PDHonline Course S244 (11 PDH)

Engineered Design of Structural Insulated Panels (SIPs)

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Beyond Code Reports: Taking SIPs From Data to Design

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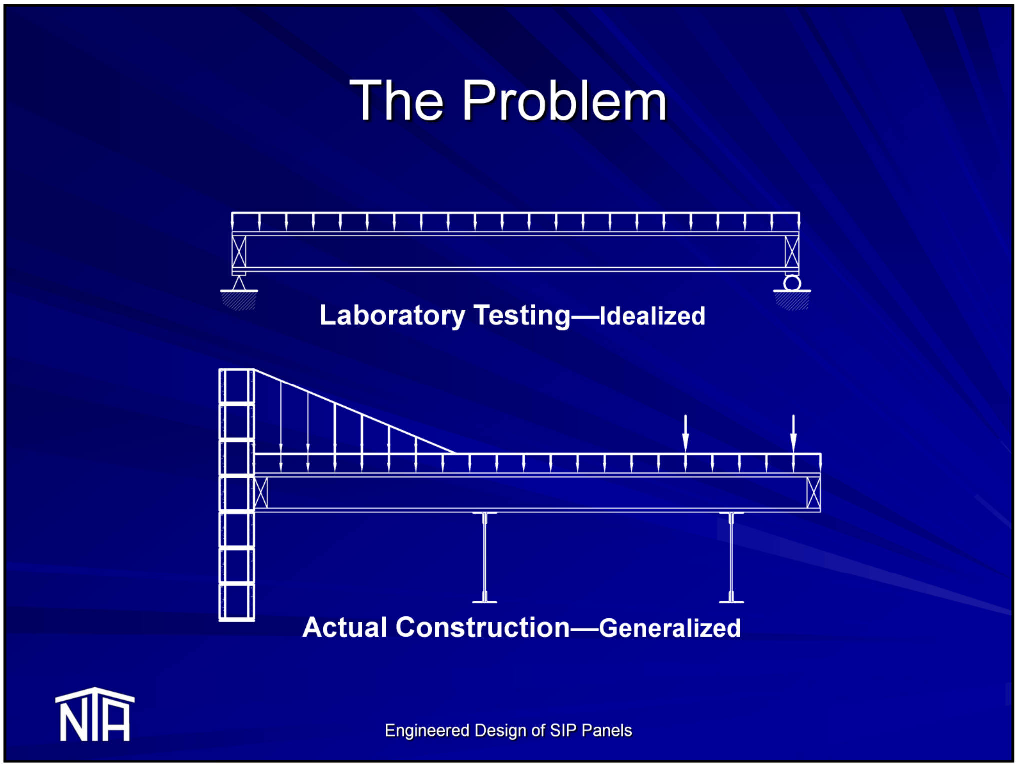
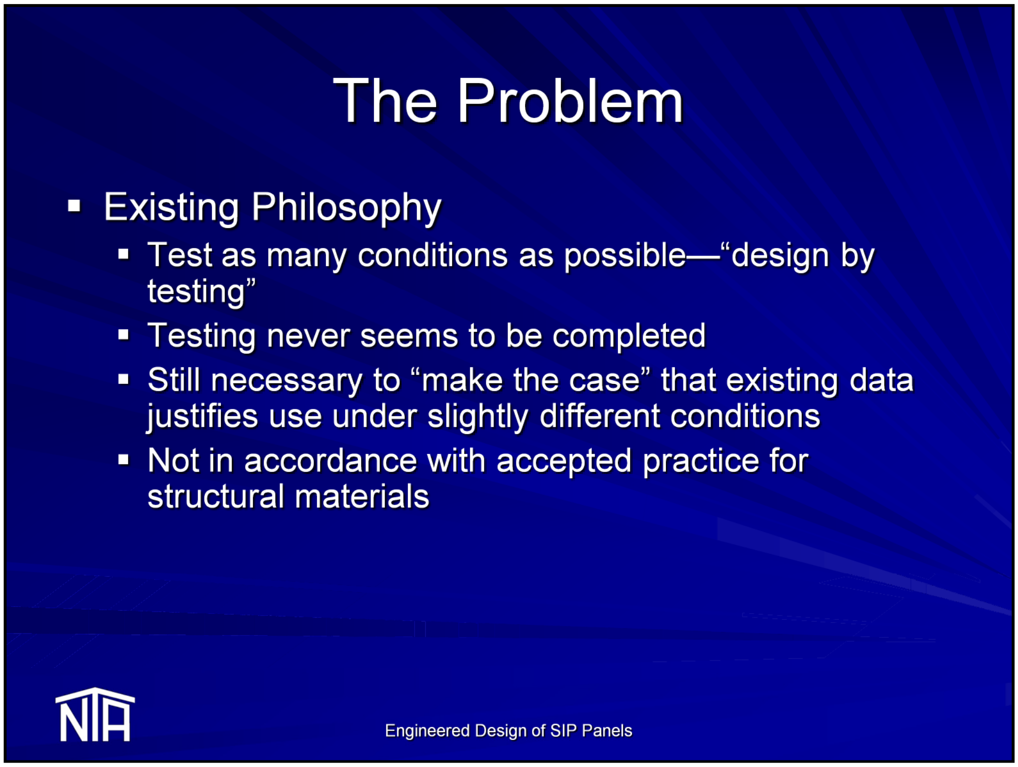


In the laboratory, specimens are tested under idealized conditions. For example, transverse load tests are typically conducted on full-size panels with simple supports and uniform loads (shown at top).

However, in actual structures such conditions rarely exist. For instance, a typical flat commercial roof (shown below) may have support and loading conditions that are much different—drifting around the parapet creates trapezoidal loading, HVAC equipment creates points loads, and these loads are applied to a panel that is continuous over multiple supports.

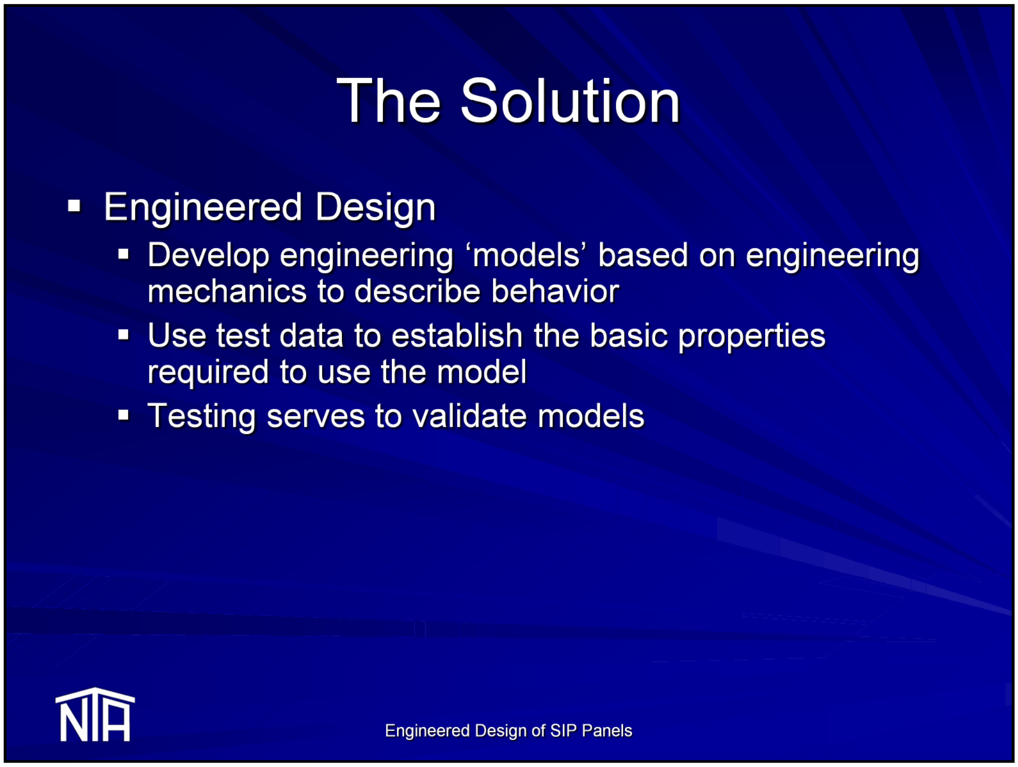
How can panels loaded in such as way be justified using the current SIP qualification techniques? The problem isn't the testing methods; it is how the data is used after the testing is completed.



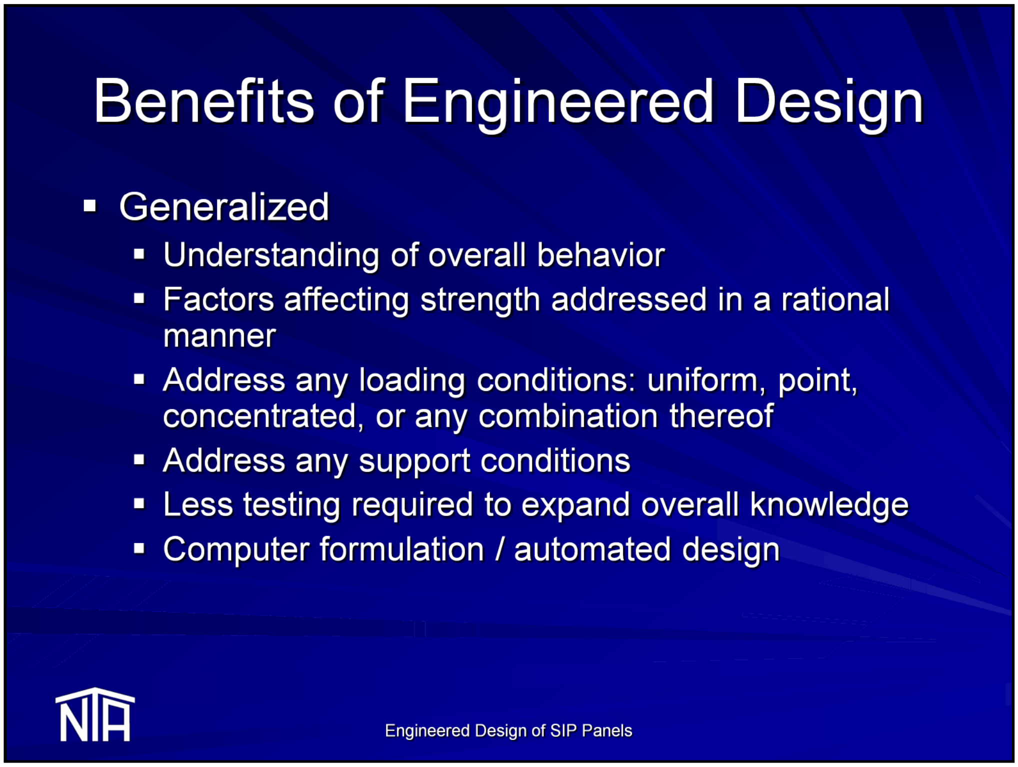
The current certification philosophy entails testing as many support and loading conditions as possible and provide a summary of these conditions in a code report or manufacturer's literature.

Under this philosophy, gaps will always exist and SIP manufacturer's will always have to "make the case" as to how their test data justifies the use of their panels under conditions different than those that were tested. This "case" is typically made by overwhelming them with data—"we spent $300,000 on testing and have 100's of test reports so it must work."

Not only is this philosophy expensive, time consuming, and reduces the credibility of the industry, but it is NOT in accordance with accepted practice for the qualification of structural materials.

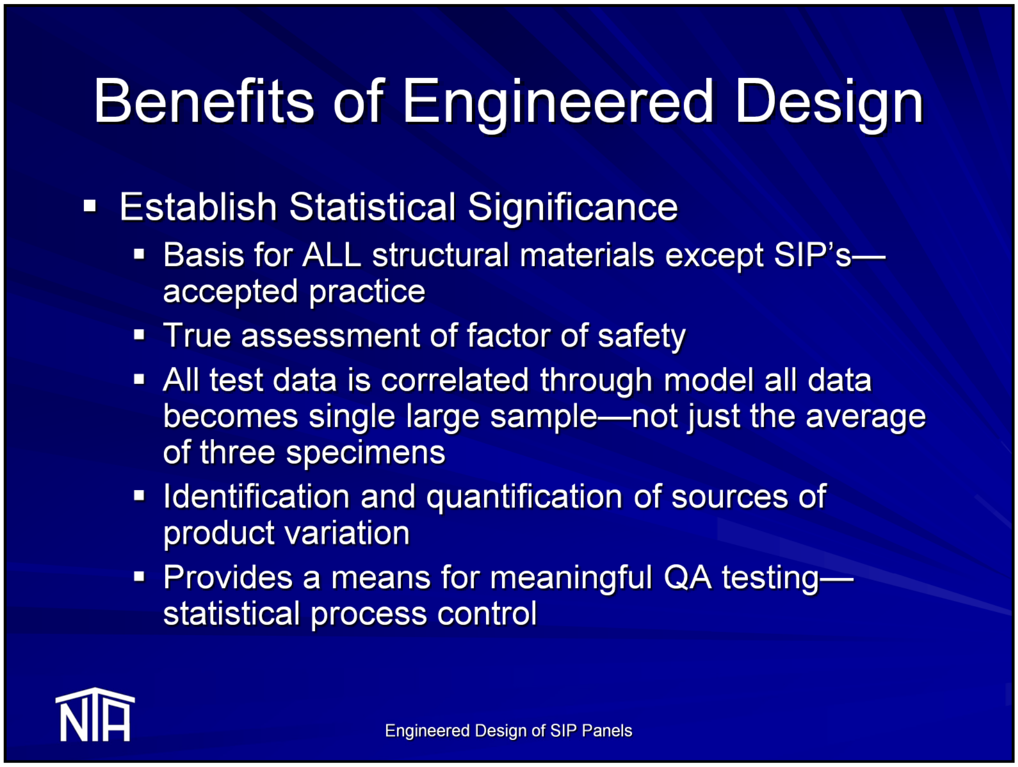


The solution to this problem is "engineered design". This approach requires the development of engineering formula's, or models, to describe the behavior of SIP panel in general terms. Once the models are established, test data are used to establish the basic properties required to use the models. Instead of the existing "design by testing" philosophy, the purpose of the testing is to validate the models.



