# Simplified models for composite elastic behavior of precast concrete insulated wall panels

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- This paper outlines a new simplified method for predicting the degree of composite action and thus the elastic moment of inertia and the elastic section modulus for precast concrete insulated wall panels.
- This simplified approach was developed by using 1 million simulations from the iterative sandwich beam theory method.
- The level of accuracy of the new method to predict the percent composite is similar to the levels of accuracy of the more complicated approaches.


Precast concrete insulated wall panels are rapidly gaining popularity because of their light weight, thermal efficiency, and economy. Typical precast concrete insulated wall panels consist of two layers of concrete separated by a layer of insulation and steel or fiber-reinforced-polymer connectors, which provide some level of composite behavior. Designs using such walls are popular for warehouse structures, cold storage, data centers, and other buildings that require large open spaces. In addition, they are gaining popularity in the nonwarehouse commercial market and can integrate architectural features. Architects like the versatility and thermal efficiency of precast concrete insulated wall panels.

Recent efforts have been made to increase the thermal efficiency of precast concrete insulated wall panels, which have historically been made with solid penetrations of concrete and steel ties, both of which result in significant thermal bridging.[1–3] Solid concrete penetrations result in high levels of composite behavior that are hard to quantify but were typical design details until recently.[4,5] Steel connectors are ductile and strong, but they create point thermal bridges that result in condensation issues and drops in apparent *R*-value compared with contemporary composite connectors.[6,7] As new connectors and analyses have become available, the use of solid zones has become less common, and panels are often now produced with unbridged edge-to-edge insulation. This change makes it critical to understand the behavior of precast concrete insulated wall panels. Although thermal efficiency may be improved when precast concrete insulated wall panels do not have solid concrete penetrations and strong, ductile steel connectors, a possible tradeoff is that structural efficiency is diminished.[7,8,9]

**Figure 1** illustrates the mechanics of precast concrete insulated wall panels. At a basic level, a noncomposite precast concrete insulated wall panel behaves as if the two layers act independently, while a fully composite panel behaves as if the two layers act as one. The actual behavior of any precast concrete insulated wall panel will be somewhat composite, but it is nearly impossible to reach the fully composite extreme without stiff connectors such as solid ribs between layers. There is experimental evidence that shows that partial composite action occurs even with such solid concrete penetrations.[4,10] Similarly, even a panel with noncomposite connectors will behave with some low level of composite action.[11] The actual behavior, as demonstrated in previous research,[12–16] is that the two wythes interact as two independent elements with some axial force and/or moment imparted by the connectors. The result is the strain profile labeled "Actual behavior" in Fig. 1.

There are multiple shear connectors available on the market. Their geometries and materials vary considerably. Further, some connectors rely on the bond of the insulation to carry some horizontal shear, but others do not. In addition, connectors can be composed of various fiber-reinforced composites or unfilled polymer or they can be made of steel. The variety of connectors has made it challenging in the past to establish a uniform design and analysis process.

Several contemporary methods for predicting behavior of wall panels rely on shear load versus shear displacement data for precast concrete insulated wall panel wythe connectors.[15,17–19] In the elastic range, which is where many precast concrete insulated wall panels are designed, the initial elastic stiffness $K_{0.5}$ is used for predicting behavior.[20] Researchers usually use double shear tests to estimate this value from the load deflection plot (**Fig. 2**), and the stiffness $K_{0.5}$ is reported in kip/in. This value and others from the load-versus-deflection plot are used in various analytical methods for predicting full-scale panel behavior, including the iterative sandwich beam theory (ISBT) that was used in the research reported in this paper.

Over the past 20 years, precast concrete insulated wall panel design has most often been accomplished with a percent composite approach that estimates the degree of composite action.[20] This approach is demonstrated by comparing partially composite stress $\sigma_{PC}$ in the diagram labeled "Actual behavior" with $\sigma_{PC}$ in the diagram labeled "Percent composite" in Fig. 1, where the approach matches the stresses (or deflections) of an advanced analysis or experimental results at cracking. Although this approach has not been codified or applied uniformly across the industry, wythe connector suppliers have typically used proprietary methods based on testing or finite element analysis to estimate the apparent composite action.[5,15,19,22] This approach has also been used to some extent in previous research.[23,24]

The method itself was developed in the early 2000s to follow the process of designing a precast concrete solid panel when fiber-reinforced-polymer connectors were popular.[25] In this process, a given panel configuration behavior is estimated by experimental or complex analysis and the deflection response or the cracking response is determined; however, this analysis is often proprietary[26] or finite element based. This part of the process is typically performed by the wythe connector supplier and then converted to a percentage that is an interpolation between 0% and 100% composite associated with the moment of inertia $I_g$ and section modulus $S$ for a noncomposite panel and fully composite panel of the same geometry and material (Eq. [1] and [2]). **Figure 3** presents this process visually.

$$S_{PC} = 100\left(\frac{S_{PC} - S_{NC}}{S_{FC} - S_{NC}}\right) \tag{1}$$

where

$S_{PC}$ = section modulus for the partially composite section

$S_{NC}$ = section modulus for the noncomposite section

$S_{FC}$ = section modulus for the fully composite section

$$I_{PC} = 100\left(\frac{I_{PC} - I_{NC}}{I_{FC} - I_{NC}}\right) \tag{2}$$

where

$I_{PC}$ = moment of inertia of a partially composite wythe

$I_{NC}$ = moment of inertia of a noncomposite wythe

$I_{FC}$ = moment of inertia of a fully composite wythe

This percentage is provided through design tables or submittal documents to the engineer. Using this percentage, the engineer would back calculate the section properties of interest ($I_g$ or $S$) for use in designing the panel as if it were any solid panel for flexural slender wall design (Eq. [3] and [4]).

