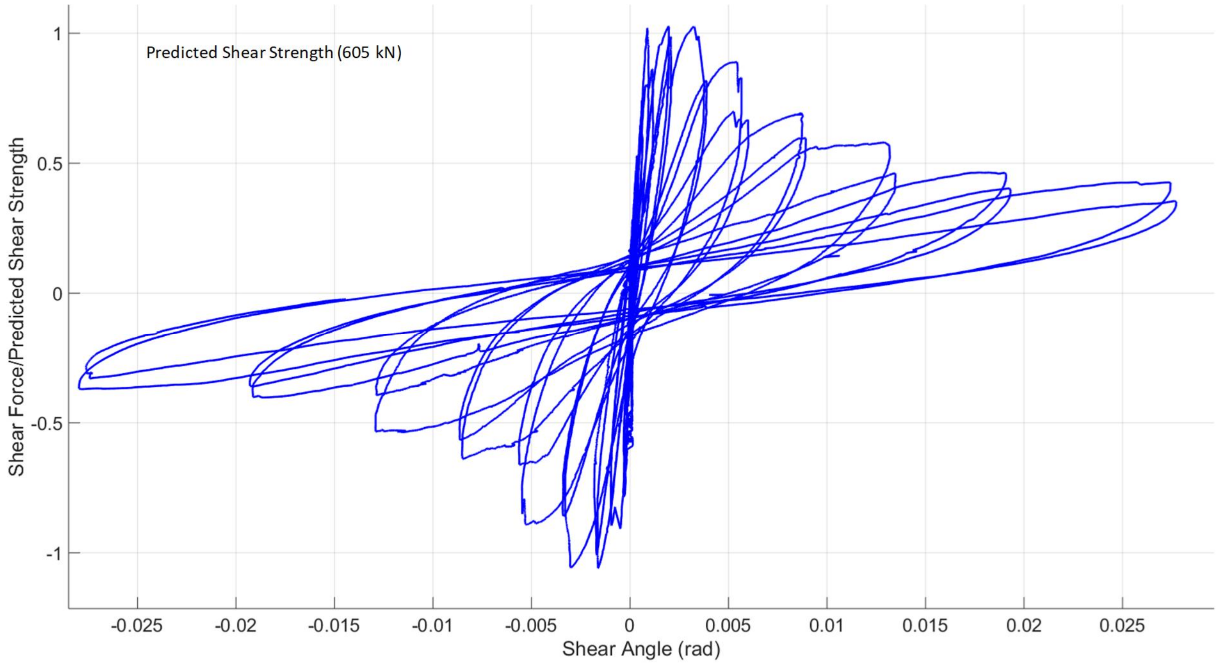

Figure 5. Load Deformation Plot of Specimen 3/6.25-4-L-NF-DT

Specimen 3/7.5-4-N-NF-DT

The failure mode of Specimen 3/7.5-4-N-NF-DT was similar to the previous specimen with some differences in strength loss after cracking. Figure 6 illustrates the progression of the diagonal tension cracking failure for the second tested specimen (3/7.5-4-N-NF-DT). No shrinkage cracking was observed previous to the start of the test. The failure in this specimen occurred in a similar progression as the previous specimen with a distinct "X" crack pattern of the diagonal tension cracks focused on one side of the specimen (Figure 6(c)). As with the previous specimen, this specimen also showed debonding of the concrete slab from the steel deck along the edges and cracking of the overhangs.

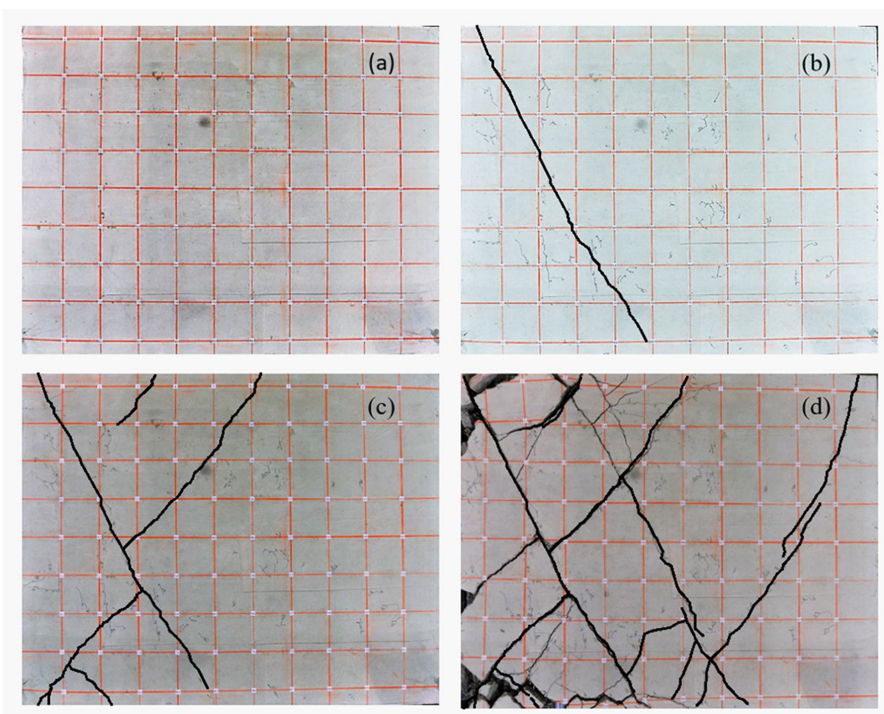

Figure 6. Progression of failure for specimen 3/7.5-4-N-NF-DT. (a) Before testing. (b) First appearance of diagonal tension cracking. (c) First appearance of diagonal tension cracking in opposite direction. (d) Crack pattern past failure

Figure 7 shows the load deformation of specimen 3/7.5-4-N-NF-DT. Specimen 3/7.5-4-N-NF-DT experienced a rapid loss in strength immediately after the first occurrence of diagonal tension cracking. Using the same procedure described for the previous specimen, the ductility of this specimen was calculated as 1.6. Diaphragm ductility is an important parameter in the seismic design of diaphragms, especially in the context of diaphragms that are expected to see inelastic action during design level earthquakes [[1],[2]].