The benefits of this approach are many. Most importantly, this approach provides a understanding of overall panel behavior. It allows us to see the big picture. As part of this, factors affecting strength are addressed in a rational manner. And, because the models are based on engineering principles the models are "generalized", meaning that analysis can be performed to address any loading or support conditions regardless of what was tested.

Economic benefits of this approach are obvious, because the behavior is understood, less testing is required to address new conditions or concerns that may arise. Additionally, an engineered design approach facilitates computer formulation and automated design—a necessity in today's fast-paced building environment.



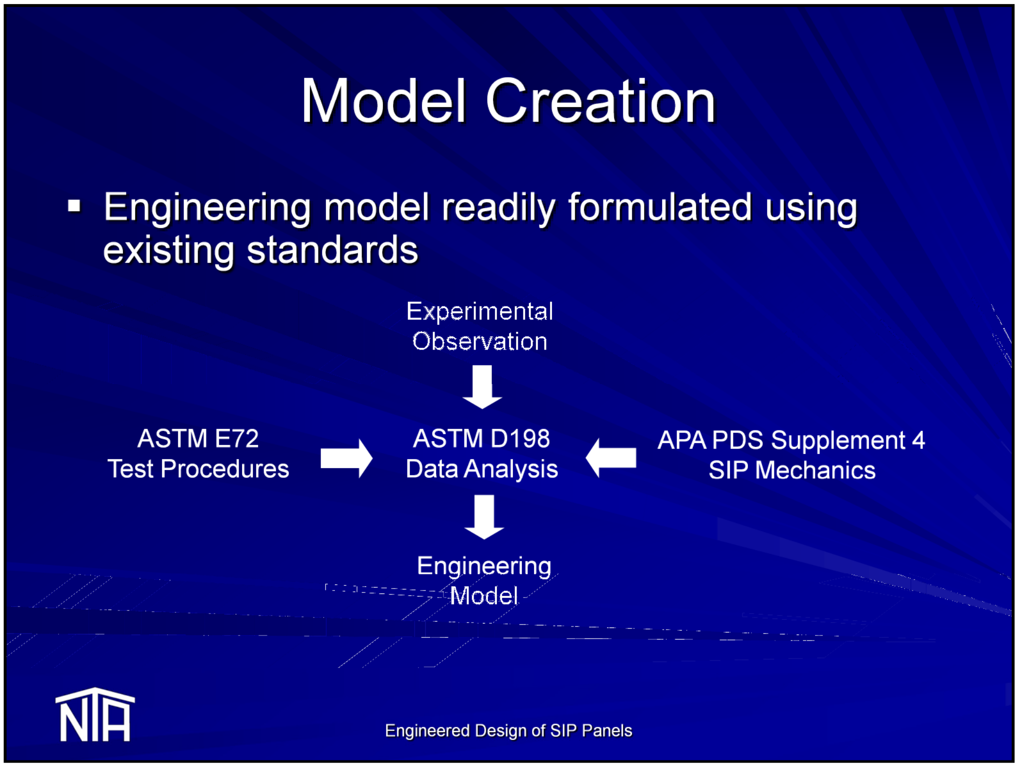
An additional benefit of engineered design that is less obvious is that it becomes possible to establish statistical significance. While "hidden" in the design procedures for common engineering materials, there is a statistical basis for all structural design. Structural loads are based on observed probabilities of occurrence and then adjusted to a required interval. While a material's ability to resist imposed loads is based on variability in strength and required strength confidence levels.

The existing methodology for establishing the strength of SIP panels is out of step with accepted practice in this regard. Testing three specimens and dividing the average by three is simple, but leaves much to be questioned. Such as, are the qualification procedures providing a consistent and appropriate factor of safety? Is it overly conservative or? What is the "true" factor of safety?

These questions cannot be answered with existing procedures. However, by establishing an engineering model of behavior it is possible to combine data from panels of all thicknesses and all spans into a single larger sample. With this larger sample it becomes possible to address these questions.

Additionally, outlying data becomes obvious making potential sources of material variation readily apparent. Similarly, in-plant QA testing becomes more meaningful through the use of statistical process control.

Now that some of the benefits have been explained, let's explore exactly how an engineering design approach can be developed for SIP panels.



Engineered design relies on “models” that describe behavior based on engineering mechanics. For SIP panels, sufficient standards already exist to formulate these models, it is just a matter of bringing all the pieces together.

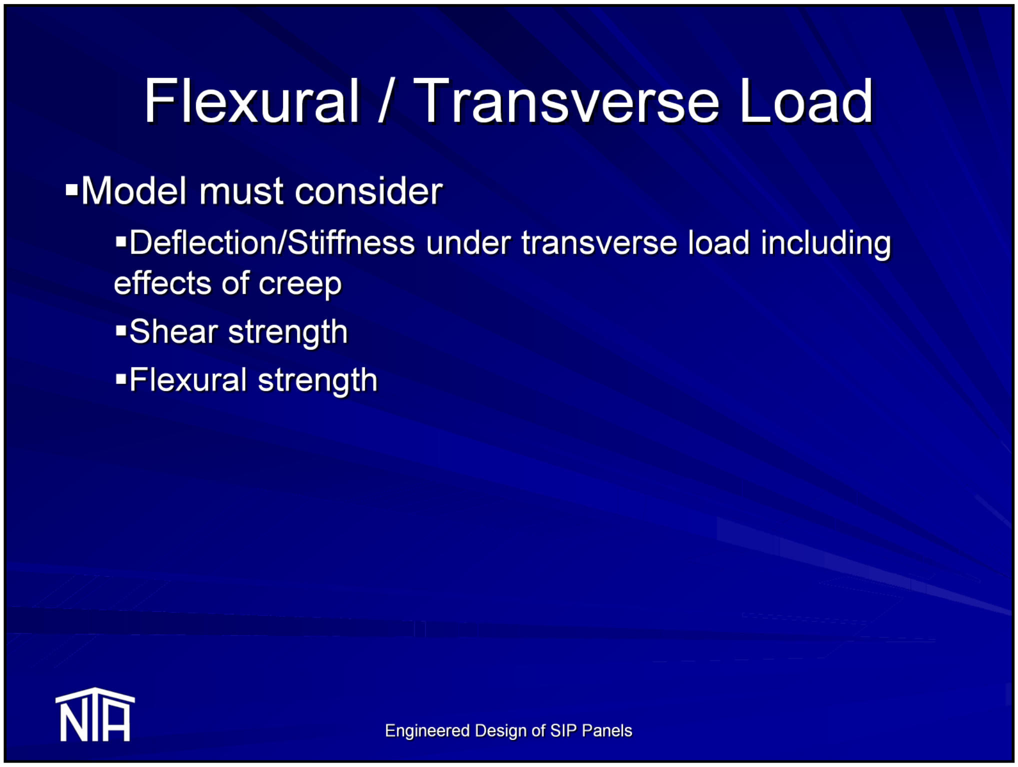
These pieces include:

1) ASTM E72, which provides test procedures for basic idealized loading scenarios, but provides no guidance on how to use the data.

2) APA Plywood Design Specification, Supplement 4, which provides engineering models for SIP behavior, but provides no guidance on how to establish the material properties to use in the models

3) ASTM D198, serves as the bridge between E72 and the APA PDS, Supp. 4. This standard, while written for lumber, provides data analysis methods for converting laboratory data into engineering properties.

Using these three standards, and guided by experimental observation, permits us to establish accurate engineering models for SIP panels. Details of a proposed engineering model will now be described; starting with flexural / transverse loading.



Based on basic engineering principles any model for SIP behavior under transverse loads must consider the following:

1) Deflection or bending stiffness under transverse loads. And, like most engineering materials, it is important that the effects of creep are addressed.
2) Shear strength
3) Flexural strength

Flexural Stiffness Model

- Simply supported deflection equation including shear under uniform loads[1]:

$$\Delta = \Delta_b + \Delta_s = \frac{5wL^4 \times 1728}{384E_b I} + \frac{wL^2}{4(h+c)G}$$

- From each E72 test calculate apparent bending modulus, E_a, from deflection data
- Calculate a value, *Ks*, which quantifies geometric parameters: panel thickness, span and loading condition
- Using all E72 data to determine pure bending modulus, E_b, and shear modulus, *G*

[1] APA. *Plywood Design Specification Supplement 4: Design and Fabrication of Plywood Sandwich Panels.* Document U814-H. March 1990.

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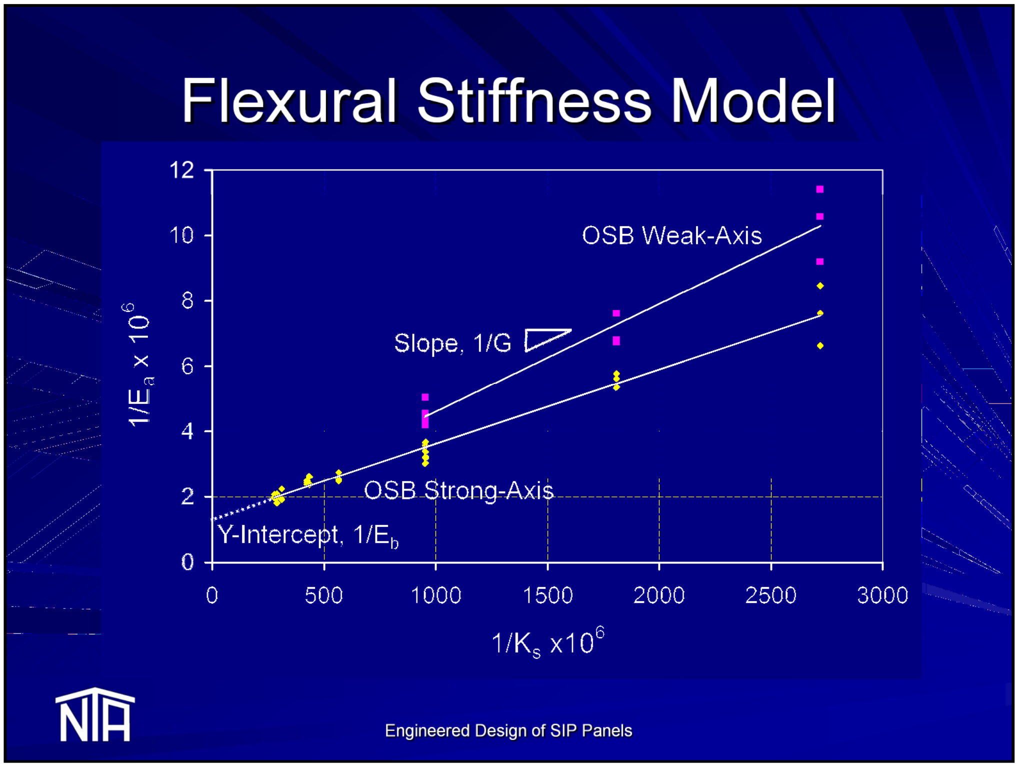
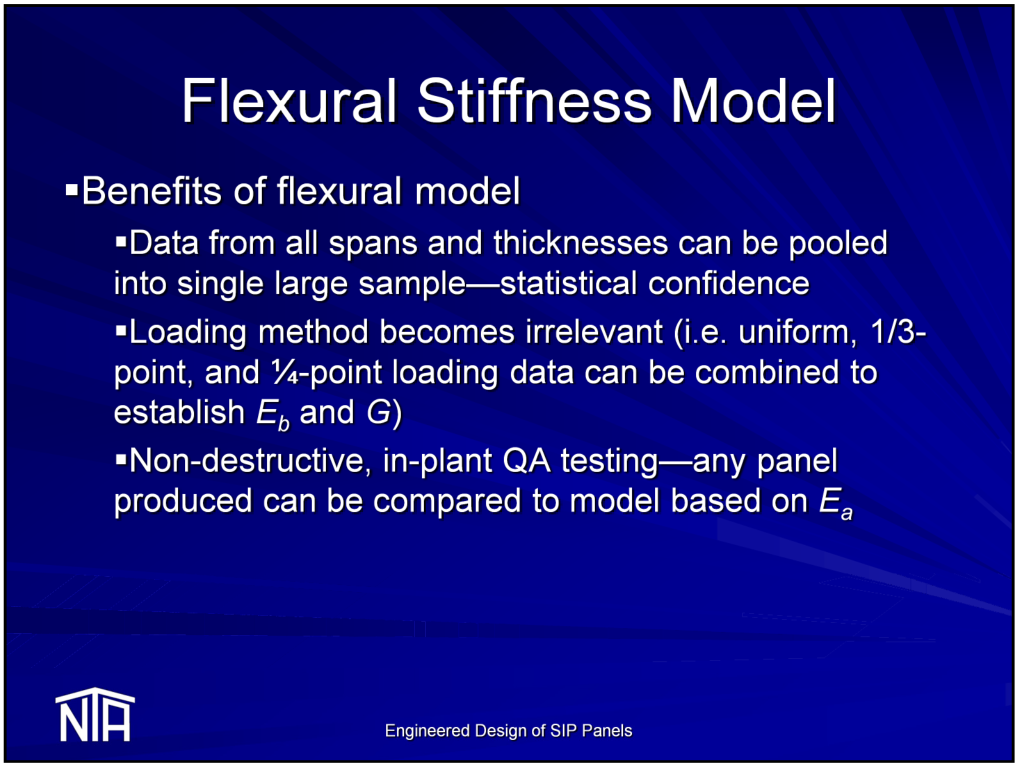
Engineered Design of SIP Panels

