COVER SHEET

Paper Number: 1755

Title: **Creep Behavior of Insulated Concrete Sandwich Panels** with Fiber-Reinforced Polymer Shear Connectors

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ABSTRACT

Insulated concrete sandwich panels has been widely used because of their advantages of light weight and energy efficiency. More recently, research has been conducted to study their applications as roof/floor panels, where long term creep behavior is an important design concern. This paper presents a combined experimental and analytical study on the creep behavior of insulated concrete sandwich panels under bending. Four concrete panels were tested for creep loading. One was a conventional solid reinforced concrete slab and this was used as the benchmark panel. The other three sandwich panels had top and bottom concrete wythes with various thicknesses and a 3" insulation layer in the middle. The wythes were connected with FRP segmental shear connectors. There were also steel reinforcing bars in both the longitudinal and transverse direction.

The tests were conducted with a static load of approximately 13.3 kN (3,000 lbs), which corresponded to the linear-elastic range of the panel's load-deflection curve. The duration of the test ranged from 150 days to 250 days for different panels. It can be concluded that one sandwich panel showed better long-term deflection results than the solid panel. Equations from American Concrete Institute (ACI) Building code and Finite Element (FE) method were used to analyse the panels. Good correlations can be observed between the FE and test results.

INTRODUCTION

The non-linear effects of concrete cracking, creep and shrinkage, when not

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understood, qualified, predicted or designed for, can be a common cause of serviceability failure in concrete structures [1]. As documented by Gilbert and Ranzi [1], approximately 50% of the final creep in a concrete structural member is developed in the first 2-3 months. The remaining 90% of the final creep is then estimated to develop in 2-3 years afterwards. Test data and finite element analysis (FEA) modeling presented in this paper are based on four precast concrete panels subjected to creep loading, which provides the insight to the structural behavior of the sandwich panels under sustained loading and sets the stage for further development.

EXPERIMENTAL PROGRAM

In this paper, three types of analyses and/or data collection are considered for the creep behavior. The first is an analytical model based on theoretical and empirical formulas for concrete creep and flexural behavior of beams. The second form of analysis utilizes the finite element method with Abaqus [2] as the solver. These first two methods are then compared with the third form of data collection which is the creep test itself.

There are four different creep test panels considered in this study. They include: 1) 8" FRP-Confined Precast Concrete Sandwich (FPCS) panel with exterior FRP plate; 2) 10" FPCS panel with exterior FRP plate; 3) 10" sandwich panel with FRP segmental shear connectors but no exterior FRP plate; and 4) 10" solid panel to act as a baseline analysis.

The first panel is the 8" FPCS panel as shown in Figure 1. The panel has the segmental FRP shear connector that anchors the top concrete wythe to the bottom concrete wythe. This panel also has an FRP plate bonded to the top and the sides of the panel.

The second creep test panel constructed and analyzed is the 10" FPCS creep test panel with the segmental FRP shear connector and the FRP plate bonded to the sides and tope of the concrete exterior face. This panel is shown in Figure 2.

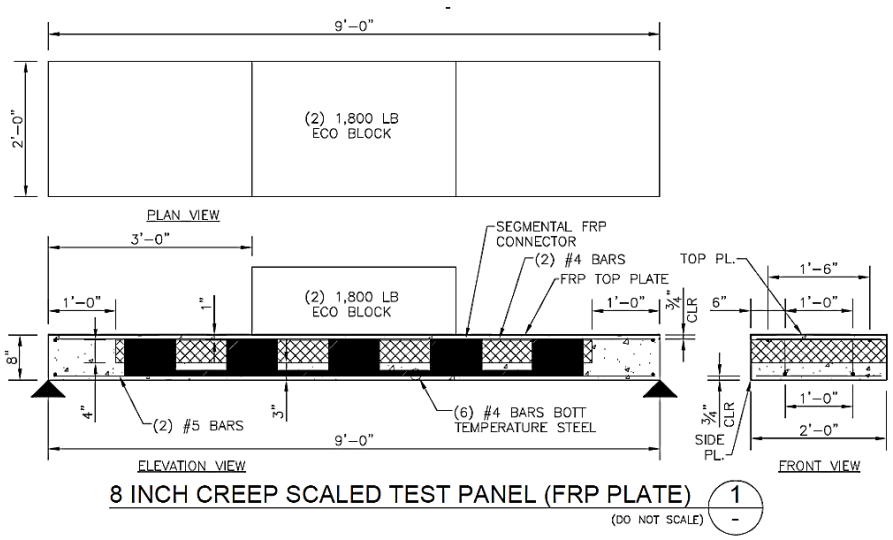

Figure 1 – 8 inch creep test panel with FRP top & side plates (FPCS)