$$\sigma_t = \frac{M}{S_{PC}} \tag{3}$$

where

$\sigma_t$ = maximum tensile stress at the outer fiber

$M$ = applied moment

$$\sigma_{midspan} = \frac{5wL^4}{384E_cI_{PC}} \tag{4}$$

where

$\delta_{midspan}$ = midspan deflection

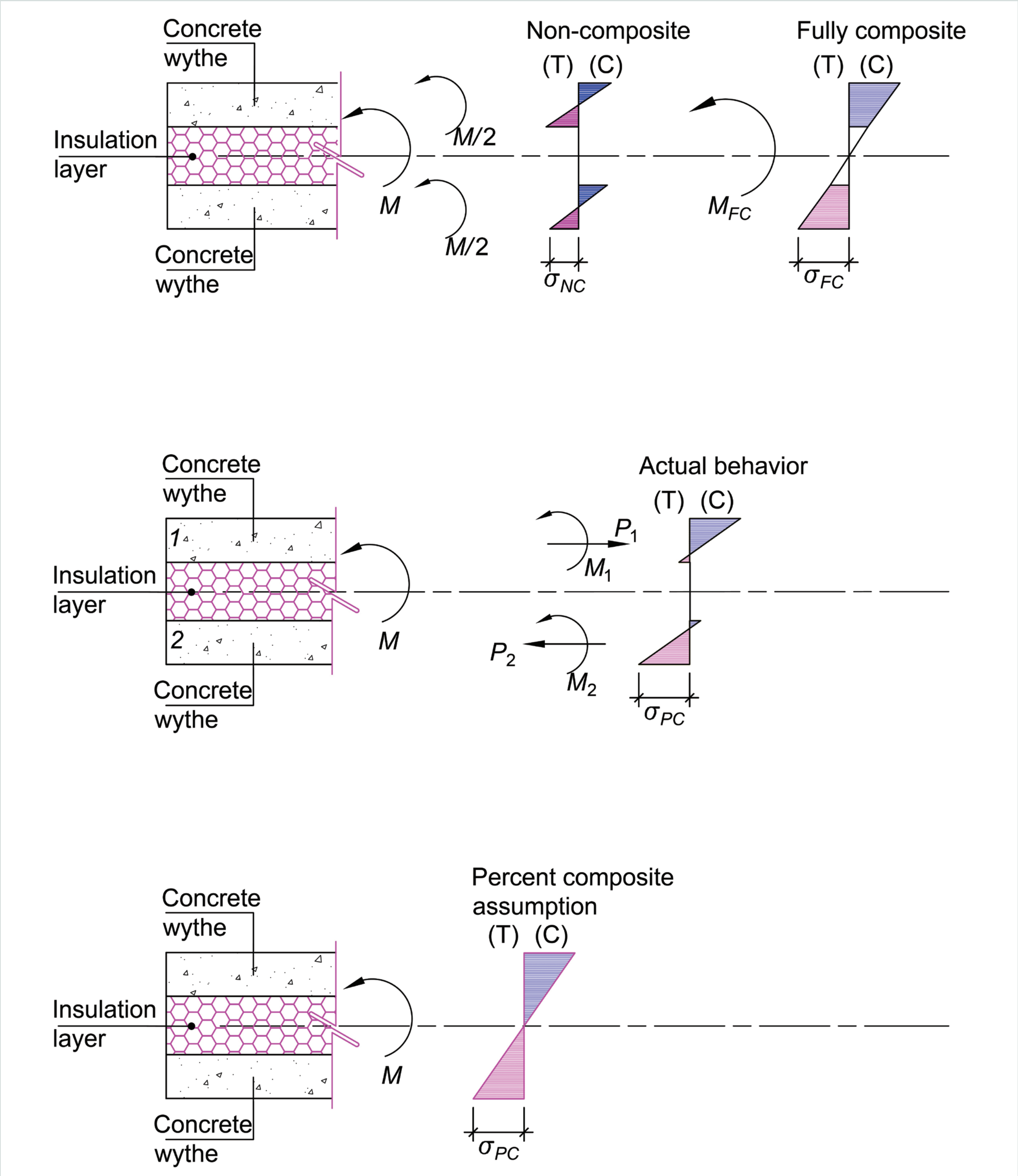



**Figure 1.** Different assumptions about strain profiles in insulated walls. Note: $M$ = applied moment; $M_{FC}$ = fully composite moment; $M_1$ = moment on wythe 1; $M_2$ = moment on wythe 2; $P_1$ = axial force from connectors on wythe 1; $P_2$ = axial force from connectors on wythe 2; $\sigma_{FC}$ = fully composite stress; $\sigma_{NC}$ = noncomposite stress; $\sigma_{PC}$ = partially composite stress.

$w$ = applied uniform load

$L$ = span length

$E_c$ = modulus of elasticity

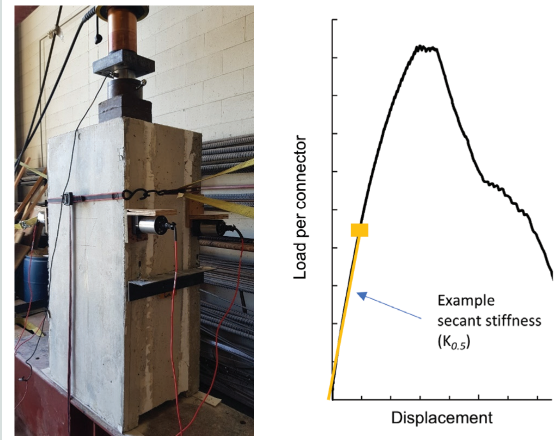
The horizontal shear design is a completely separate limit state that is not covered in the approach here; it is typically handled by shear flow or similar methods.[8,9,27] For a given panel, it is expected that the percentages of composite action will be different for cracking and deflection because the mechanics are different from that of a solid component and $I_{PC}$ can no longer be related to $S_{PC}$ through the distance from the centroid to the outer fiber $c$ (for example, stress distribution in Fig. 2). To the uninitiated, this process seems counterintuitive and duplicative. Although it is true that the process is duplicative, it has greatly facilitated design in a proprietary market for many years and it continues to be used as of the writing of this paper.

The reliance on the percent composite approach to design continues, despite the fact that closed form,[12,28] iterative,[15,17,18] and finite element solutions[6,15,29,30] have been available for many years. Currently, the U.S. engineering community seems to be moving away from the percent composite approach in favor of finite element approaches,[25] but the percent composite approach is still commonly used and may be codified in the future PCI design standard for precast concrete insulated wall panels.

Finite element analysis or other complex analysis methods can be challenging for a practicing engineer to apply to the design of precast concrete insulated wall panels. Many engineers are not familiar with the finite element modeling techniques validated for precast concrete insulated wall panels or the mechanics of the various methods available. Engineers who are inexperienced or unfamiliar with these methods will benefit from an independent check of results developed using alternate means.

This paper aims to create an aid to these issues. A statistically derived and empirically validated method was developed to estimate the percent composite for the critical cracking and deflection calculations of partially composite precast concrete insulated wall panels. The goal of this method is not to replace existing design approaches but rather to provide a supplementary design aid that can be quickly implemented without any of the software required to implement the more complex methods. Engineers may be reluctant to use a statistically derived equation for behavior that could be determined in other ways, but complicated approaches have gained little traction in the engineering world in the past 50 years and are difficult to enforce in a building code environment. Further, the American Concrete Institute's *Building Code Requirements for Structural Concrete and Commentary* (ACI 318-19)[31] includes many statistically derived and semi-empirical equations that are used to describe complex phenomena. For example, in ACI 318-19, the post-tensioned unbonded tendon stress increase at ultimate, $\Delta_{fps}$, is an entirely statistical formula despite phenomenological models available in the literature.[32–34] Furthermore, concrete beam shear design in ACI 318-19 is semi-empirically derived, compared with the phenomenological modified compression field theory used in other code documents.[35,36]

The following sections outline the development of a statistically derived estimate of the percent composite (as defined in Eq. [1] and [2]) for precast concrete insulated wall panels. These equations are derived based on nearly 1 million simulations using ISBT and validated with experimental data.