Starting with flexural stiffness. SIP panel stiffness, unlike all common engineering materials, is governed by the shear stiffness of the core. This fact requires modification of some familiar engineering equations. To account for this, the deflection equation of a simply supported beam under uniform load must be modified to include an additional term and property, the shear modulus, represented as *G* in the equation. This deflection equation contains two unknown values, the elastic modulus, *E*, and the shear modulus, *G*, all other values can be determined from the geometry of the SIP and the loading conditions.

As you know, in order to solve for two variables it is necessary to have at *least* two equations that relate the variables. Accordingly, to solve for E_b and *G* it is necessary use ASTM E72 data from multiple spans and depths.



Each ASTM E72 data point can expressed in terms of two values: the apparent modulus of elasticity, E_a, and a shear constant, K_s, which is calculated based on the geometry of the panel and loading conditions. As shown in the resulting plot, the test data correlate very well using the proposed stiffness model. Additionally, a best fit line through the data permits us to find the pure bending modulus, E_b (Y-intercept), and the shear modulus, G (slope). As expected, the values for E_b and G vary with the orientation of the OSB facing.

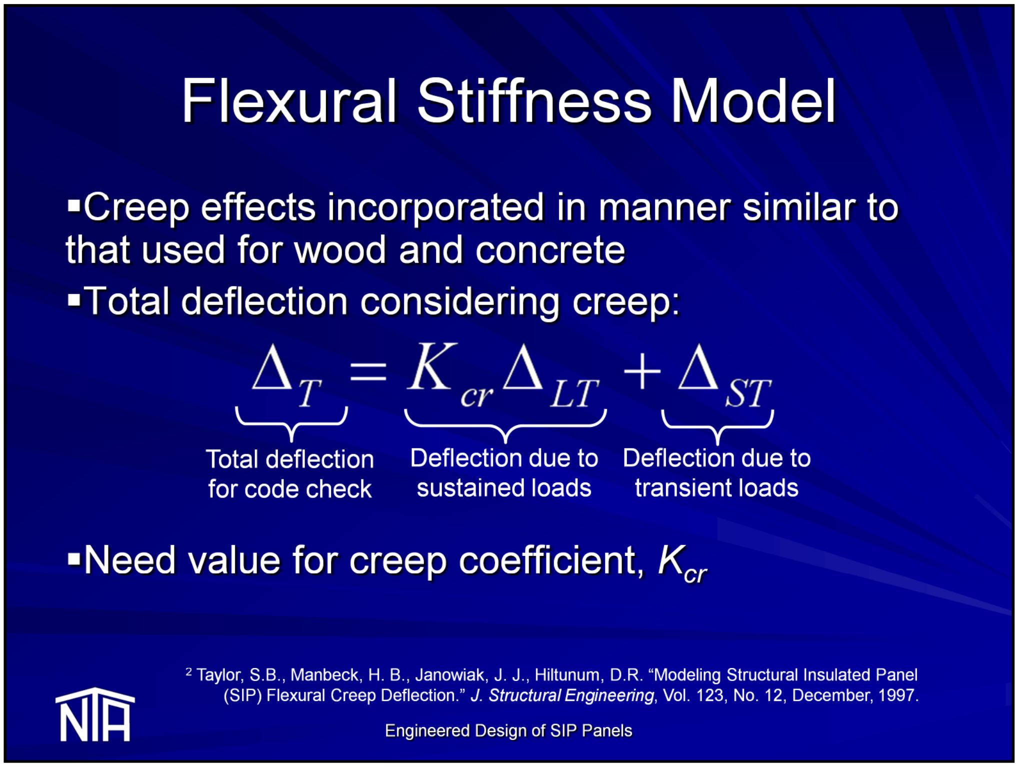


The benefits of the proposed stiffness model include:

1) Data from all SIP spans and thickness are pooled and combined into a single large sample which allows us to establish statistical significance. More importantly, a large body of data can be represented by two simple values E_b and G, in each direction—no need to dig through reports or use a table to estimate deflection.

2) The method of loading becomes irrelevant—uniform, ¼-point, or 1/3-point test data can be combined. Tests can be performed under any support and loading conditions as long as a deflection equation, including shear effects, can be derived. The geometric conditions of the test are contained in the constant, K_s.

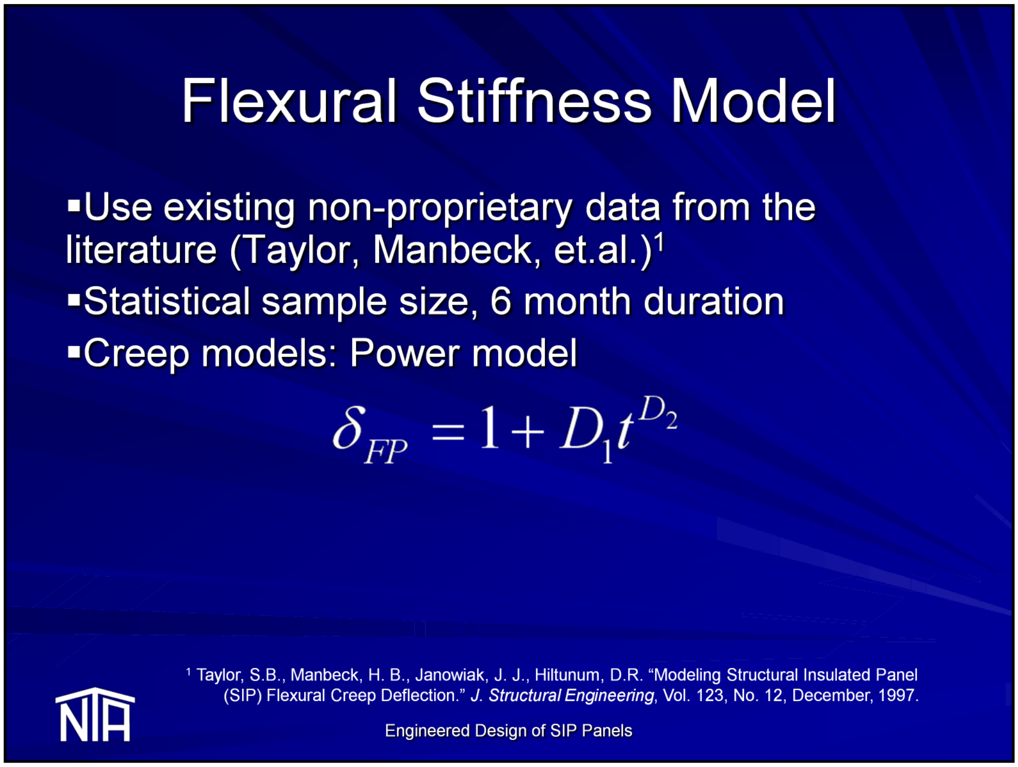
3) Non-destructive, in-plant QA testing could be conducted on any panel of any size or thickness and the values compared to a single set of control values.



The stiffness model discussed so far considers only short term test loading, but in actual structures loads are applied for much longer periods. Accordingly, the long-term deflection under sustained loads must be addressed in a rational manner. As previously mentioned, all non-metallic materials creep under sustained load, the common design expression used to account for such behavior is provided.

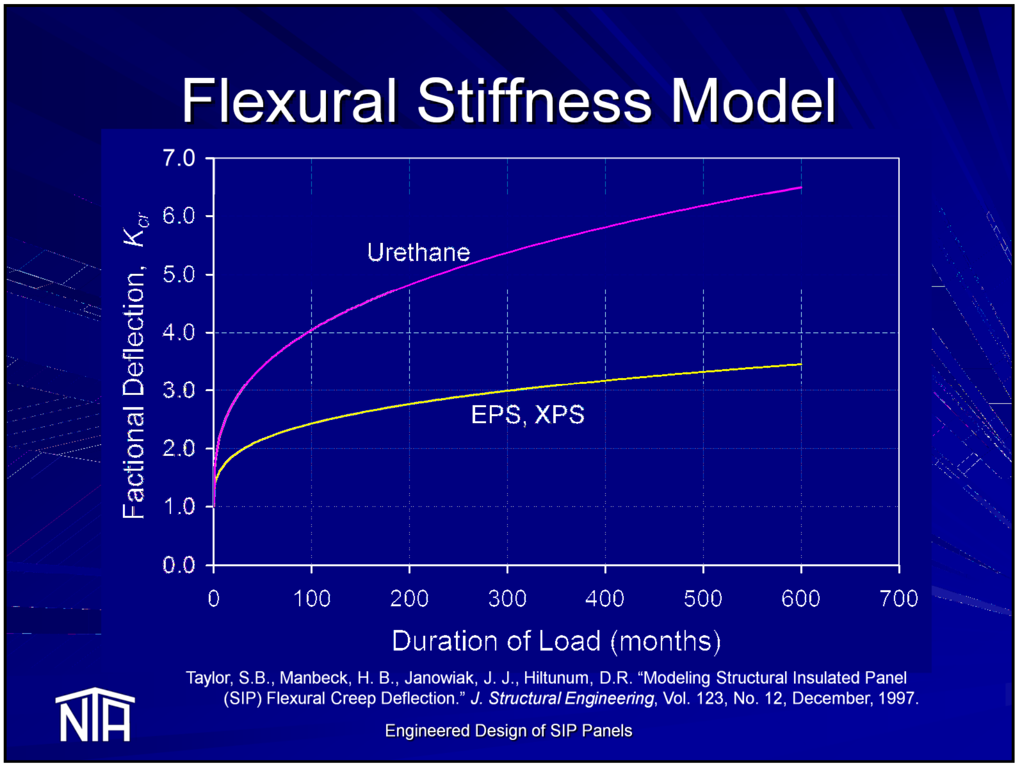
This equation expresses the total deflection as a sum of the deflections resulting from short-term, D_{LT}, and long-term loads, D_{ST}. The deflection due to long-term loads is increased by a multiplier, K_{cr}, which is based on creep testing.

Now we just need a value for K_{cr}.



A literature review yielded a single comprehensive creep study on SIP panels. The study, conducted in the 90's, tested a large number of samples from 4 different panel manufacturers. The study considered EPS and urethane cores of various thicknesses (3.5 to 7-inches in thickness). The data cover a load duration from zero to 6 months for EPS and zero to 3 months for urethane.

The report establishes and assesses various creep models based on the experimental data. The report concludes that the 'Power Model' best models and predicts SIP creep behavior. The general equation for the power model is provided. Terms D_1 and D_2 are provided in the report for both EPS and urethane.