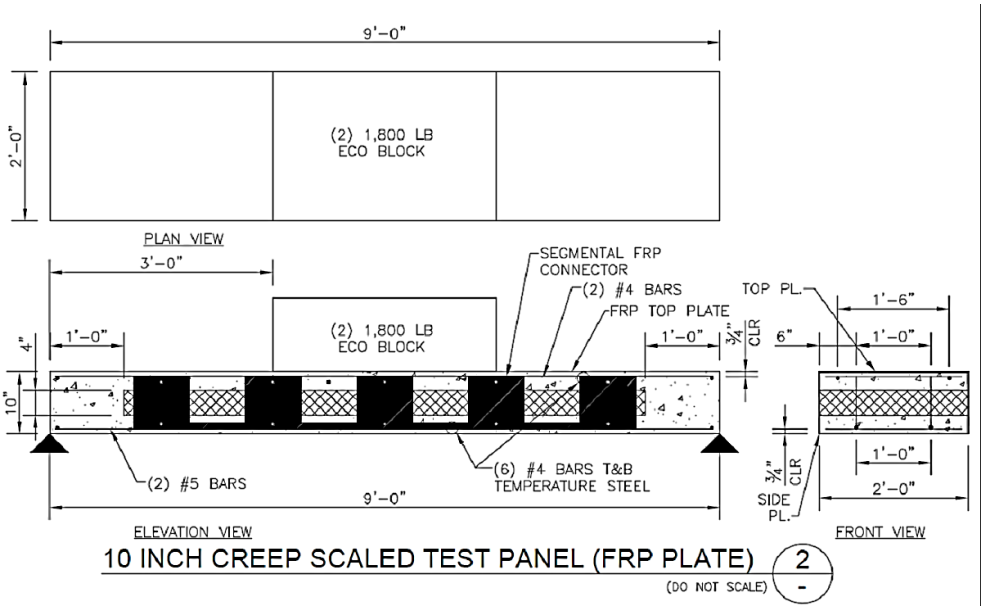

Figure 2 – 10 inch creep test panel with FRP top & side plates (FPCS)

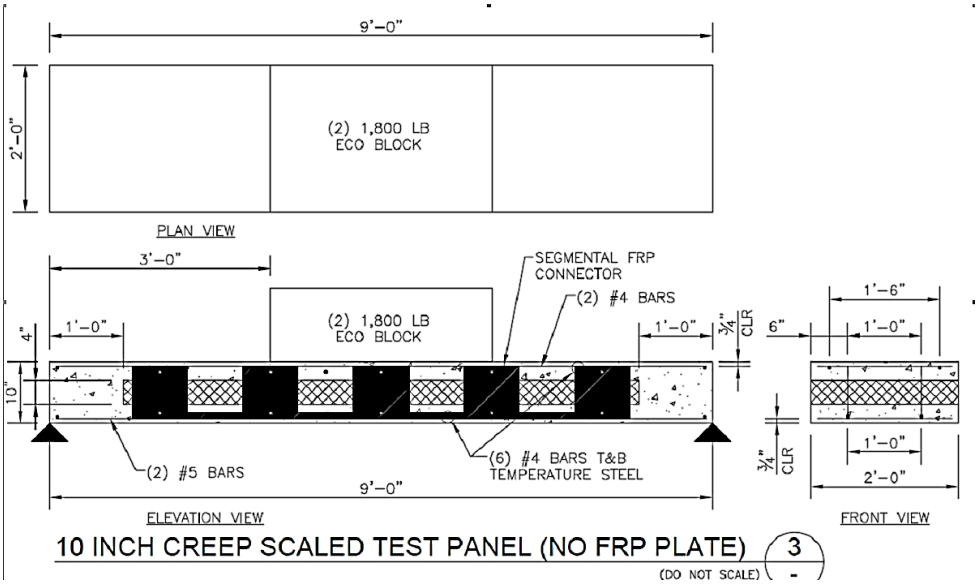

Figure 3 – 10 inch creep test panel with no FRP plate

The third creep test panel is the 10" sandwich panel with the segmental FRP connectors in the upward orientation and no external FRP plates. Figure 3 shows the construction details of this panel.

Finally the 10" solid reinforced concrete test panel, used as the benchmark panel, is shown in Figure 4. This panel is also identical to the 10" solid concrete test panel used in a previous study loaded to failure [5].

A summary of the panel loading and the actual weights of the blocks on each panel is shown in Table I.

TABLE I – CREEP TEST BLOCK WEIGHTS

Specimen	Weight of Block 1 (lbs)	Weight of Block 2 (lbs)	Total Load (lbs)
Solid Slab	1552	1504	3056
10" Sandwich Panel	1540	1542	3082
8" FPCS Panel	1565	1572	3137
10" FPCS Panel	1598	1576	3174