Double shear test where the center layer is pushed relative to the outer layers shearing the connectors

Example load-versus-displacement curve to indicate stiffness of connector.

**Figure 2.** Double shear testing. Note: $K_{0.5}$ = initial elastic stiffness.

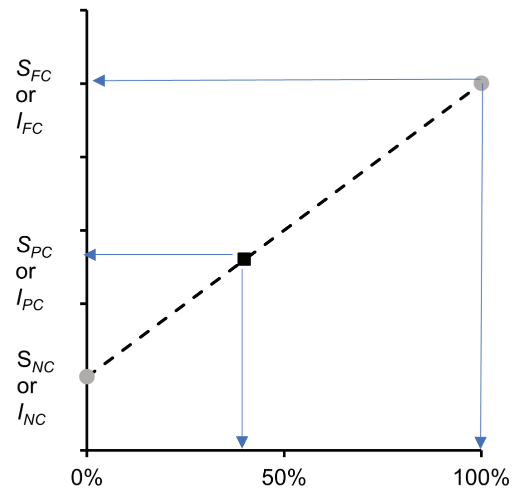



**Figure 3.** Demonstration of converting percent composite to section modulus and moment of inertia properties. Note: $I_{FC}$ = moment of inertia of fully composite wythe; $I_{NC}$ = moment of inertia of noncomposite wythe; $I_{PC}$ = moment of inertia of partially composite wythe; $S_{FC}$ = section modulus for fully composite section; $S_{NC}$ = section modulus for noncomposite section; $S_{PC}$ = section modulus for partially composite section.

## Research significance

Solutions to the elastic behavior of precast concrete insulated wall panels have existed since at least the 1960s,[12] and finite element strategies have been used since the 1980s,[6,37] but these types of solutions have largely been unpalatable or unimplementable on a wide scale in U.S. engineering practice. This paper presents a simple-to-implement set of equations to predict the elastic percent composite for a precast concrete insulated wall panel. The work presented here is not intended to be a design procedure, but it can give precast concrete engineers a starting point for preliminary sizing and estimating or serve as a point of reference for proprietary software that is difficult to replicate.

## Analytical investigation methodology

The primary goal of this paper is to create a simplified linear approximation of the values for percent composite for both cracking and deflection, with the approach having the following general properties:

- The approach is reasonably accurate for a typical range of wall configuration parameters and is not expected to compete with the accuracy of more complex software-based approaches.
- The models rely only upon a small number of variables readily accessible to the practicing engineer with model forms that can be calculated using nothing more than a basic calculator.
- The models for cracking and deflection have identical forms, albeit with different coefficients.
- The models directly predict a unit-invariant percent composite action for cracking and deflection, making it easy to use for both metric and imperial unit calculations.

There was no mathematical way to balance these mostly qualitative objectives across the various models considered during development. Fortunately, among the various statistical models considered by the authors, the simplified linear approximation presented in this paper was the most accurate and easiest to implement.

The development of these simplified approximations requires many observations of percent composite estimates (for both cracking and deflection) across a wide range of different precast concrete insulated wall panel configurations. Unfortunately, the small number of actual experiments on precast concrete insulated wall panels makes it impossible to rely solely on observed measurements when developing a simplified approximation. Further, experimental precast concrete insulated wall panels tend to be smaller than the walls used in actual design, and the current lack of an engineering design standard for precast concrete insulated wall panels creates high variability in the strength measurements taken by the different research groups performing the experiments. For these reasons, the simplified linear approximation described in this paper was developed using the random generation of wall configurations and composite action output from the analytical ISBT approach, which has previously been shown to provide high-fidelity approximations of the cracking and deflection behavior of precast concrete insulated wall panels.[18]

The ISBT approach relates an initial assumed slip profile between the two concrete layers to flexural sectional behavior using axial slip and rotational slip kinematic relationships at connector locations. Slips at the connector locations can then be used with standard beam mechanics, treating each layer as a separate beam with these connector forces acting upon them. The slip profile can then be iterated to maintain static equilibrium at all sections to determine the final slip profile and internal forces. These mechanics were adopted into design software in recent years because of the lack of uniform prediction methodologies.

The dataset development requires the simulation of hundreds of thousands of wall panel configurations and their corresponding composite action values using the ISBT method. The following are the primary assumptions made by the ISBT models used in the simulations: linear stiffness of connectors and other material, uniform spacing of the connectors at 12 in. (300 mm) centers, simply supported panels, and uniform loading. Although connectors are not always spaced at a 12 in. interval in practice, they are commonly uniformly spaced. Uniform spacing is also convenient for the simulations, ensuring that odd spacings were not simulated for different panel geometries. This uniform connector and spacing simplification is shown to predict behavior well in experimental and simulated panels with other connector spacings when the panels contain uniform connector distributions. As expected, there is less accuracy for the limited number of experiments with nonuniform connector distributions (that is, more connectors at the ends); this observation will be discussed in the Experimental Results section.

The ISBT method was used to simulate 1 million panels in R 4.2.0[38] using random combinations of the variables in **Table 1**. Variable ranges were selected to represent most experimental precast concrete insulated wall panel configurations discussed in the "Experimental Results" section, as well as the vast majority of the precast concrete insulated wall panel configurations used in practice. Each variable was simulated on a discrete scale, with the jump between possible values indicated by the increment column in Table 1. These simulated observations were used to train (that is, fit) simple statistical models to predict percent composite strength. These simulated observations are referred to hereafter as training data. Attempts to expand the simulated ranges of these variables began to overwhelm the training data with impractical variable combinations, which compromised efforts to find a simplified approach that would work for typical panels. Given this constraint, wall configurations with variables outside the specified ranges should not use the simplified linear approach presented in this paper.

While the variable ranges in Table 1 reasonably encapsulate typical precast concrete insulated wall panel configurations, it is possible to generate combinations of parameters not practical for actual use. The model-fitting process assumes that most of these unreasonable variable combinations wash out when modeling averages; however, a few combinations

**Table 1.** Variables considered in the iterative sandwich beam theory method

| Variable | Range | Increment |
|---|---|---|
| Length or span $l$, in.* | 120 to 540 | 0.25 |
| Wythe layer thickness $w_x$, in.* | 3 to 5 | 0.25 |
| Insulation layer thickness $I_s$, in. | 2 to 4 | 0.25 |
| Height (that is, width) $h$, in. | 16 to 144 | 0.25 |
| Modulus of elasticity (concrete) $E_c$, ksi* | 3000 to 6200 | 1 |
| Modulus of rupture (concrete) $f_r$, ksi | 0.35 to 0.77 | 0.01 |
| Average elastic stiffness of connectors $k$, kip/in./ft²* | 0 to 300 | 0.1 |

Note: 1 in. = 25.4 mm; 1 ft = 0.305 m; 1 kip = 4.448 kN; 1 ksi = 6.895 MPa.
*Variables were also used in the simplified linear approximation.

lead to numerical issues with the ISBT predictions (that is, excessively high shear stiffness, grossly different wythe thicknesses). For this reason, only observations where the ISBT predicted percent composite action values between 0% and 100% for both cracking and deflection were retained. As a result, 0.5% of the 1 million observations in the master dataset were removed. Of the remaining observations, 80% were used to train the simplified linear approximation, while the other 20% of remaining observations were used for model testing.