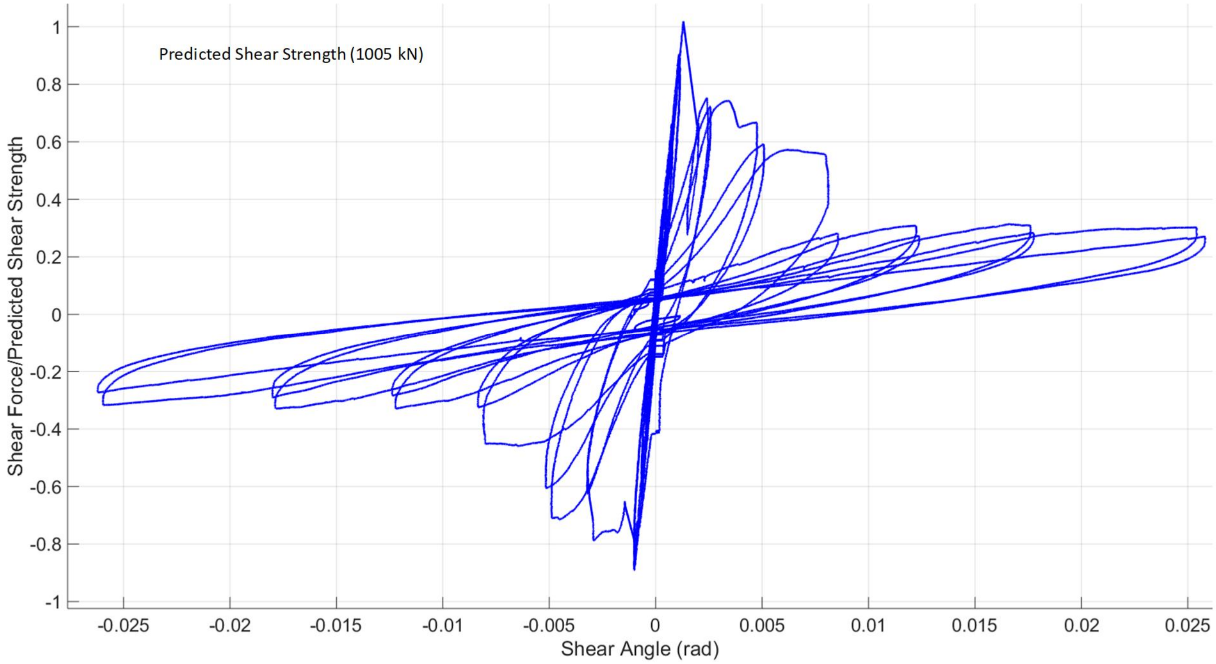

Figure 7. Load Deformation Plot of Specimen 3/7.5-4-N-NF-DT

Strength and Stiffness Results

Table 2 summarizes the strength predictions and results for the specimens tested to date. The results support the proposed modification to existing AISI equations for composite diaphragm strength with a measured strength that is 2% greater than predicted for both specimens. Subsequent testing is required to further validate the use of Equation (1). *Table 2* also summarizes the stiffness results for the specimens tested to date. As described previously, the stiffness is measured using a secant stiffness through a point at 40% of the ultimate shear strength of the specimen. Measured stiffness for Specimen 3/7.5-4-N-NF-DT showed close agreement with the proposed predicting equation while Specimen 3/6.25-4-L-NF-DT, which had lightweight concrete fill, showed a higher stiffness than predicted. Further testing is needed to validate the use of Equation (2) and the associated lightweight factor for predicting the stiffness of composite diaphragms.

Table 2. Strength and Stiffness Results for Tested Specimens

Test Specimen	Predicted Strength (kN)	Measured Strength (kN)	Predicted Stiffness (kN/cm)	Measured Stiffness (kN/cm)
3/6.25-4-L-NF-DT	605	618	1742	2828
3/7.5-4-N-NF-DT	1005	1023	3305	3149

CONCLUSION

This paper investigated the seismic performance of steel deck composite diaphragms through an experimental program that includes six specimens. To date, two cantilever diaphragm specimens have been tested. The results obtained from these specimens support the proposed modification to the AISI equation used to predict the shear strength of composite diaphragms. However, the measured stiffness suggests that more testing is required to validate the use of Equation (2) for predicting the shear stiffness of composite diaphragms. The tested specimens also seem to have inconsistent levels of ductility which warrants further investigation into the sources of ductility in composite slab diaphragms. Subsequent specimens will aim to investigate the effect of concrete type and thickness in ductility as well as the failure of the shear studs used as perimeter fasteners. Four specimens remain in the testing program and are expected to be completed this year.

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