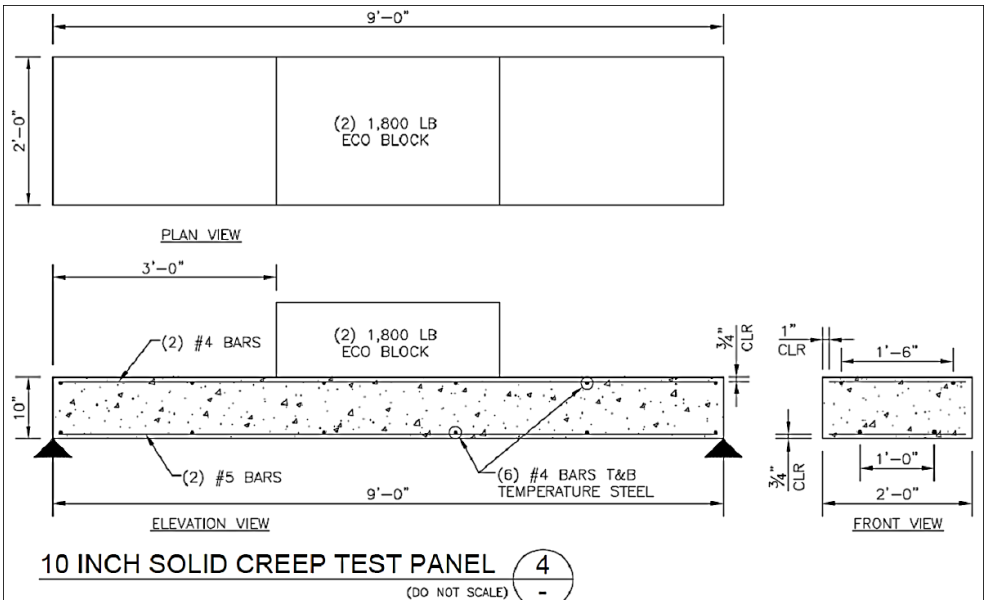

Figure 4 – 10 inch solid creep test panel

ANALYTICAL MODELS

The ACI 318 code [3] has provisions for immediate deflection requirements and long-term sustained load deflection. Sustained loading will create creep strains in the concrete which are additive to the shrinkage strains and the immediate instantaneous loading strain. The sum of the instantaneous deflection due to live loads, the sustained portion of the deflections due to dead load and any sustained live load is provided by the formula in Wight & MacGregor [4]:

$$\Delta = \lambda_{to,\infty}\Delta_{iD} + \Delta_{iL} + \lambda_{\infty}\Delta_{iLS} \qquad (1)$$

where Δ_{iD} is instantaneous deflection due to dead load; Δ_{iL} is instantaneous deflection due to live load; Δ_{iLS} is deflection due to sustained portion of the live load; $\lambda_{to,\infty}$ is long term deflection factor for load applied at time t_o; and λ_{∞} is long term deflection factor for loading longer than 5 years; respectively.

The initial deflection when the concrete panel is placed on the blocks can be derived by the formula:

$$\Delta_{iD} = \frac{5w_{SW}L^4}{384E_C I_{gt}} \tag{2}$$

where the Young's modulus of concrete can be calculated based on ACI 318 [3] as:

$$E_c = 57000 * \sqrt{f'c} = 57000\sqrt{4600} = 3{,}865{,}928\,psi \tag{3}$$

The transformed gross moment of inertia is:

$$I_{gt} = \frac{b_w h^3}{12} + b_w h\left(\frac{h}{2} - y_t\right)^2 + (n-1)A_s(d - y_t)^2 + (n-1)A_s'(d' - y_t)^2 \tag{4}$$

Selfweight of the concrete panel is

$$w_{sw} = b_w h\gamma = (24in)(10in)(0.084\,pci) = 20.139\frac{lb}{in}$$

The length of the panel between supports is L=108 inches. Therefore,

$$\Delta_{iD} = \frac{5w_{SW}L^4}{384E_C I_{gt}} = \frac{5(20.139lb/in)(108^4)}{384(3{,}865{,}928\,psi)(2101.4in^4)} = 0.0044in \tag{5}$$

Following the same method, Δ_{iTL} can be calculated as 0.0172371". Therefore, the instantaneous live load deflection then becomes:

$$\Delta_{iL} = \Delta_{iTL} - \Delta_{iD} = 0.0172371 - 0.0047 = 0.0125in \tag{6}$$

The multipliers for incremental time are shown in Table II.

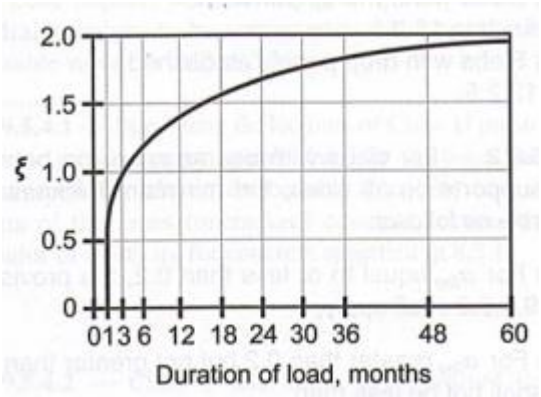

Figure 5 – ACI multiplier for long term deflection (ACI 318 [3], Figure R9.5.2.5)

TABLE II – ACI LOAD DURATION MULTIPLIERS

Duration of Load (months/days)	Mulitplier (ξ)
1/30	0.5
3/90	1
6/180	1.2
12/365	1.4

The compression steel ratio is:

$$\rho' = \frac{2\left(0.20in^2\right)}{\left(10in\right)\left(24in\right)} = 0.0017 \tag{7}$$

The sustained load multiplier is [3]:

$$\lambda_\Delta = \frac{\xi}{1+50\rho'} \tag{8}$$

The sustained load factor (λ_Δ) from ACI 318 [3] Equation 9-11 and the resulting deflections are shown in Table III.

For reference, the plot of the solid slab creep deflection is shown in Figure 6 and the duration was set for 365 days. This represents the standard code-based analytical method currently available to the engineer. The ACI figure will be compared to the test data and FEA analysis later in this paper.