The trends observed in **Fig. 4** are the motivation for the final modeling approach, which shows the strong, asymptotic relationship that connector stiffness $k$ and wall length (or span) $l$ share with percent composite strength for both cracking and deflection on the training dataset. The number of observations in the training dataset is large enough that it would be impossible to differentiate between individual points in a traditional scatterplot. For this reason, observations are binned into a hexagonal lattice, where colors represent the number of observations that fall within each cell of the lattice.[39,40] The orange line represents a locally smoothed trend line, which is fit as a single variable generalized additive model, which fits a smoothed trend line through data without assuming a specific model form.[41] The smoothed trend line mathematically balances the degree of smoothness in such a way that the general trend is captured without trying to represent random variation in the data.

The shape of the trend lines in Fig. 4 inspires the use of an asymptotic regression model with the mathematical form in Eq. [5]).

$$\hat{y} = a - \frac{a}{x+1} \tag{5}$$

where

$\hat{y}$ = the predicted output (in this case, percent composite)

a = horizontal asymptote

x = some data input

It is reasonable to assume in this context that $a$ is less than or equal to 100. To preserve the simplicity of the simplified modeling approach, the choice was made to set $a$ equal to 100 and use a two-stage modeling approach to adjust the slope and curvature of the asymptotic regression line for different precast concrete insulated wall panel configurations. Equations (6) and (7) present this two-stage modeling approach for estimating percent composite action ($\hat{\beta}_I$ for cracking or $\hat{\beta}_{Sm}$ for deflection).

$$\hat{b}_w = b_0 + b_1\left(\frac{c_1 k}{100}\right) + b_2\left(\frac{c_2 l}{100}\right) + b_3\left(\frac{1}{c_2 w_a}\right) + b_4\left(\frac{1}{c_3 E_c}\right) \tag{6}$$

where

$\hat{b}_w$ = estimated asymptotic regression coefficient

$b_0$ = regression coefficient

$b_1$ = regression coefficient

$c_1$ = constant for unit conversion (the constant equals 1 when the imperial units indicated in Table 1 are used)

$b_2$ = regression coefficient

$c_2$ = constant for unit conversion (the constant equals 1 when the imperial units indicated in Table 1 are used)

$b_3$ = regression coefficient

$w_a$ = average wythe layer thickness

$b_4$ = regression coefficient

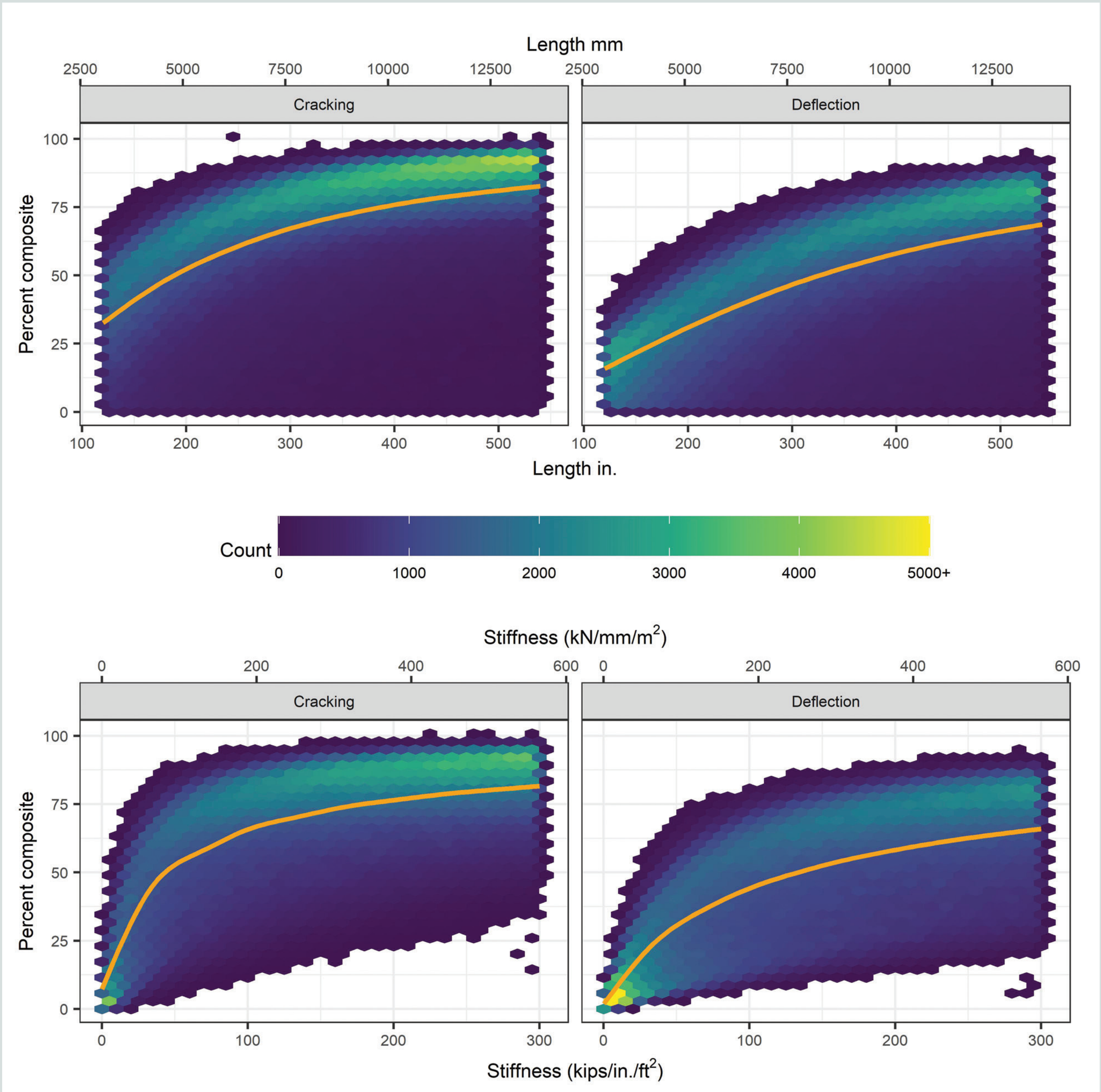



**Figure 4.** Binned scatterplots showing the relationship that wall length *l* and connector stiffness *k* share with percent composite strength. Orange lines represent the smoothed trend estimate of the relationship using generalized additive models.