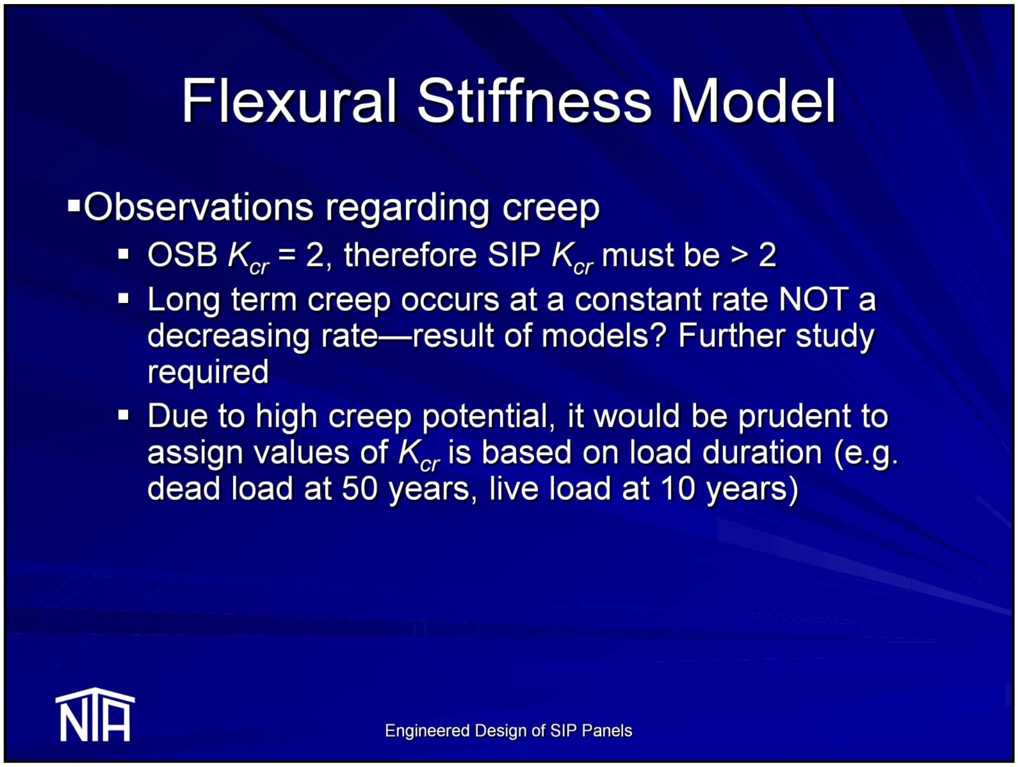


Plots of the two models are shown. The vertical axis is fractional deflection, which is the ratio of long-term deflection to immediate deflection. This value is equal to the term K_{cr} in the proposed creep design equation. In the plot, the duration of load is extrapolated to 600 months, or 50 years, which is the typical design life of a structure. From the plot is it apparent that the creep potential of urethane core panels is about twice as great as EPS core panels. Also, it is important to note that long-term creep occurs at a constant rate rather than a decreasing rate, as in other materials. This behavior may be the result of the power model, but further research, over greater periods of time would be required to verify or disprove this behvaior.

Flexural Stiffness Model

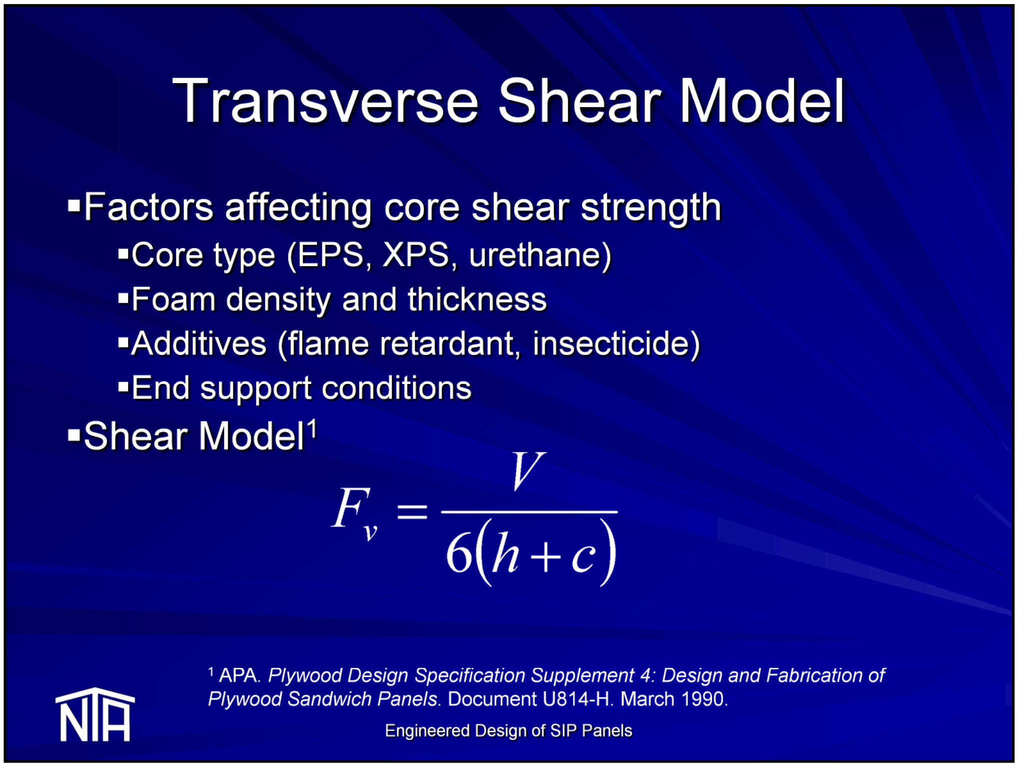
Material	Creep Coefficient, K_{cr}
EPS, XPS Core SIP	4.0
Urethane Core SIP	7.0
Seasoned Lumber	1.5
OSB or Wet Lumber	2.0
Reinforced Concrete	2.0

Comparing the Kcr term for permanent loads with other common construction materials, the Kcr for SIP panels is greater than other commonly used materials; however, this should be expected.

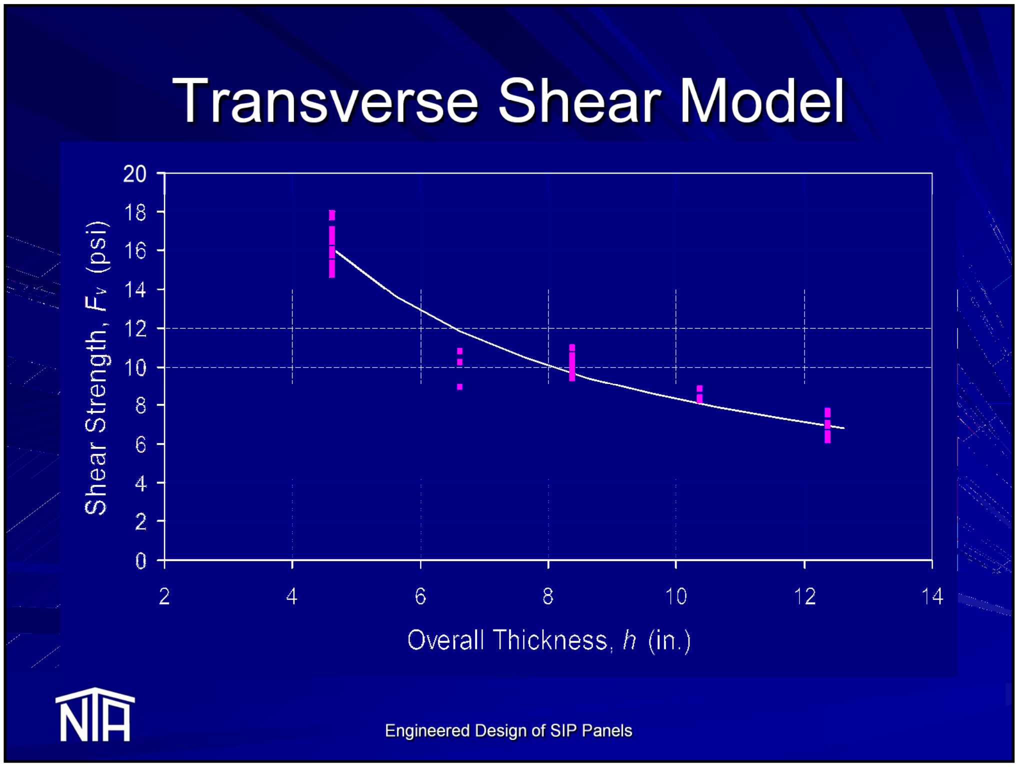


The Kcr for OSB is 2.0, because SIPs are comprised of OSB and foam plastic, the creep potential of a SIP would be expect to be greater than 2.0. Also, as previously mentioned, the long-term creep rate appears to be constant. This may be the result of the Power Model rather than actual creep behavior, but this would require more research at longer durations to assess.

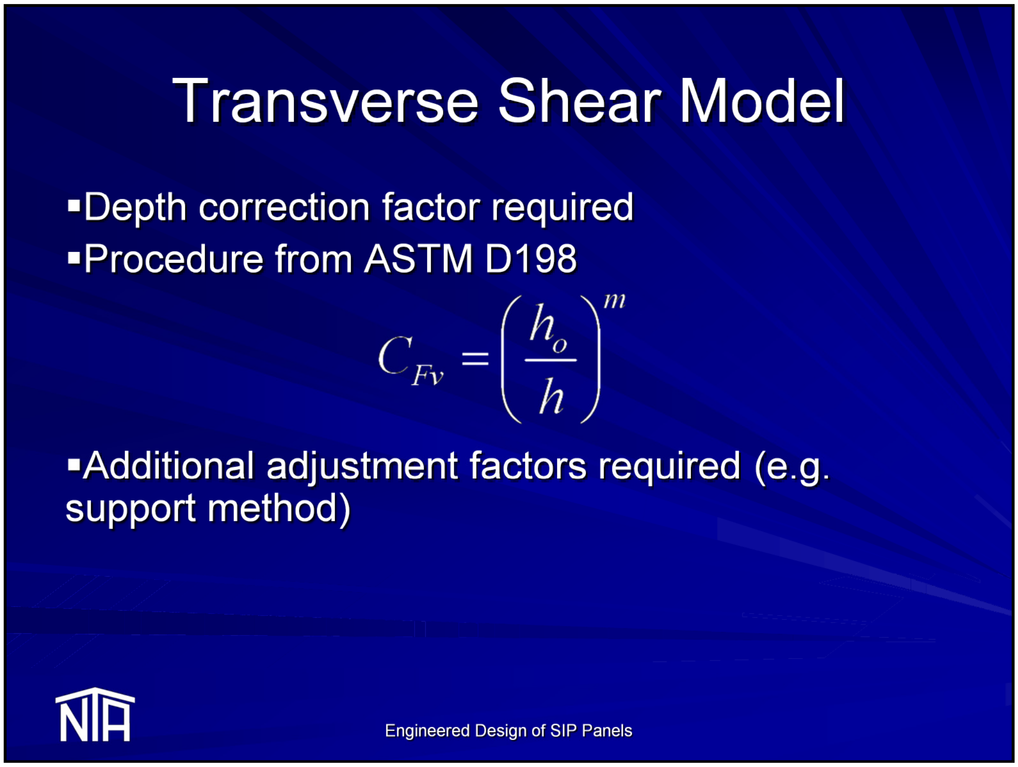
Existing construction materials only apply creep to permanent loads, such as dead load; however, because of the relatively high-creep potential of SIPs under load any design method should consider the duration of loads other than dead loads and assign K_{cr} values for each load type based on duration.



Moving on to transverse shear, known factors affecting the core shear strength include: core type, density, thickness, additives, and end support conditions. From basic engineering mechanics, the shear stress in a SIP can be expressed as shown in the equation provided. Using ASTM E72 ultimate load data from panels failing in shear (nearly all panels tested with simple supports) the ultimate shear stress *Fv* can be calculated.

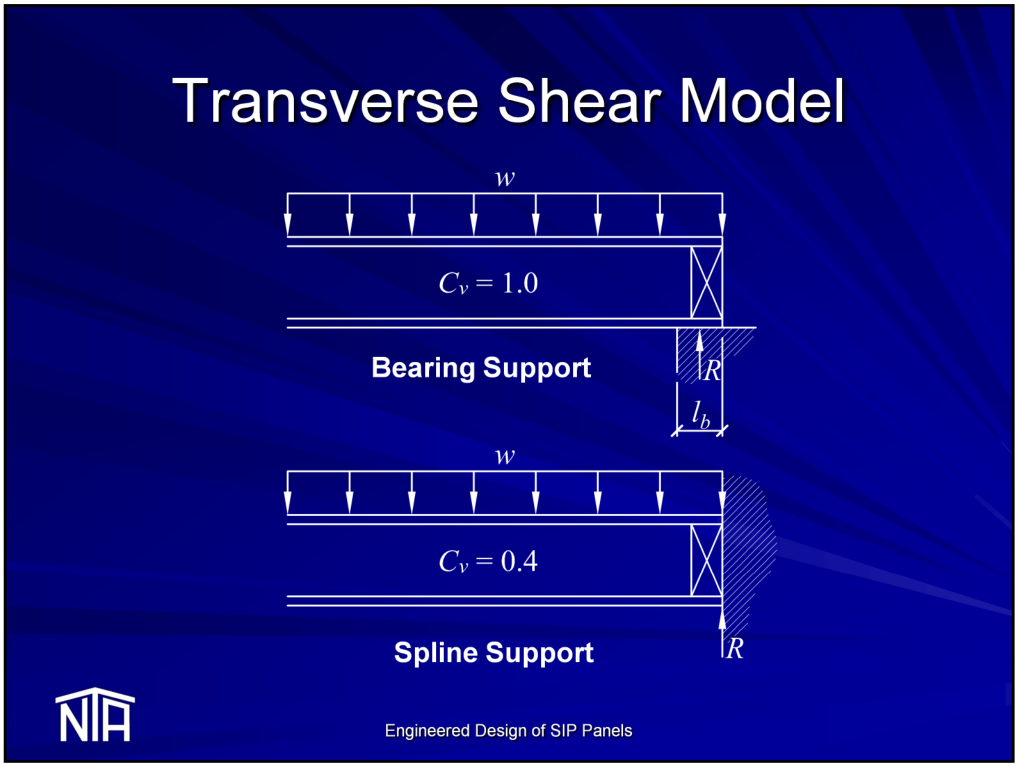


Plotting the shear stress verses the panel thickness, as shown in the plot, reveals that shear strength decreases as panel depth increases. This strength reduction is not accounted for by engineering mechanics but may be accounted for by a depth correction factor.