TABLE III – ACI SUSTAINED LOAD FACTORS AND DEFLECTIONS

Time (days)	Variable (ξ)	Variable (λ_Δ)	10" Solid (in)	8" Solid (in)
0	0	0	0.012537	0.023968
30	0.5	0.460829	0.02048	0.038389
90	1	0.921659	0.028424	0.052811
180	1.2	1.105991	0.031601	0.058579
365	1.4	1.290323	0.034779	0.064348

10" Solid (in)		8" Solid (in)	
Δ_{iD}=	0.0047	Δ_{iD}=	0.007326
Δ_{iTL}=	0.017237	Δ_{iTL}=	0.031294
Δ_{iL}=	0.012537	Δ_{iL}=	0.023968

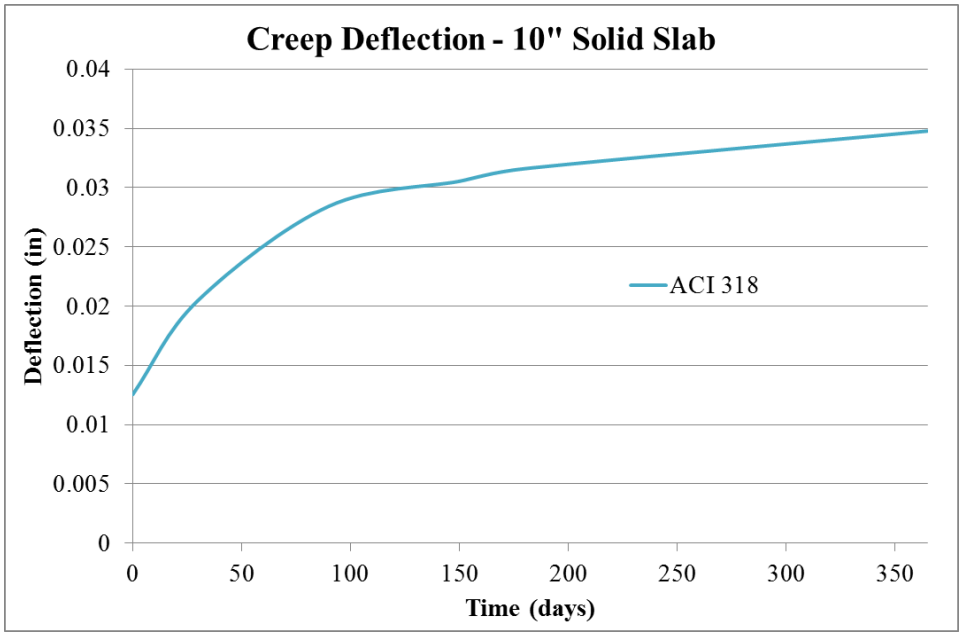

Figure 6 – Analytical creep deflection, ACI 318

EXPERIMENTAL INVESTIGATION

The four specimens were statically tested with 3-point bending as a simply supported beam and loaded with two ecology blocks as shown in Figure 7, Figure 8 and Figure 9, respectively. The weights of the ecology blocks were provided in Table I. Further detail of the test set up is explained in [5].

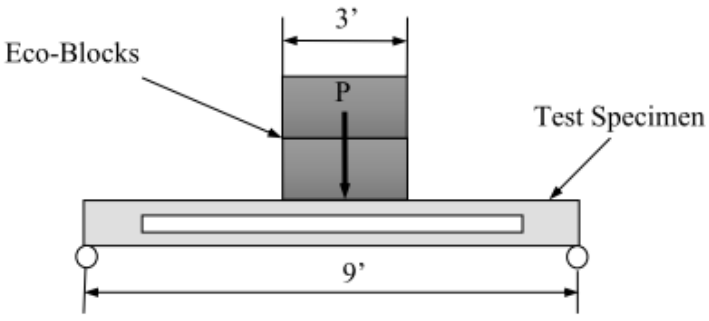

Figure 7 – Creep test loading diagram

Figure 8 – Creep test set up for 10" FPCS panel

Figure 9 – Creep test panel set up for 8" FPCS, 10" sandwich and 10" solid panel

All creep test panels were covered with a tarp. In Figure 8, the 10" FPCS panel was placed on the loading dock under the building canopy and therefore never received any direct sunlight. Three of the panels were located in the open environment as shown in Figure 9. These three panels were set up outside in the driveway and are indicated as items 1, 2 and 3 in Figure 10. These three panels also resulted in the highest deflection values which presumably were influenced by shrinkage creep and mechanical breakdown in the interstitial zones due to temperature fluctuations from day to night. In the plot shown in Figure 10, areas are highlighted and numbered with explanations as follows:

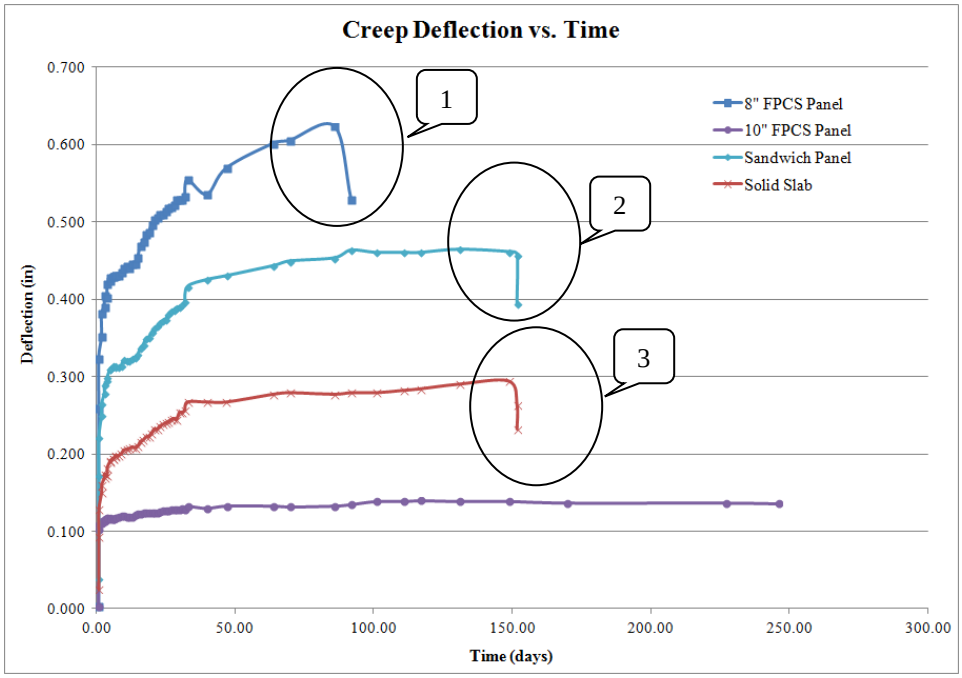

Figure 10 – Creep deflection vs. time, Norris [5]

1. The dial gages had been moved at this panel such that they no longer recorded any data. For that reason, deflection data acquisition at this panel was halted.
2. At 150 days the load was removed from the panel and the elastic recovery in the sandwich panel is shown.
3. At 150 days the load was removed from the panel and the elastic recovery in the solid panel is shown.

The testing of the four panels for creep deflection was performed in an uncontrolled and exterior environment. Notable factors/influences regarding the testing of these panels for the 150 day duration are as follows:

1. The panels were outside.
2. The panels were not protected/secured from public or natural disturbances.
3. The creep deflection of the panels is both influenced by mechanical creep strain along with shrinkage creep strain. Thermal strain cannot be ruled out, however it most likely had less of an effect when compared to the shrinkage creep and the arid climate it was tested.

The mid-span deflection vs. time of the four panels was compared to the quarter point deflections and these deflection plots can be seen in Figure 11. The three exterior panels shown in Figure 9 have the highest initial peak deflection at the placement of the load then the recordings taper off as normal creep deflections occurred over time.

Analytical hand calculations were performed on the solid slab along with finite element analysis and the initial deflection of the solid slab with the two ecology blocks are 0.014 inches and 0.031 inches, respectively, as shown in Table IV. The initial deflection of the solid slab in Figure 11 is 0.124 inches and this is an order of magnitude higher than both of the hand calculation and finite element analysis results. Adjusting for this discrepancy is the quarter point deflection comparison with no initial deflection as shown in Figure 12.

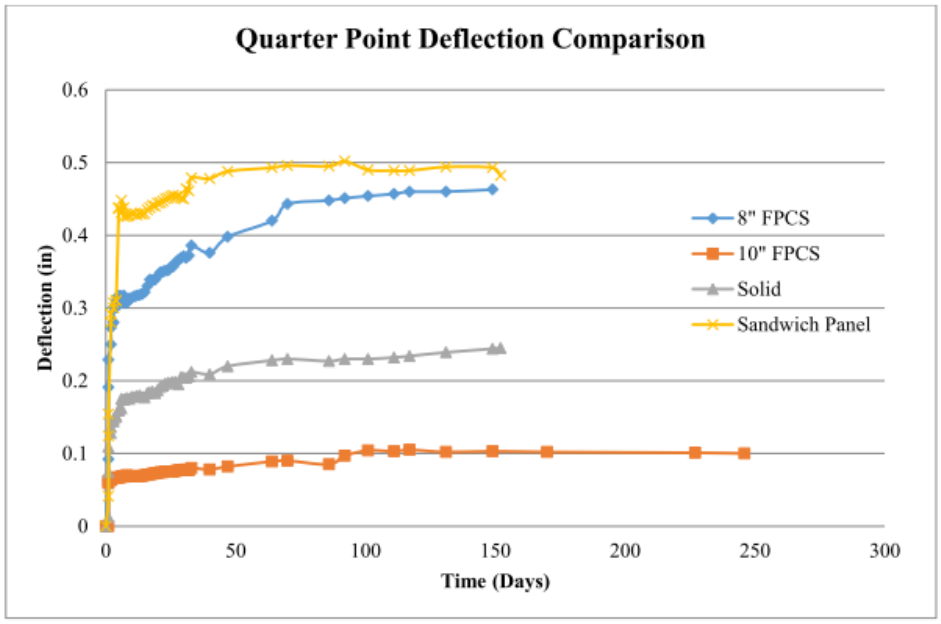

Figure 11 – Quarter point deflection vs. time, Norris [5]

Even with the no initial deflection adjustment, there still remains a sharp increase in deflection at the early stages of the test. Quite possibly the panels had experienced a high level of shrinkage creep strain and this caused the panels to deflect rapidly in the beginning stages of the test and/or support settlement. The panels were placed on test blocks and loaded in July of 2013 and this is the height of the hot and dry seasonal environment in Moscow, ID, where the panels were located. Furthermore explanations of the data collected were provided in [5].