$c_3$ = constant for unit conversion (the constant equals 1 when the imperial units indicated in Table 1 are used)

$$\hat{\beta}_1 \text{ or } \hat{\beta}_{S_m} = 100\left(1 - \frac{1}{\hat{b}_w\left(\frac{c_1 k}{100}\right)\left(\frac{c_2 l}{100}\right)^2 + 1}\right) \quad (7)$$

The coefficients $b_0$, $b_1$, $b_2$, $b_3$, and $b_4$ are fit using ordinary least squares regression on the training dataset. The estimated coefficients for the stage one model for cracking *cr* are -0.25, -0.01, -0.01, 1.23, 936, respectively. For deflection, the estimated coefficients are -0.06, -0.003, -0.004, 0.32, 340, respectively. The use of three digits is required to ensure necessary precision due to the large numbers computed in the final calculation.

## Example application

To illustrate the use of the function, a realistic full-scale panel from Salmon et al.[42] was used. This panel has a span of 29 ft (8.8 m) and width of 8 ft (2.4 m) with a configuration of a nominal 2.5-3-2.5 in. (64-76-64 mm) and prestressed with five ⅜ in. (10 mm) diameter strands. Fifteen glass-fiber-reinforced polymer semi-continuous shear connector bars with length of 10 ft (3 m) were used as shear ties. Using the ISBT method, the panel cracking load and deflection is 71 lb/ft$^2$ (350 kg/m$^2$) and 0.92 in. (23 mm), resulting in a cracking percent composite of 78% and a deflection precent composite of 52%.[18] The experimental percent composites were 68% for cracking and 58% for deflection. Using the proposed model, it was considered that the wall from Salmon et al.[42] has a length of 348 in. (8840 mm), an average wythe layer thickness of 2.75 in. (69.9 mm), modulus of elasticity of 4524 ksi (31,190 MPa), with stiffness at 73 kip/in./ft$^2$ (140 kN/mm/m$^2$). Using the estimated coefficients $b_0$, $b_1$, $b_2$, $b_3$, and $b_4$ and $c_1 = c_2 = c_3 = 1$, the resulting cracking and deflection percent composite estimates derived from the proposed model are calculated using Eq. (6) and (7).

$$\hat{b}_w(cr) = (-0.25) + (-0.01)\left[\frac{(1)(73)}{100}\right] + (-0.01)\left[\frac{(1)(348)}{100}\right] + 1.23\left[\frac{1}{(1)(2.75)}\right] + 936\left[\frac{1}{(1)(4524)}\right] = 0.362$$

$$\hat{\beta}_{S_m} = 100\left\{1 - \frac{1}{(0.362)\left[\frac{(1)(73)}{100}\right]\left[\frac{(1)(348)}{100}\right]^2 + 1}\right\} = 76\%$$

$$\hat{b}_w(def) = (-0.06) + (-0.003)\left[\frac{(1)(73)}{100}\right] + (-0.004)\left[\frac{(1)(348)}{100}\right] + 0.32\left[\frac{1}{(1)(2.75)}\right] + 340\left[\frac{1}{(1)(4524)}\right] = 12$$

$$\hat{\beta}_1 = 100\left\{1 - \frac{1}{(0.12)\left[\frac{(1)(73)}{100}\right]\left[\frac{(1)(348)}{100}\right]^2 + 1}\right\} = 52\%$$

This example shows the simplicity of the simplified approximation for predicting full-scale data and the accuracy of the fit as compared with the ISBT approach. This method, despite its simplicity, shows strong agreement with the ISBT approach and is competitive when compared with more-complicated methods from the literature when estimating the strength and deflection of experimental data.

## Considerations for machine learning

The implementation of more-complex machine learning approaches, namely regression trees[43] and random forests were also considered.[44] Details regarding how these methods can be used in an engineering context are provided by Wheeler et al.[45] Ultimately, both machine learning approaches were abandoned because they failed to provide the combination of simplicity and accuracy achieved by the previously described linear model approach. Further, the complexity of the random forest approach rivals those of many of the physics-based models already known to provide highly accurate estimates of percent composite strength. When simplicity is no longer desirable, the authors recommend using physics-based approaches, such as the ISBT method, which was used to train all the statistical models considered in this paper.

# Results and discussion

## Comparison to simulated data

**Figure 5** summarizes the accuracy of the simplified linear approximation on the test set that was not part of the training data. This test set contained nearly 200,000 observations randomly generated using the ISBT approach. Like Fig. 4, Fig. 5 bins the observations within a hexagonal lattice with colors representing the number of points in each bin. A smoothed trend line generated with a generalized additive model shows the average ratio of the true cracking and deflection strength against the estimated values obtained using the percent composite predictions calculated using the linear approach. The accuracy ratios are made by using actual estimates of cracking and deflection as calculated from the percent composite predictions. This allows the accuracy ratios to account for the difference between fully composite and noncomposite actions and avoids the inflated variance in accuracy ratios that comes when comparing near-zero percent composite predictions.

Figure 5 shows agreement between the linear approximation and the adapted ISBT approach for deflection, with nearly every linear approximation being within 10% of the simulated ISBT value and the average ratio being nearly equal to 1, which indicates no approximation bias, across the entire range of percent composite predictions. The results for cracking are slightly worse than those for deflection. However, the model displays virtually no bias across the spectrum of estimated values except for the smallest values of percent cracking composite (below 15%). The overall bias (the average ratio) of the linear approximation on the ISBT test dataset is 1.0 for both cracking and deflection, while the overall coefficient of variation (COV), that is, bias divided by the standard deviation, is 0.04 for cracking and 0.03 for deflection. These overall summaries confirm that the simplified linear approximation shows strong consistency with the adapted ISBT method despite its simpler form.

## Comparison to experimental data

While the results on the ISBT test dataset show the effectiveness of the simplified linear approximation, it was still necessary to determine the effectiveness of the approximation on real observations. For this evaluation, the authors used a