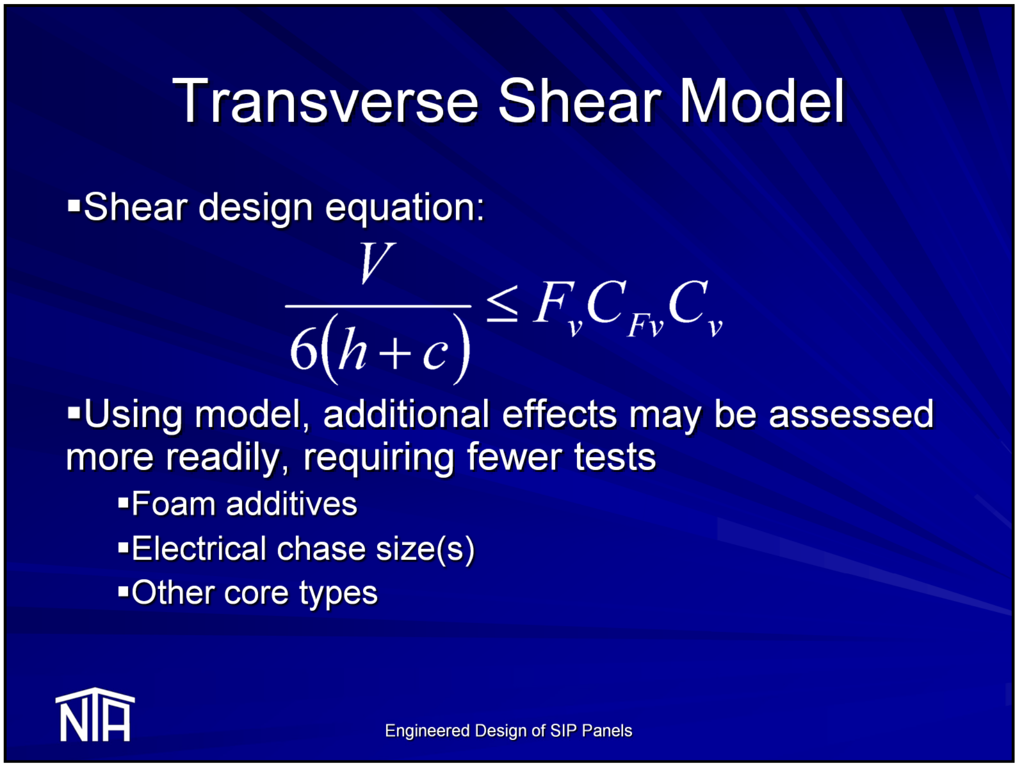


A basis for the formulation of such factors is provided in ASTM D198. The proposed equation expresses a shear depth correction factor, C_{Fv}, in terms of a reference depth, h_o, and the design depth, h. The curvature of the relationship is established by an exponent, m. Using simple curve fitting techniques m may be established for a given foam.

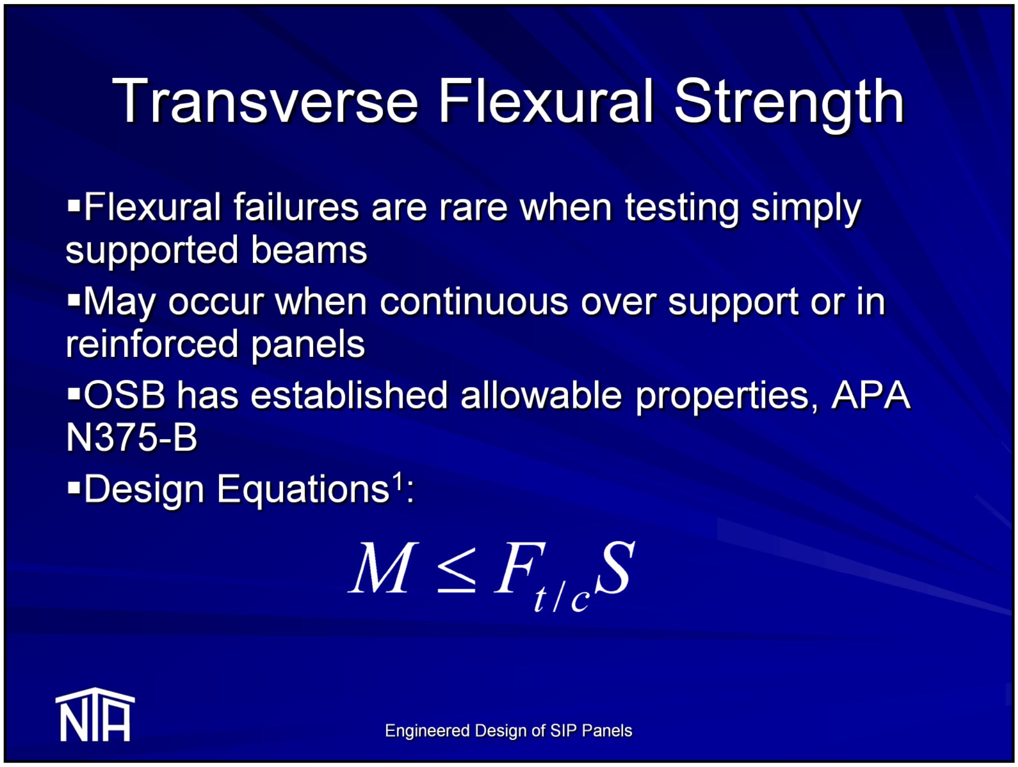
Additional adjustment factors are required to account for other SIP behavior that is not predicted by engineering mechanics.



One such factor relates to the method of panel support. Two common conditions include "bearing support" and "spline support" conditions. "Bearing support" is the most commonly tested condition and exists when bearing is provided on the facing opposite the applied load. This condition results in the greatest shear strength. The "spline support" condition, which results when bearing is provided on the same facing to which the load is applied, results in a reduced shear strength. A correction factor, presented here as *Cv*, accounts for support affects may be used to account for support effects in the engineering model.

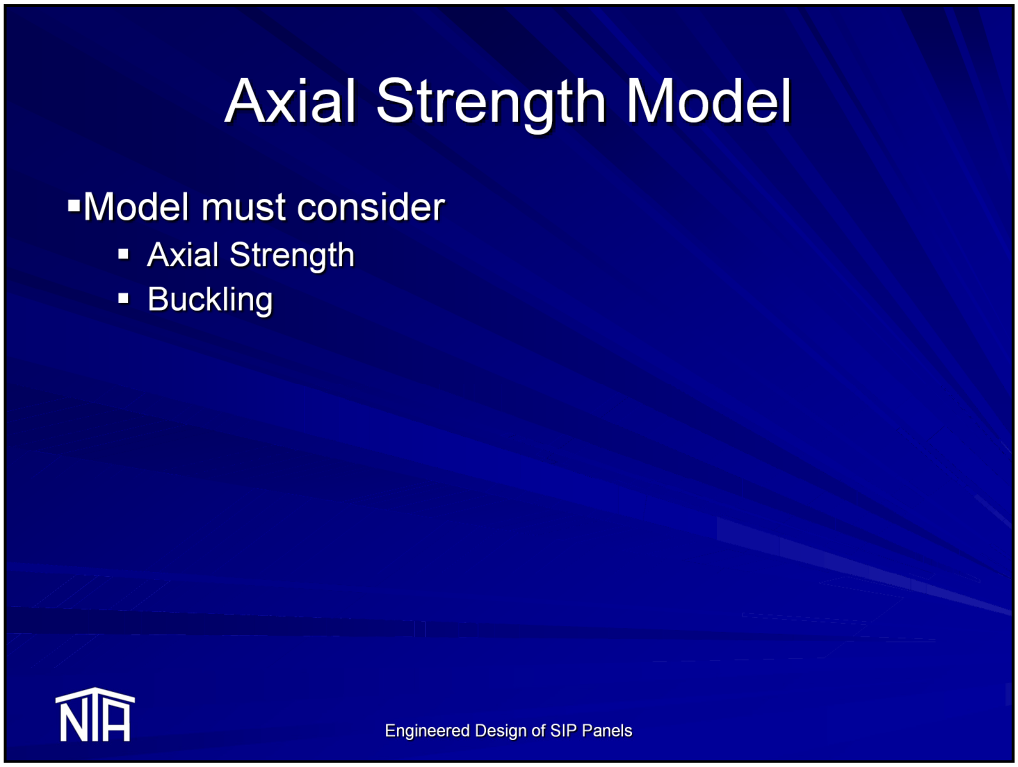


Adding the aforementioned correction factors to the originally proposed equation results in the equation shown. Additional factors could be developed for other strength influences, such as foam additives or the presence of electrical chases of various sizes. The advantage of investigating additional factors in the context of an engineering model is that "overlapping" influences such as depth, or support conditions, may not need to be fully re-assessed. Orin other words, it may be possible to address additional factors with fewer tests.



Looking at flexural strength. In general, tests on simply supported SIP panels exhibit shear failure at ultimate load NOT flexural failure of the facings. However, flexural failure may occur in panel continuous over a support or in panels with structural splines.

APA document N375-B establishes allowable properties and design methodology for OSB panels. Using these values, the bending moment in SIP panels should comply with the proposed equation.



Moving on to axial loads, a engineering model of axial loads must consider: axial strength, and buckling.

Axial Stiffness Model

- Axial Strength[1]:

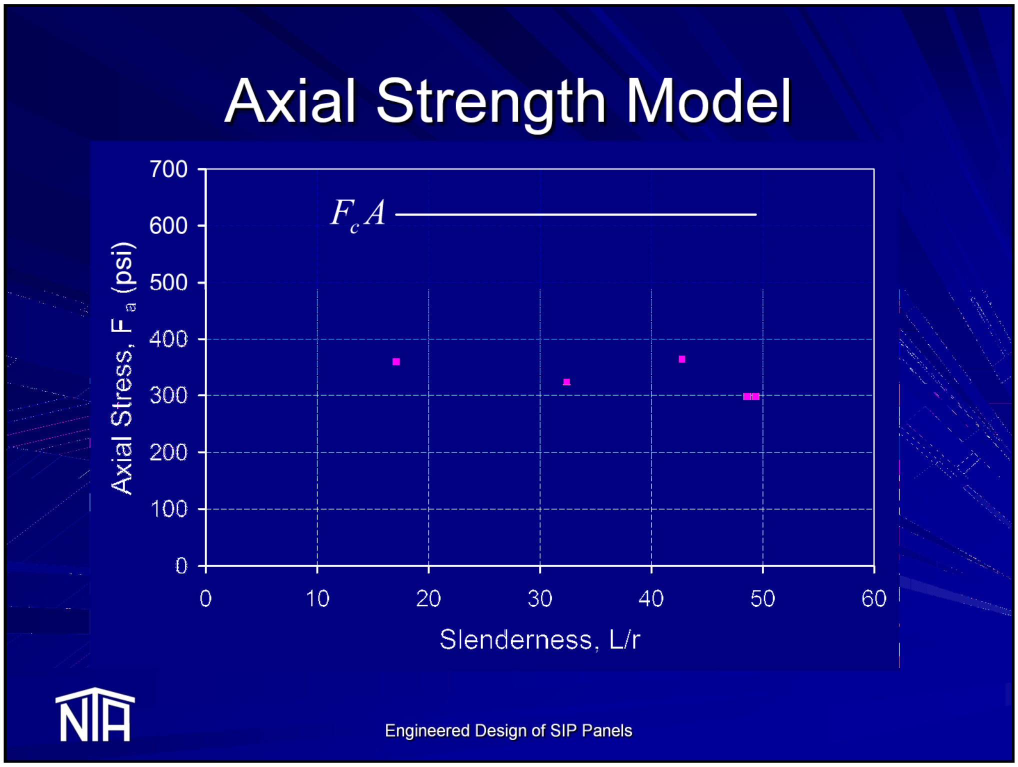
$$P \leq F_c A$$

- Axial Buckling[1]:

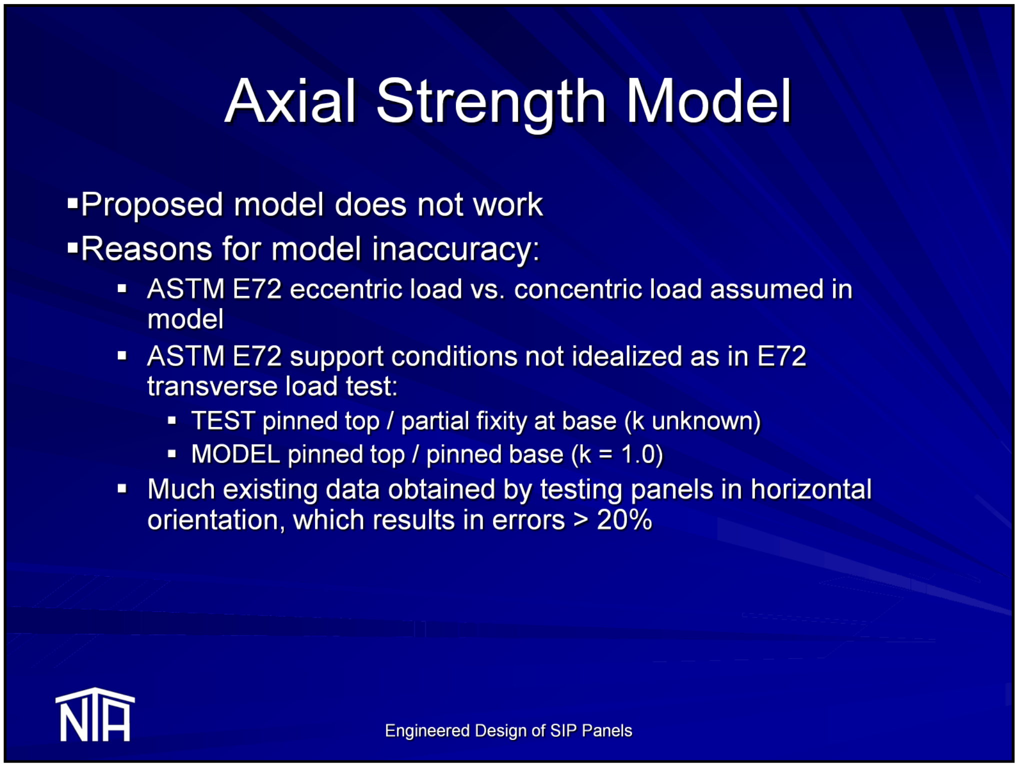
$$P \leq P_{cr} = \frac{\pi^2 E_c I}{3 \times (12L)^2 \left[1 + \frac{\pi^2 E_c I}{(12L)^2 \times 6(h+c)G} \right]}$$

[1] APA. *Plywood Design Specification Supplement 4: Design and Fabrication of Plywood Sandwich Panels.* Document U814-H. March 1990.

Based on the referenced documents, proposed equations for axial strength and stiffness are provided.



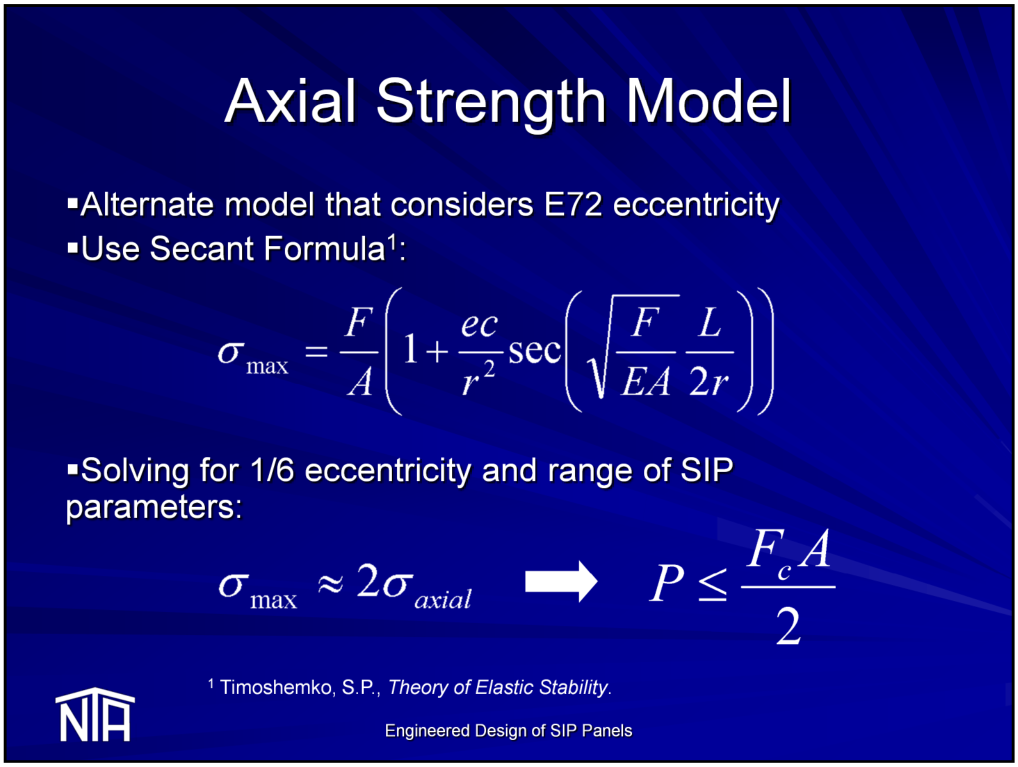
However, comparing the proposed models to actual data (as done in the plot) shows that the models do NOT reflect tested behavior—the tested strength is about ½ the strength predicted by the model.



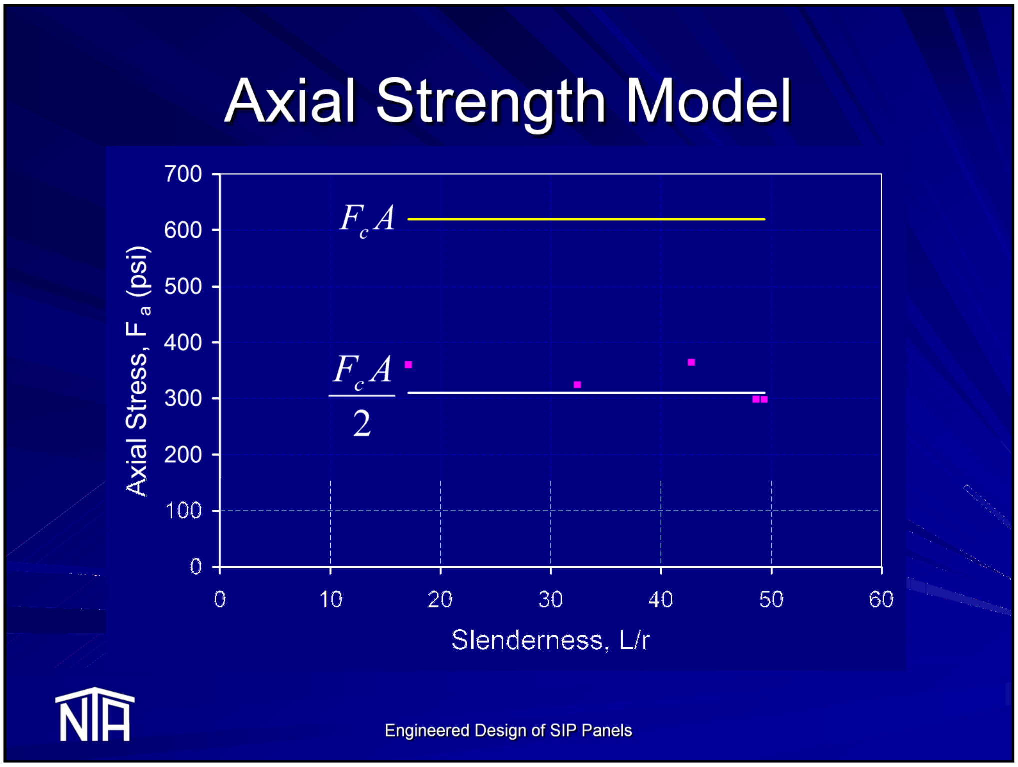
Why doesn't the proposed model work?

Unlike transverse flexural tests, it is much more difficult to achieve "idealized" conditions when testing for axial load. The proposed models assume that loads are concentrically applied (Euler buckling) and that the member is "pinned" at both the top and bottom. However, when testing in accordance with ASTM E72, the test requires a minimum eccentricity and the member end conditions are "pinned" at the top and "partial fixed" at the base.

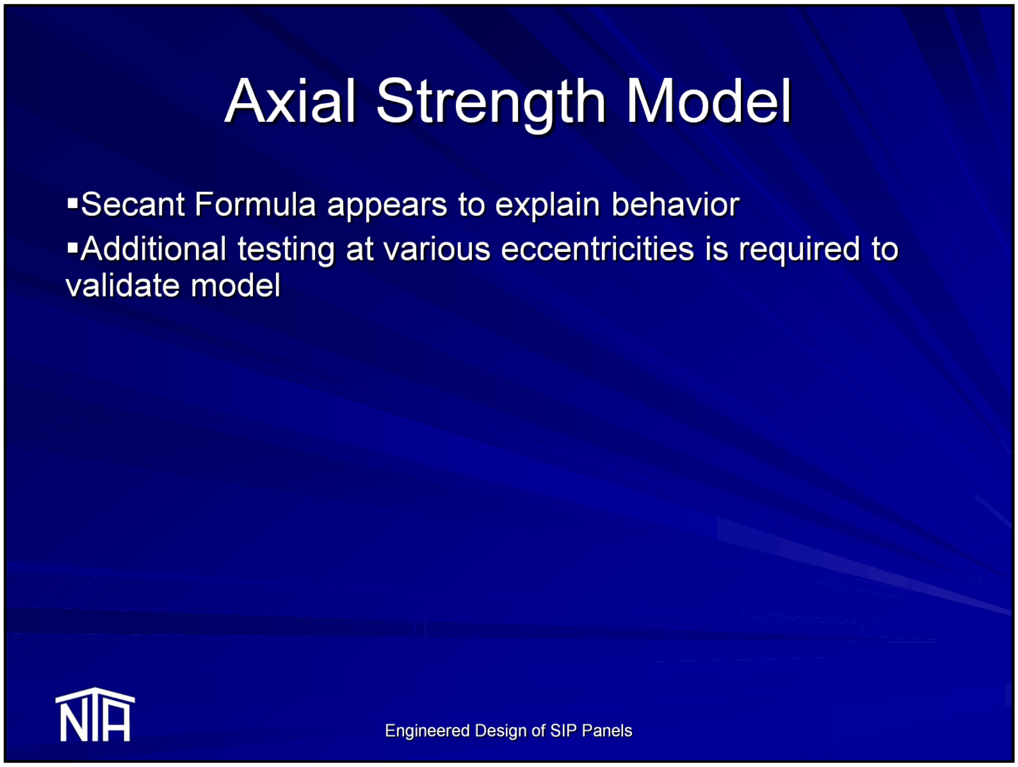
To further obscure the true behavior, considerable scatter exists in existing data sets due to differences in testing methods among testing laboratories. Much existing data is from panels tested in a horizontal position rather than vertically. A simple uncertainty analysis performed on horizontal test procedure shows that axial values obtained from such tests are in error by 20% from the true axial value for 8-ft panels with greater errors as the panel length increases. This error is due to the additional eccentricity resulting from the panel deflecting under its own weight.



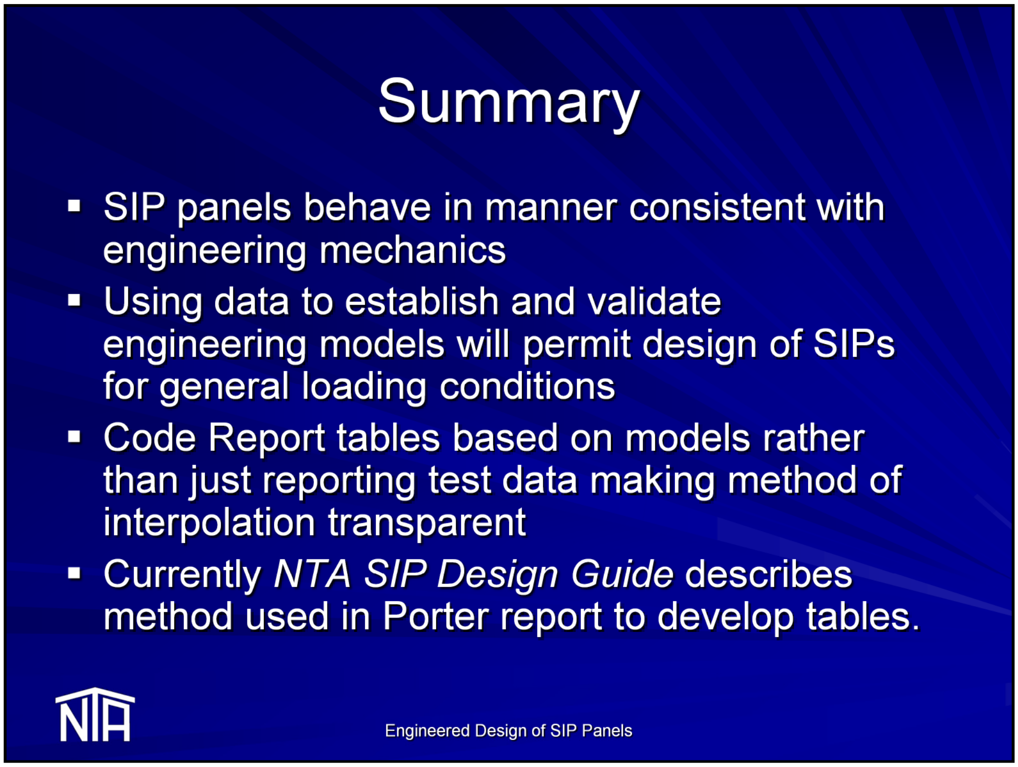
Because existing models in the *APA PDS, Supp. 4* do not match with qualification test data other equations were investigated which more closely approximate the ASTM E72 test procedures. One such equation is known as the Secant Formula. This formula calculates the maximum stress in the extreme fiber of an eccentrically loaded column. Interestingly, if the secant formula is solved for the ASTM E72 eccentricity and for the range of thicknesses and spans common to SIP panels, the result is the same. In general, the secant formula predicts that a SIP tested to ASTM E72 will have a maximum stress equal to twice the stress under true axial loading. Or in other words, the maximum axial load is ½ the strength predicted using APA N375-B.