TABLE IV – 10" SOLID PANEL DEFLECTION CALCULATIONS

10" Solid Reinforced Concrete Panel		
Analysis Method	Load	Midspan Deflection (in)
ACI 318	Selfweight + 3,056 lbs	0.014
Finite Element Analysis	Selfweight + 3,056 lbs	0.031

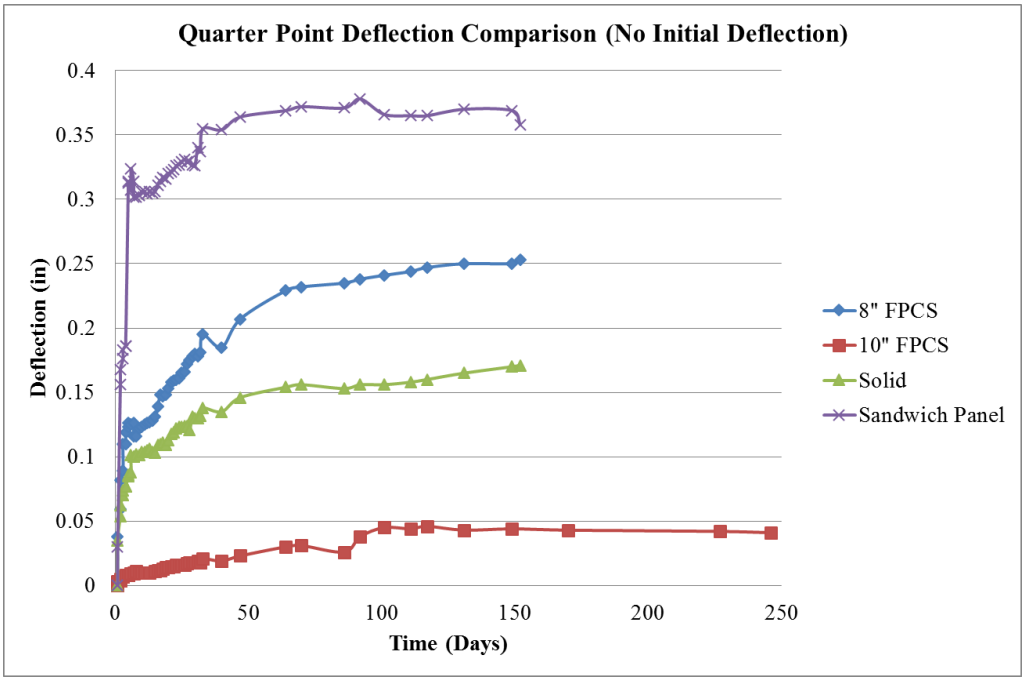

Figure 12 – Quarter point deflection vs. time, no initial deflection

FINITE ELEMENT ANALYSIS

Creep effects in concrete structures has been studied since the 1970's and many analytical models have been published in codes such as the ACI model, the Comite Euro-Internationale du Beton (CEB), Federation international de la precontrainate (FIP) model, the Japan Society of Civil Engineers (JSCE) model, the Gardner and Lockman (GL) model and Model B3. Evaluation of existing commercial software programs and the code-based models themselves, i.e., ACI 209 [6], [7], show that they underestimate the effects of multi-decade creep in large-span prestressed bridges [8]. Yu [8] and others have studied and documented concrete creep models for over 30 years and have shown that a successful concrete creep model is based on many constituent sections and algorithms that account for water-cement ratio, temperature, relative humidity, prestress loss, and sun exposure to name a few. Bazant et al. [9] have commented that engineers strive to find a model to predict creep and shrinkage from as few parameter as possible. Specifically, they intended to use only the strength of the concrete as the sole design variable to determine the concrete creep strain. A model such as this would be more convenient and user-friendly, however it is not realistic and therefore a rigorous model, well tested against suitable number of specimen results over a long period of time, should be developed and used.

Simple Creep Power Law – Strain Hardening

Abaqus [2] includes in its solver a few different creep models that can be used in lieu of creating a UMAT subroutine. One approach is to create a subroutine that incorporates the engineering properties of the concrete materials. The approach taken here is to use the simplified creep power law function and fit it to the solid panel test data. Next step is to verify the same formula on the FPCS sandwich panel and then

extrapolate that out to several years (since the test was only 180 days). From Abaqus User's Manual, Section 23.2.4, the equivalent deviatoric creep strain increment is determined by the following equation:

$$\dot{\varepsilon}_{cr} = \left(A\tilde{q}^{n}\left[(m+1)\bar{\varepsilon}^{cr} \right]^{m} \right)^{\frac{1}{m+1}} \qquad (9)$$

where, $\bar{\varepsilon}^{cr}$ is the equivalent creep strain, $\tilde{q}$ is the uniaxial deviatoric stress, *t* is the total time, and *A*, *n* and *m* are defined constants and functions of temperature. For the 10" solid concrete creep test panel the following values were used for the defined constants:

A = 1E-09
n = 2.25
m = -0.5

These values were obtained through curve fitting functions in excel from the actual creep test data plots.