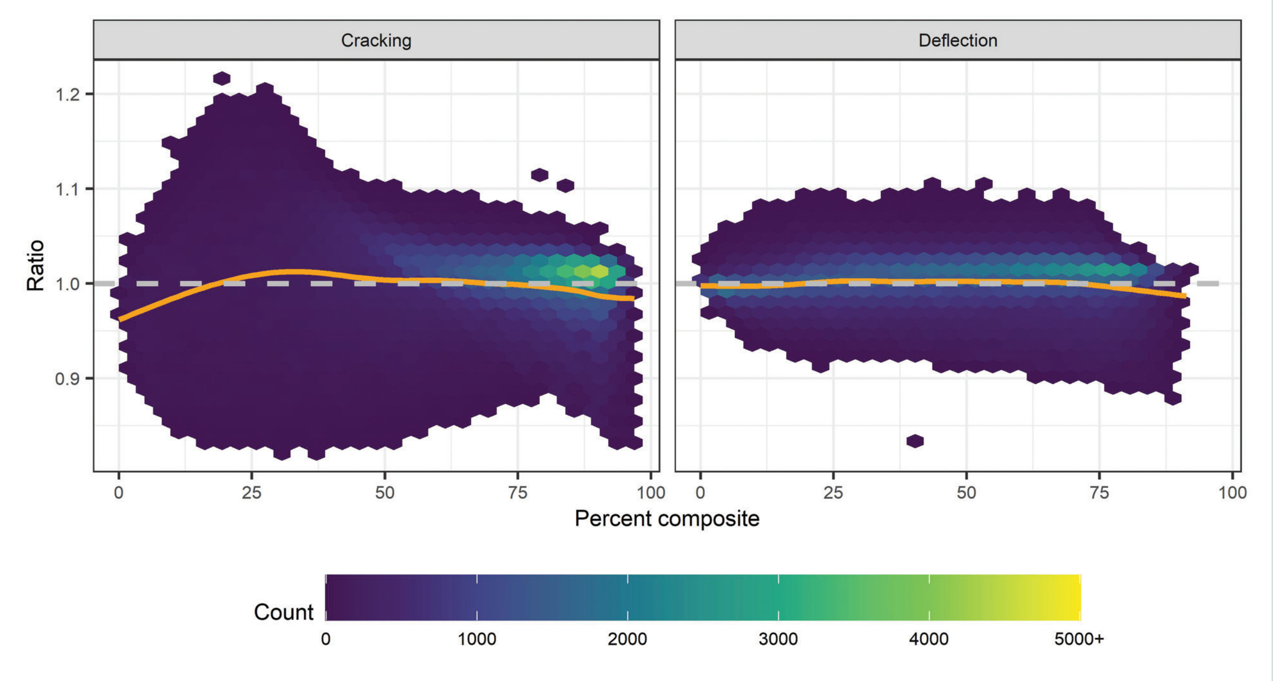



**Figure 5.** The ratio comparison between the cracking and deflection composite values generated by the iterative sandwich beam theory (ISBT) across the values of percent composite action estimated by the simplified linear approximation. Values above 1 (grey dashed line) indicate that the ISBT-generated composite value was greater than the value estimated by the simple linear approximation. The orange line represents the smoothed trend estimate of the ratio using generalized additive models.

dataset of 69 precast concrete insulated wall panel experiments conducted by multiple researchers (**Table 2**).[11,16,27,42,46–53]

Of these 69 experiments, 25 used two-point loading rather than the uniform loading that the simplified approximation was designed to estimate. Additionally, the protocol for construction and testing experimental panels varied from researcher to researcher, which makes it difficult to separate variability in estimation error due to modeling error from error due to differences in wall panel testing or construction. For this reason, accuracy results were grouped according to the paper publishing the experimental unit.[54] Results are only shown for papers using uniform loading with at least five experimental units.

**Figures 6** and **7** show boxplots of the observed versus predicted ratios for cracking and deflection percent composite for each reference using seven methods available in the literature for predicting composite strength and deflection. For brevity, detailed descriptions of each method have not been provided but can be found in the cited references. The methods selected from the literature can be grouped into three categories. The first category is closed-form methods, which include those described by Holmberg and Plem[12] and Allen.[55] The Holmberg and Plem and Allen methods are based on closed-form solutions to the elastic behavior of precast concrete insulated wall panels that incorporate kinematic relationships between axial and rotational slip and sectional behavior and assume a continuous shear layer. Those methods have not previously been compared to a large database of precast concrete insulated wall panels for accuracy. The primary difference between the two methods is the way they introduce the core shear stiffness and local bending stiffness of the panel component. As evidenced by the predictions in Fig. 6 and 7, the difference seems to be negligible.

**Table 2.** Panels in the experimental dataset

| Reference | Number of panels | Load configuration |
|---|---|---|
| 46 | 6 | Four-point loads |
| 47 | 6 | Four-point loads |
| 27 | 5 | Uniform |
| 48 | 9 | Uniform |
| 16 | 5 | Uniform |
| 49 | 5 | Two-point loads |
| 50 | 4 | Two-point loads |
| 51 | 11 | Uniform |
| 52 | 8 | Two-point loads |
| 53 | 4 | Two-point loads |
| 11 | 4 | Two-point loads |
| 42 | 1 | Uniform |

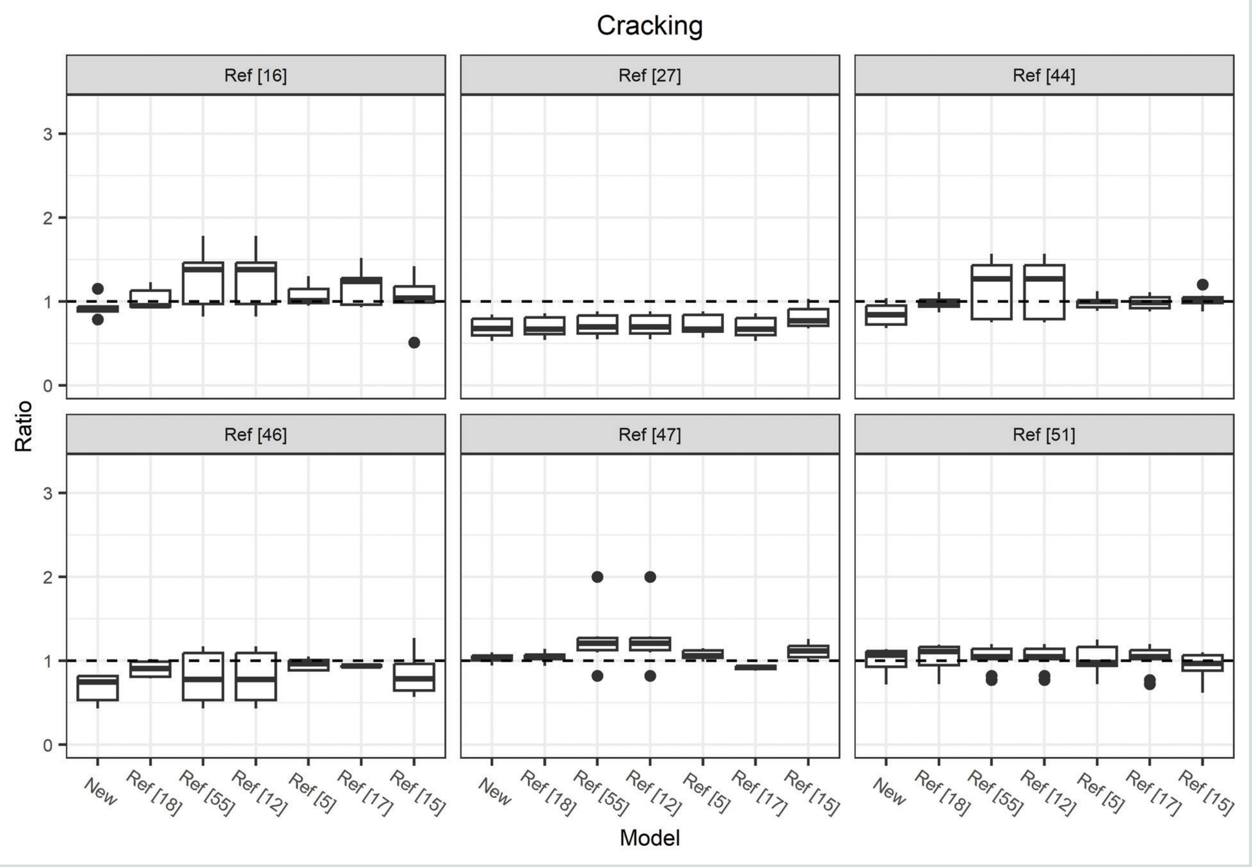



**Figure 6.** Comparison of the observed versus predicted ratio for cracking for precast concrete insulated wall panel experiments as organized by reference number. Values above 1 indicate that the observed strength was greater than the predicted strength.