Returning to the axial load plot, the secant formula appears to accurately predict SIP panel strength under eccentric loading.



While the secant formula appears to model axial behavior, few tests have been run at eccentricities different than that required by ASTM E72. Testing at additional eccentricities may validate the use of the secant formula for other eccentricities commonly found in design, such as balloon framing where the eccentricity equals half the panel thickness.



In summary, as I have shown in this presentation, SIP panel behavior CAN be modeled using engineering mechanics. Existing test data can be analyzed to establish engineering models which will permit flexible design of SIP panels under loading and support conditions that cannot be assessed in the laboratory. Additionally, code report tables can still be provided for "prescriptive" design, but such table should be based on engineering design so that the method for developing the tables is transparent.

The methods and equations presented in this presentation are the methods currently used internally by NTA, Inc. for SIP panel design and are available in written form with more detail upon request.

NTA INC.

NTA TESTING LABORATORIES, INC.

Engineered Design of Structural Insulated Panels

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Engineered Design of Structural Insulated Panels

- Overview
  - Sources of Design Information
  - Transverse Loads
  - Axial Loads
  - Shear Wall & Diaphragm Loads

Sources of Design Information

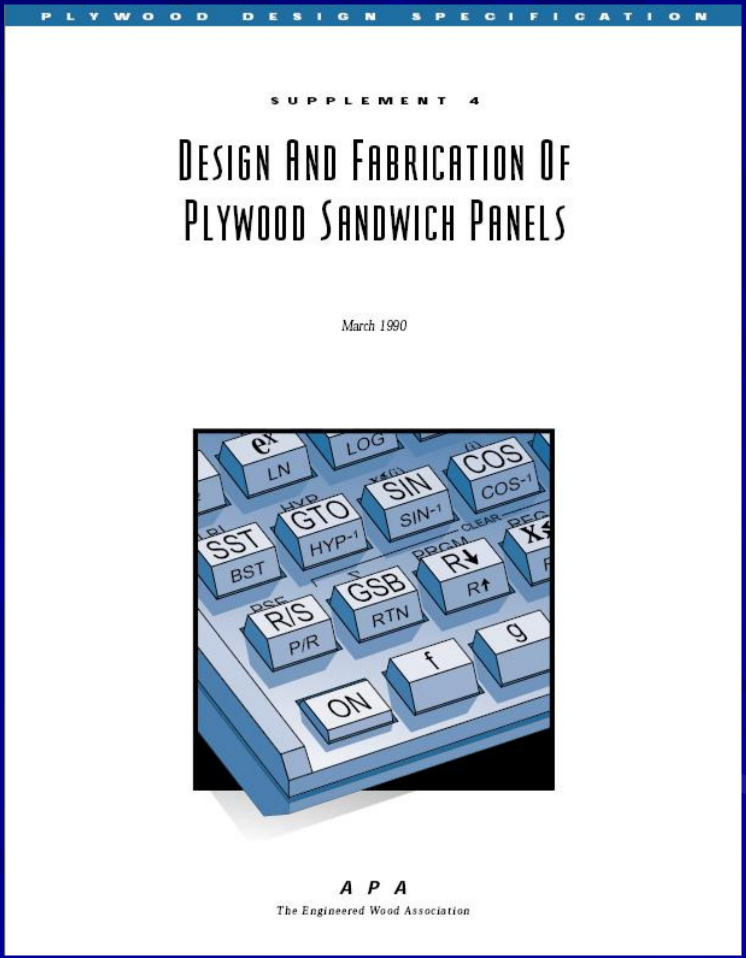
- SIP Manufacturer
  - Architectural/detail manuals showing typical construction and connections
  - Level of detail varies significantly between manufacturers
  - Prescriptive with little or no engineering properties

Sources of Design Information

- IRC Prescriptive Design
  - 2007 Supplement to the IRC, Section R614
  - Prescriptive method limited wind and seismic
  - Walls only, limited heights and thicknesses

Sources of Design Information

- *APA PDS Supplement 4- Design & Fabrication of Plywood Sandwich Panels*
  - Adopted by reference in IBC
  - Provides design method based on mechanics
  - Does not address important design issues such as creep and support effects
  - Does not provide typical material properties for design



Sources of Design Information

- Code Research Reports (NTA, ICC-ES)
  - Based on ICC-ES Acceptance Criteria AC04
  - Prescriptive with little or no engineering properties
  - Not clear what is based on testing vs. interpolation
  - Interpolation methods are not specified or provided
- NTA is working with SIPA and APA to develop engineering design standards
- NTA SIP design guide available

SIP Structural Behavior

- Scope
  - General behavior, actual values will vary—refer to manufacturer's data
  - Symmetric SIPs
  - OSB facings
  - EPS, XPS or polyurethane cores
  - Non-structural splines (Block or Surface)

Flexural Behavior

- Based on transverse load testing with simple supports (ASTM E72)
- Elastic, *E*, and shear, *G*, moduli determined using procedures in ASTM D198
- Flexural stiffness governed by shear modulus of core
- Properties vary with orientation of OSB facings
  - 8-ft spans OSB may be in either direction
  - >8-ft spans OSB in strong direction

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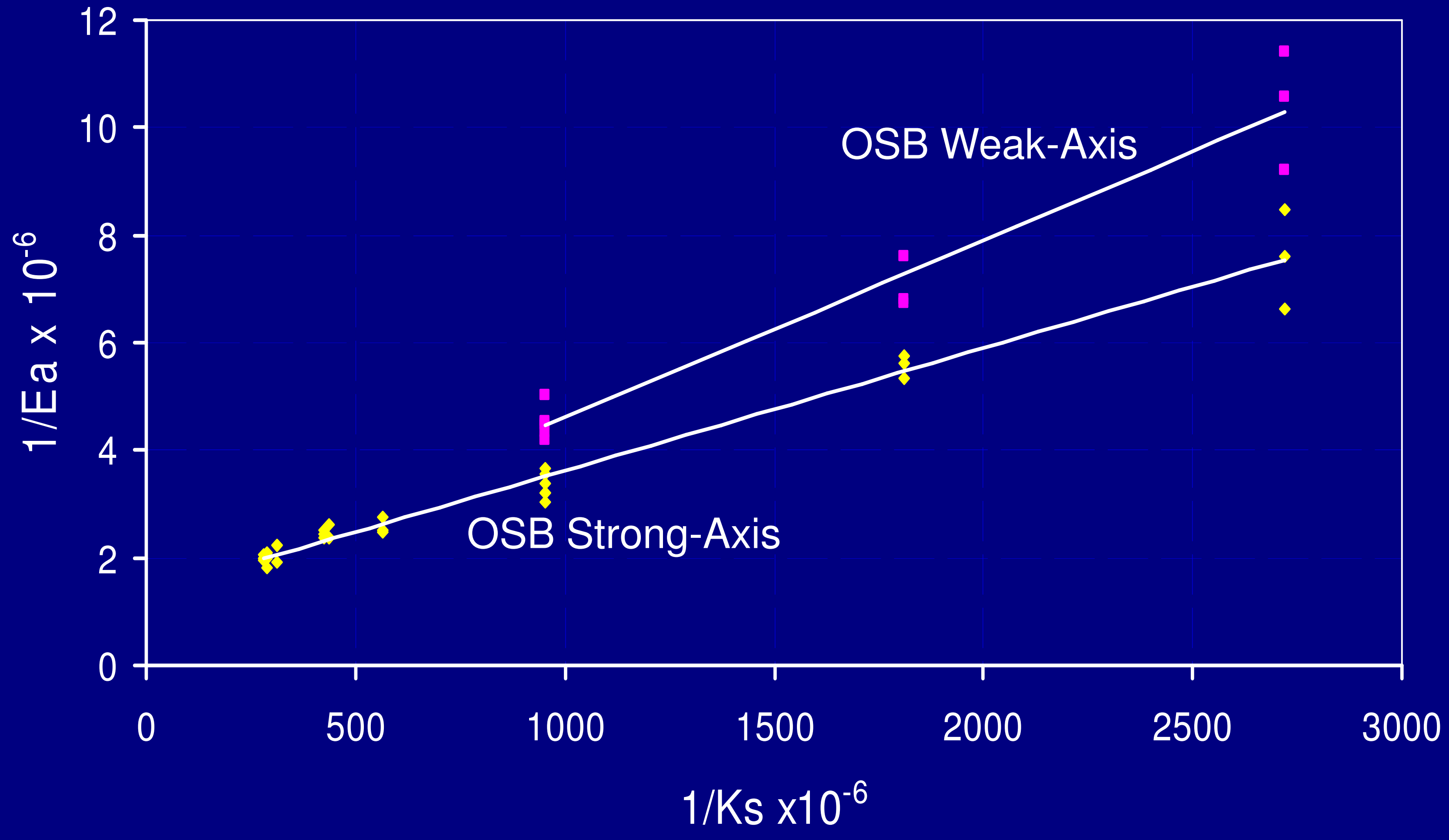
Flexural Behavior



Deflection Calculation Methods

- Simply supported deflection equation with shear

$$\Delta = \Delta_b + \Delta_s = \frac{5wL^4 \times 1728}{384 E_b I} + \frac{wL^2}{4(h+c)G}$$

- FEA software
  - SIP moduli (*E*, *G*) cannot be input directly. *G* typically based on Poisson's ratio

$$G = \frac{E}{2(1+\nu)}$$

  - Shear deformations considered at nodes only, NOT between nodes, must discretize—read manual

Flexural Creep

- Deflection under sustained loads
- Creep models: Power model[2]