TEST RESULTS VS. ANALYTICAL AND FE PREDICTIONS

The creep tests in this study provide a preliminary idea of how the sandwich panels, in particular the FPCS sandwich panel, perform over the duration of static linear loading. Considering the data in generalized form and ignoring severable variables and factors, a simple power creep law model can be used to show correlation to the test panels and then provide a generalized and conservative prediction to the long term effects. The 10" solid panel, both test data and FEA data, is shown in Figure 13. In the FEA model the initial selfweight of the panel is measured as the first step, and then the applied creep load is incorporated as the subsequent step for the allotted time duration. The power law previously described matches well with the available data. It is interesting to note the ACI 318 creep equation plot is vastly under-conservative.

With this generalized simple creep power law showing good correlation to the test data, it can then be used for the 10" FPCS sandwich panel to see how well it matches that test data. The comparison between the solid panel and the FPCS sandwich panel is shown in Figure 14.

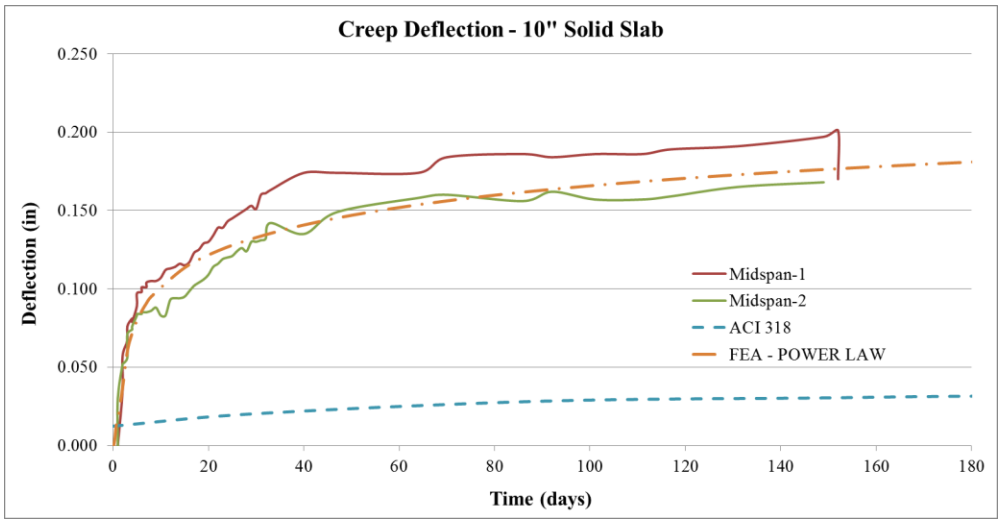

Figure 13 – 10 in. solid concrete creep test panel 4 deflection

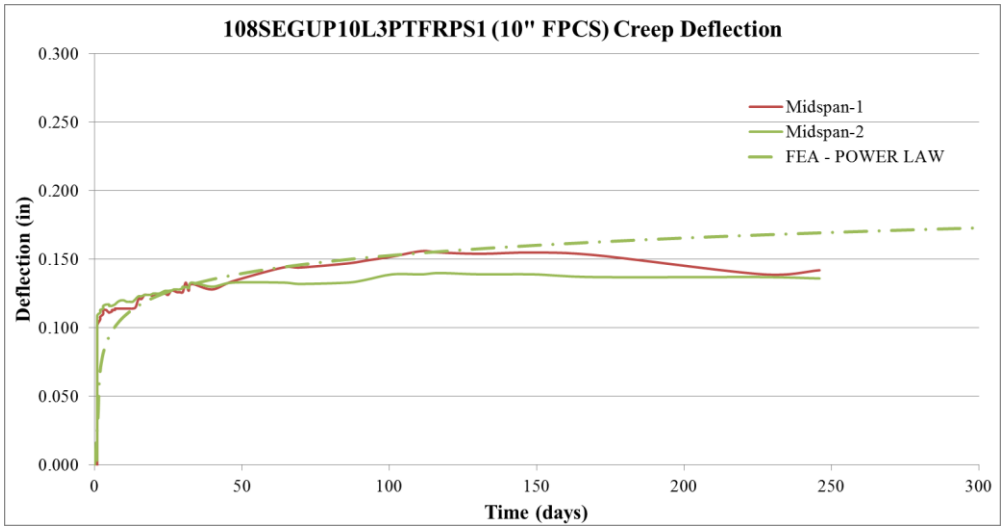

Figure 14 – 10 in. FPCS sandwich creep test panel 2 deflection

The power law used for the FPCS sandwich panel is providing conservative results for the 180 day span and can be considered as the upper limit to this approach. When extrapolating that curve out to 30 years the estimated final creep deflection is less than 0.25 inches which can be seen in Figure 15. For the 9' span, the 0.25 inch deflection would constitute a deflection ratio of L/432 which is acceptable per building code and ACI standards. Once again the load on the panel, which distributed into a surface load is:

$$W = (3{,}174 \text{ lbs})/(2' \times 9') = 176 \text{ psf} >>> \text{than any service live load}$$

The load is not distributed over the surface of the panel. However when considering the total load of the ecology blocks over the area of the panel, the surface live load is far greater than any code specified pressure load such as 20 psf for roofs, or additional dead

load material weights or even snow loading. Therefore, considering the estimated 30 year creep deflection of L/432 with this loading is remarkably good and acceptable.