The second category is iterative methods, which have more flexibility and can capture different geometries and any connector spacing; these methods are known as the simplified model,[15] mechanics-based model,[17] and the ISBT.[18] The simplified method is an iterative method that adds the force couple created by the connectors to the noncomposite resistance after multiple iterative loops to enforce equilibrium through calculation of the slip profile. A further simplification in that method is the consideration of only the rotational slip component, neglecting the axial slip component of the aforementioned methods. The ISBT, as described previously, treats each wythe as a continuous beam element, whereas the mechanics-based model takes similar mechanics but discretizes each wythe into finite length sections. A similar iterative scheme is then implemented to enforce force equilibrium, and curvatures are integrated to obtain deformations following convergence. The third category is the matrix analysis method, termed the beam-spring model.[5] Each of these three methods uses reference-reported geometry, material properties, and double shear elastic stiffness to make its predictions.[56]

These results show that, at best, the simplified linear approximation presented in this paper does as well or better than the more complicated industry-standard methods for cracking and deflection. At worst, the simplified linear approach slightly underestimates experimental cracking and deflection but performs no worse in prediction than the lower-performing industry standard methods. Notably, the simplified approach's deflection predictions did not perform well when compared to data from Gombeda et al.,[27] which investigated panels with connectors concentrated at the ends or in a hybrid configuration, as opposed to a uniform configuration. The method presented herein should only be applied to situations with uniformly spaced connectors.

It should be noted that most of the previously established methods tend to perform poorly in estimating the true values of percent composite action for at least one of the experimental data sets cited in this paper. **Table 3** summarizes the bias and COV for the uniform loading results (Fig. 6 and 7) as well as the experimental results subject to two-point loading. The results in this table show that cracking loads tend to, on average, be slightly underestimated for experimental panels subject to uniform loading and underestimated for experimental panels subject to two-point loading. The bias in the simplified linear approximation is reduced in both uniform and two-point loading scenarios when considering deflection, though all methods tend to have a higher COV for deflection predictions. Table 3 results reveal that the new approach

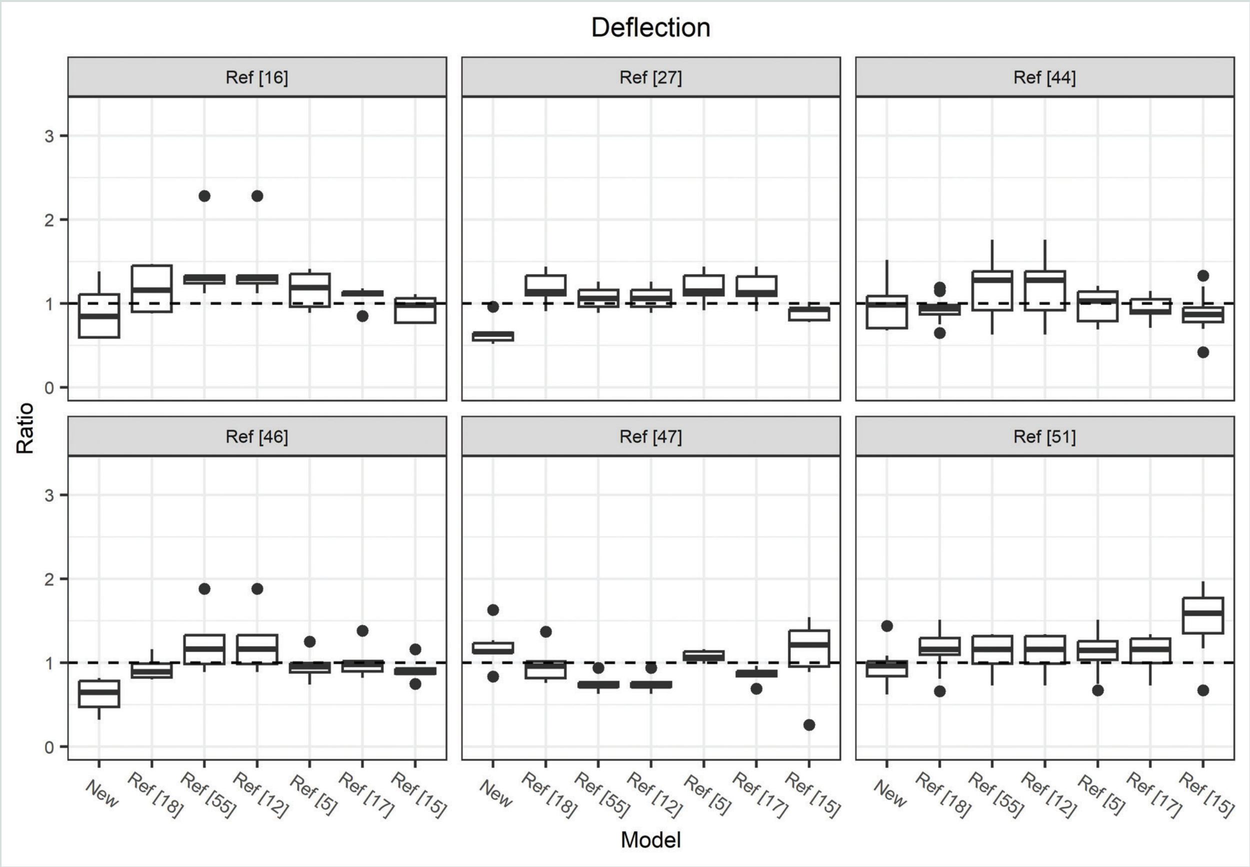



**Figure 7.** Comparison of ratios for observed deflection versus predicted deflection for precast concrete insulated wall panels. Values above 1 indicate that the observed strength was greater than the predicted strength.