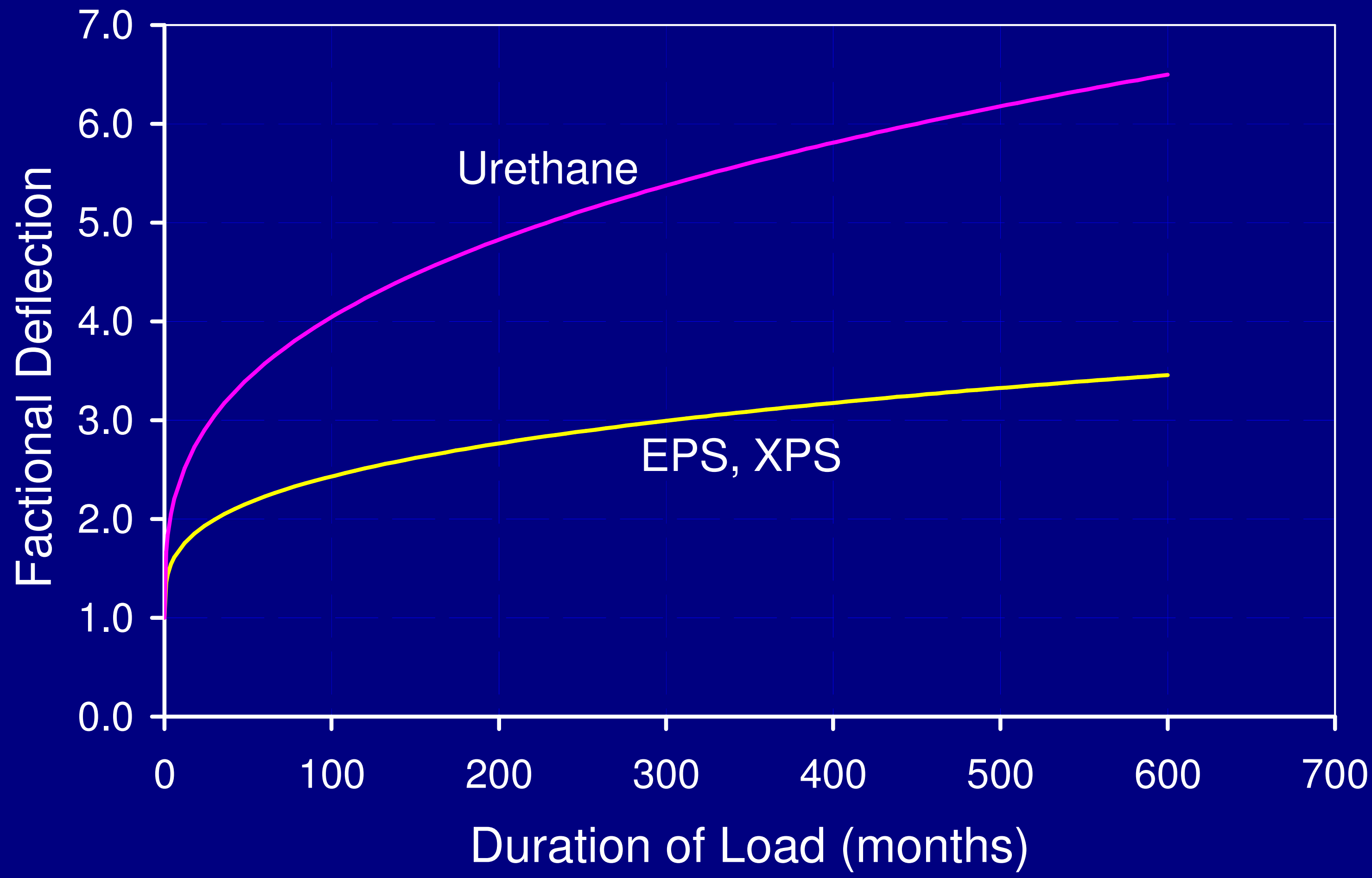
$$\delta_{FP} = 1 + D_1 t^{D_2}$$

- Deflection equation considering long term loads

$$\Delta_T = K_{cr} \Delta_{LT} + \Delta_{ST}$$

[2] Taylor, S.B., Manbeck, H. B., Janowiak, J. J., Hiltunum, D.R. "Modeling Structural Insulated Panel (SIP) Flexural Creep Deflection." *J. Structural Engineering*, Vol. 123, No. 12, December, 1997.

Flexural Creep



Taylor, S.B., Manbeck, H. B., Janowiak, J. J., Hiltunum, D.R. "Modeling Structural Insulated Panel (SIP) Flexural Creep Deflection." *J. Structural Engineering*, Vol. 123, No. 12, December, 1997.

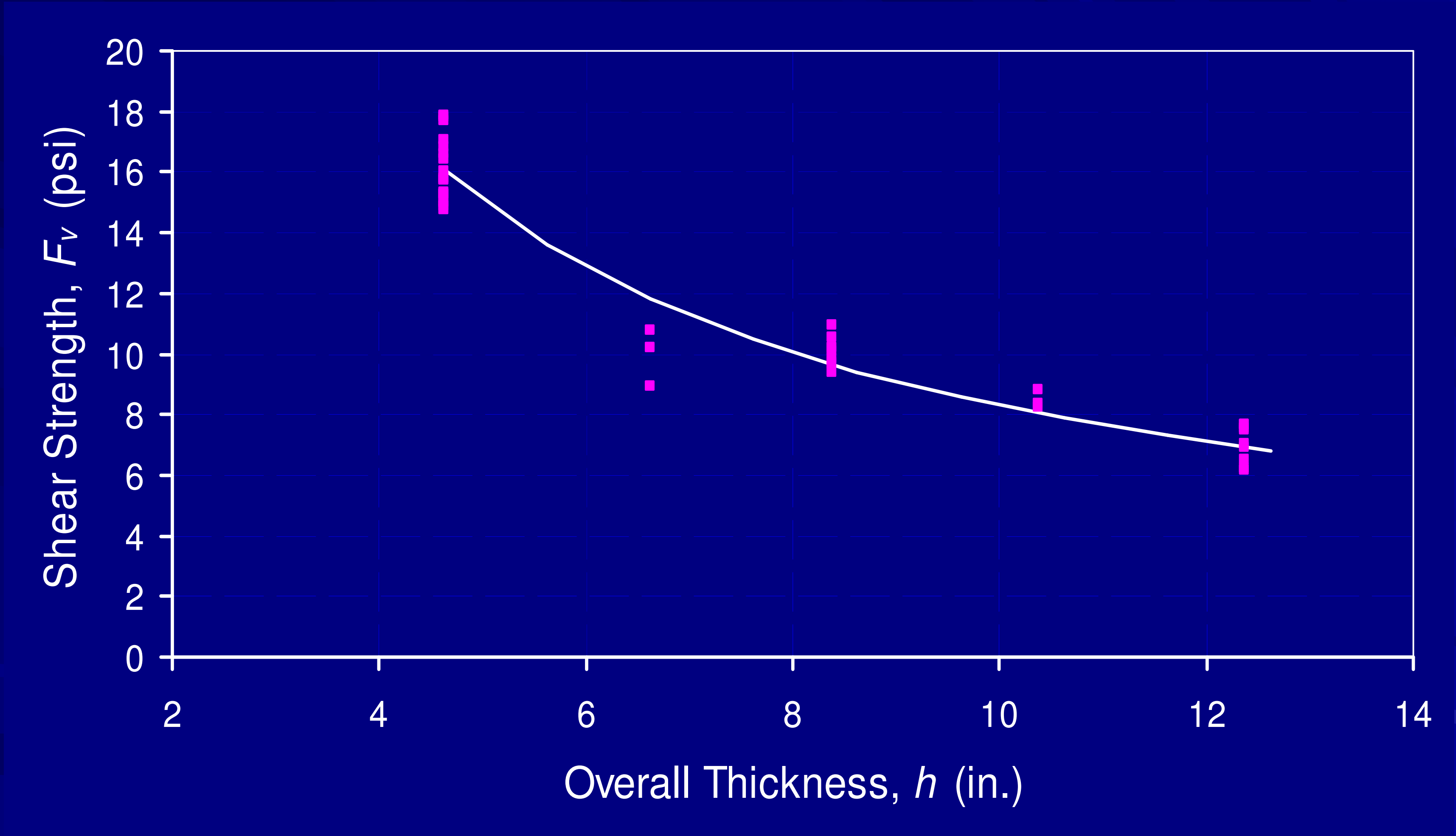
Flexural Creep

Material	K_{cr}
EPS, XPS Core SIP	4.0
Urethane Core SIP	7.0
Seasoned Lumber	1.5
OSB or Wet Lumber	2.0
Reinforced Concrete	2.0

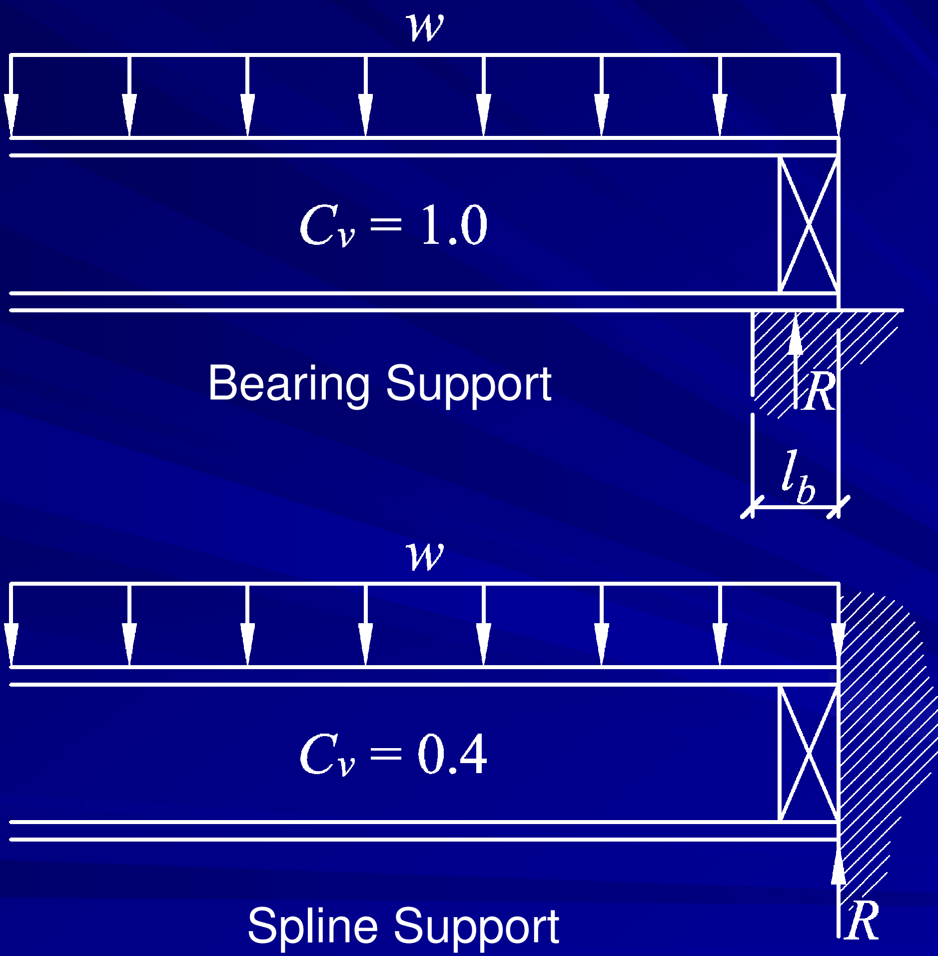
Transverse Shear Strength

- Factors affecting core shear strength
  - Core type (EPS, XPS, urethane)
  - Foam density and thickness
  - Additives (flame retardant, insecticide)
  - End support conditions

Transverse Shear Strength



Support Conditions



“Axial” Strength

- Axial tests in accordance with ASTM E72 include eccentricity equal to 1/6 the panel thickness
- Not Euler Buckling—instead Secant Formula

$$\sigma_{\max} = \frac{F}{A}\left(1 + \frac{ec}{r^2}\sec\left(\sqrt{\frac{F}{EA}}\frac{L}{2r}\right)\right)$$

- For SIP parameters:

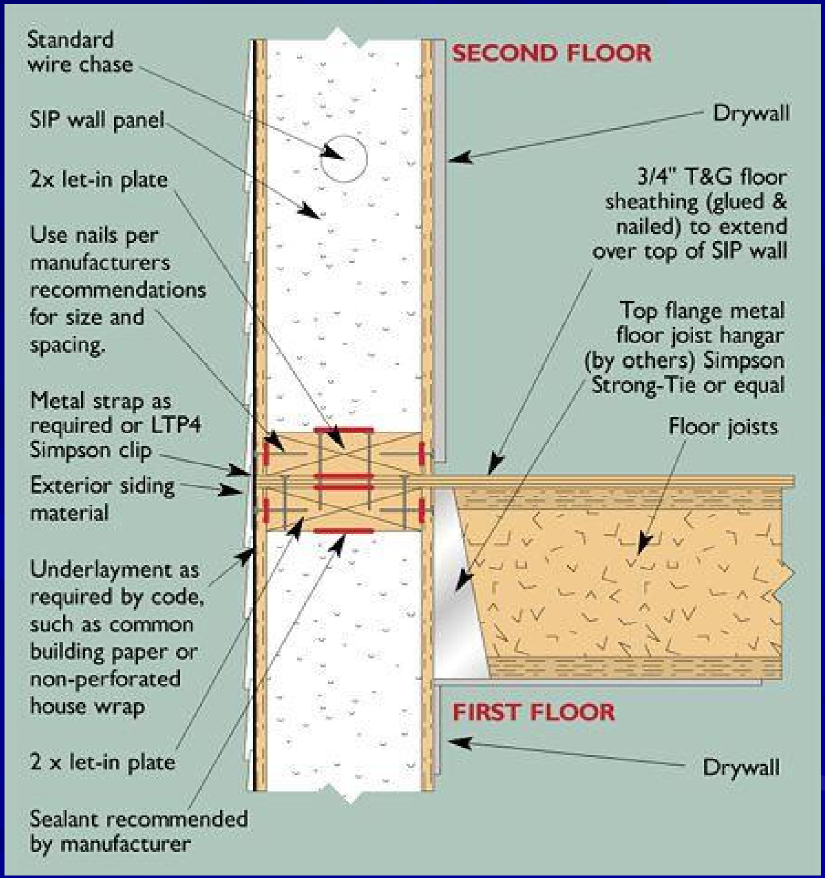
$$\sigma_{\max} \approx 2\sigma_{axial}$$

"Axial" Strength

- SIP capacity limited to one-half allowable compressive strength OSB facing under true axial load
- *APA N375-B Design Capacities of APA Performance Rated Structural Use Panels* provides allowable values for OSB facings
- ASTM E72 eccentricity intended to be "incidental"

"Axial" Strength

- Most eccentricities are not incidental and eccentricities greater than 1/6 the thickness often result (e.g. balloon framing)



Shear Wall & Diaphragm Strength

- Monotonic shear wall strength similar to conventional stud wall with equivalent edge fastener spacing
- Diaphragm strength similar to blocked diaphragm with equivalent edge fastener spacing
- Cyclic/seismic performance currently under debate
  - SIP panel structures have performed well during seismic events
  - Influence of sealants on cyclic response in laboratory