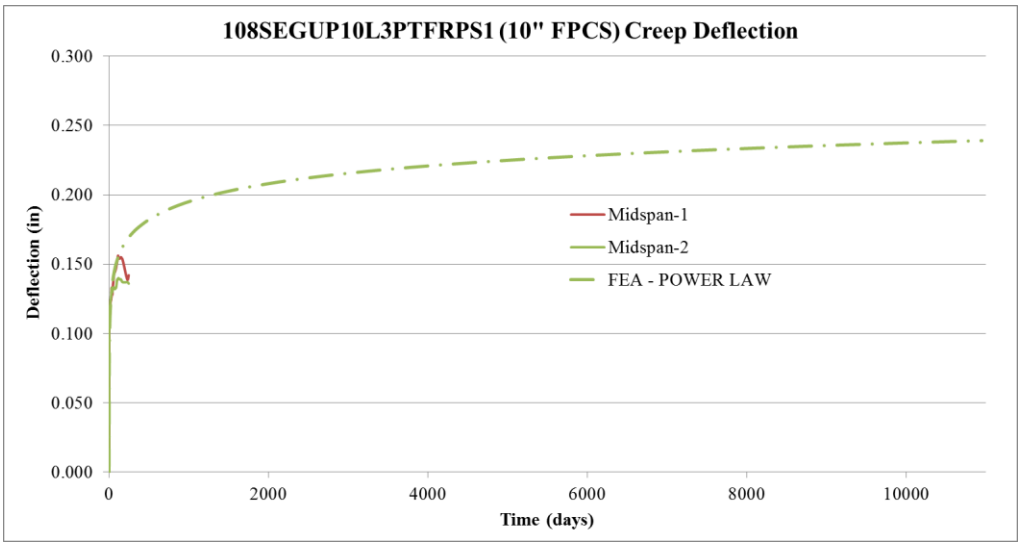

Figure 15 – Estimated long term creep effects for 10" FPCS panel

CONCLUSIONS

The four panels tested for creep loading in this research varied in type of construction and in some cases environmental influences. Three of the panels were outside and covered with a tarp during the test and one panel was under a building canopy at a loading dock, also covered. The 10" FPCS panel showed the best creep results because of the confining effect provided by the FRP enclosure. The 8" panel showed the highest deflections over the same time period.

ACI equations were used to calculate the creep deflections. An FEA is presented in this paper and the FEA results correlated well with the test results. Although with the variability in the loading and the environmental effects, it is difficult to develop an FE analysis creep model to capture the effects of the test accurately and then to extrapolate that to long-term predictions, this FEA model can be further improved by using one of the published creep subroutine models by Bazant et al. [8] or another accepted constitutive model. These algorithms have several variables in the subroutine that need to be accounted for to provide an accurate creep prediction. This will be done in a following study.

It is noted that only one panel was tested for each type with limited time period. Future creep testing can be conducted where two of each type of panel will be tested in a controlled temperature and humidity environment. The panels can be tested for a much longer time to be correlated with the creep analysis model based on the algorithms presented by Yu et al. [8].

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REFERENCES

1. R. I. Gilbert and G. Ranzi, *Time-dependent behaviour of concrete structures*. CRC Press, 2010.
2. ABAQUS, "ABAQUS Documentation." Dassault Systèmes, Providence, RI, USA, 2013.
3. ACI Committee 318, *Building Code Requirements for Structural Concrete (ACI 318-08)*. Farmington Hills, MI, 2011.
4. J. K. Wight and J. G. MacGregor, *Reinforced Concrete: Mechanics and Design*, 6th ed. Prentice Hall, 2011.
5. T. G. Norris, "Bending Behavior of Insulated FRP-Confined Concrete Sandwich Panels with FRP Plate Shear Connectors," University of Idaho, Moscow, ID, 2014.
6. ACI Committee 209, *Prediction of Creep, Shrinkage and Temperature Effects in Concrete Structures*. Farmington Hills, MI: American Concrete Institute (ACI), 2008.
7. ACI Committee 209, *Guide for Modeling and Calculating Shrinkage and Creep in Hardened Concrete*. Farmington Hills, MI: American Concrete Institute (ACI), 2008.
8. Q. Yu, Z. P. Bazant, and R. Wendner, "Improved algorithm for efficient and realistic creep analysis of large creep-sensitive concrete structures," *ACI Struct. J.*, vol. 109, no. 5, 2012.
9. Z. P. Bažant, Q. Yu, and G.-H. Li, "Excessive Long-Time Deflections of Prestressed Box Girders. I: Record-Span Bridge in Palau and Other Paradigms," *J. Struct. Eng.*, vol. 138, no. 6, pp. 676–686, Jun. 2012.
10. Z. ˇk P. Bažant, Q. Yu, and G.-H. Li, "Excessive Long-Time Deflections of Prestressed Box Girders. II: Numerical Analysis and Lessons Learned," *J. Struct. Eng.*, vol. 138, no. 6, pp. 687–696, Jun. 2012.