**Table 3.** Summary of the biases and coefficients of variation for the experimental data

| | | New | Al-Rubaye et al. (2021) | Allen (1969) | Holmberg and Plem (1965) | Al-Rubaye et al. (2019) | Jensen et al. (2020) | Gombeda et al. (2017) |
|---|---|---|---|---|---|---|---|---|
| Two-point loads | Bias | 1.33 (1.13) | 1.11 (1.22) | 0.91 (1.28) | 0.91 (1.28) | 1.11 (1.04) | 1.15 (1.26) | 0.97 (1.16) |
| | COV | 0.27 (0.47) | 0.21 (0.44) | 0.27 (0.48) | 0.27 (0.48) | 0.21 (0.32) | 0.16 (0.42) | 0.37 (0.49) |
| Uniform loads | Bias | 0.88 (0.90) | 0.97 (1.06) | 1.06 (1.14) | 1.06 (1.14) | 0.98 (1.07) | 0.97 (1.03) | 0.97 (1.09) |
| | COV | 0.21 (0.33) | 0.16 (0.23) | 0.32 (0.3) | 0.32 (0.3) | 0.16 (0.2) | 0.18 (0.19) | 0.2 (0.36) |

Note: Values outside of parentheses are for cracking composite. Values in parentheses are for deflection composite. COV = coefficient of variation.

tends to have a lower COV than the methods from Allen[55] and Holmberg and Plem[12] but a higher COV than the ISBT[18] and mechanics-based model.[17] The best methods for predicting percent composite action are, as expected, better than the simplified approach. However, the simplified approach is reasonably accurate in predicting percent composite action for the experimental data, and, in many cases, it has a smaller COV than existing approaches in the literature. Further, when the assumptions behind the adapted ISBT approach are met (namely, uniform placement of the connectors), as is the case with the data from Cox et al.,[47] the simplified approach is as accurate as any other method considered in this paper in estimating percent composite action.

## Conclusion

This paper has outlined a new simplified method for predicting percent composite and thus the elastic moment of inertia and the elastic section modulus for precast concrete insulated wall panels. One million simulations from the popular ISBT method were used to statistically develop this simplified approach. Furthermore, the new method was compared with the limited experimental data that are available. This dataset comprised 69 panels with various connectors, configurations, and loadings. The following conclusions are made from this investigation:

- The simplified model displays virtually no bias across the spectrum of estimated values except for the smallest values of percent cracking composite (below 15%).

- The overall bias (the average ratio) of the linear approximation on the simulated test dataset is 1.0 for both cracking and deflection, whereas the overall COV is 0.04 for cracking and 0.03 for deflection.

- The training data assumed uniform loading and uniform connectors, so it was expected to perform best on experiments that match those parameters. For such panels, the new method reports a bias of 0.88 and COV of 0.21 for cracking loads. By comparison, the bias for other available methods with reported biases ranges from 0.97 to 1.06, and the COV for those methods ranges from 0.16 to 0.32. This comparison indicates that the new method slightly underpredicts cracking loads when compared with the more complicated approaches, but the new method has a relatively low COV.

- For the two-point load dataset, the bias increased to 1.33 (high bias indicates a conservative prediction) and the COV was 0.27. By comparison, the bias for other available methods with reported biases ranges from 0.91 to 1.15, and the COV for those methods ranges from 0.16 to 0.37. Again, this comparison indicates that the level of accuracy of the new method is similar to that of the more complicated approaches.

Based on these conclusions, the following recommendations are made for the use of the simplified method presented in this paper:

- The new method is suitable for panels with more than 15% estimated composite behavior and uniform connectors for the range of variables investigated (see Table 1).

- Although the accuracy of this method is similar to that of many of the other complex methods, some engineers may find the new method unsuitable for final design because it is statistically derived. In those circumstances, the new method is recommended as a simple and independent way to check results from more complicated approaches.

This paper has not explored applications of the simplified linear approximation for complex panels (for example, panels with openings and nonuniform connectors). A rigorous exploration of how the simplified method might be adapted for application to such panels is a topic for future work.

## Acknowledgments

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## Notation

$a$ = horizontal asymptote

$b_0$ = regression coefficient

$b_1$ = regression coefficient

$b_2$ = regression coefficient

$b_3$ = regression coefficient

$b_4$ = regression coefficient

$cr$ = cracking

$c_1$ = constant for unit conversion

$c_2$ = constant for unit conversion

$c_3$ = constant for unit conversion

$e_c$ = modulus of elasticity

$E_c$ = modulus of elasticity

$f_r$ = modulus of rupture

$h$ = height (width)

$I_{FC}$ = moment of inertia of fully composite wythe

$I_{NC}$ = moment of inertia of noncomposite wythe

$I_{PC}$ = moment of inertia of partially composite wythe

$I_S$ = insulation layer thickness

$k$ = connector stiffness

$K_{0.5}$ = initial elastic stiffness

$\ell$ = wall length

$L$ = span length

$M$ = applied moment

$M_{FC}$ = fully composite moment

$M_1$ = moment on wythe 1

$M_2$ = moment on wythe 2

$P_1$ = axial force from connectors on wythe 1

$P_2$ = axial force from connectors on wythe 2

$S_{FC}$ = section modulus for fully composite section

$S_{NC}$ = section modulus for noncomposite section

$S_{PC}$ = section modulus for partially composite section

$w$ = applied uniform load

$w_a$ = average wythe layer thickness

$X$ = data input

$\hat{\beta}_\ell$ = percentage composite of cracking

$\hat{\beta}_{Sm}$ = percentage composite of deflection

$\delta_{midspan}$ = midspan deflection

$\sigma_{FC}$ = fully composite stress

$\sigma_t$ = maximum tensile stress at the outer fiber

$\sigma_{NC}$ = noncomposite stress

$\sigma_{PC}$ = partially composite stress

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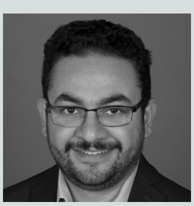

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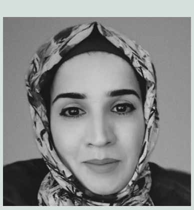

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## Abstract

This paper outlines a new simplified method for predicting the degree of composite action (percent composite) and thus the elastic moment of inertia and the elastic section modulus for precast concrete insulated wall panels. This simplified approach was developed by using 1 million simulations from the iterative sandwich beam theory method. The overall bias (average ratio) of the linear approximation on the simulated test dataset is 1.0 for both cracking and deflection, and the overall coefficient of variation (COV) is 0.04 for cracking and 0.03 for deflection. When compared with data from previously published experiments, the new method has a bias of 1.02 and COV of 0.32 in cases where the experiment conforms to the assumptions of the new method. By comparison, the reported biases of other available methods, which are more complicated to use, range from 0.97 to 1.06, and the COVs of other available methods range from 0.16 to 0.32. Thus, the level accuracy of the new method to predict the percent composite is similar to the levels of accuracy of the more complicated approaches.

## Keywords

Composite action, cracking, deflection, insulated wall panel, ISBT, iterative sandwich beam theory, percent composite, sandwich beam theory method, statistical modeling.

## Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process. The Precast/Prestressed Concrete Institute is not responsible for statements made by authors of papers in *PCI Journal*. No payment is offered.

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