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Compressive Strength of Composites for Aircraft Structures

a report by
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A new methodology is presented in this article to substantiate design possibilities obtained through the building block approach. New measurement technology and damage evolution theory is used to substantiate the compressive strength of composites used for aircraft structures. For this purpose, compressive strength is predicted in terms of other material properties that are not sensitive to sample size and preparation. The proposed methodology is validated with experimental data for several commercially available materials.

Introduction

The compressive strength of polymer matrix composites (PMC) often controls the design of aircraft structures but it is very difficult to measure because various test fixtures give different results depending on sample preparation and sample size. None of the existing fixtures (Suppliers of Advanced Composite Materials Association (SACMA) SRM-1R-94, American Society for Testing & Materials (ASTM) D5379 and ASTM D695, etc.) can be used to measure the compressive strength of production parts because of sample size. As a result of the larger imperfections present in a real part, the compressive strength of large production parts is usually lower than the value obtained from laboratory samples. Machining small samples out of large production parts is not an option because PMCs are usually damaged in the process.

Airframe manufacturers use the 'Building Block' approach to substantiate the design possibilities used for the design of large structures.[1] First, design possibilities are established from coupon tests. Then, structural elements are tested to confirm design possibilities. Next, larger elements, or sub-components, are tested to reconfirm the design possibilities. Finally, a full-scale test is performed to prove the entire design. Since this is an expensive process, any reduction of testing brings substantial savings in time and cost.

The thesis of this paper is that the compression strength of structural elements can be predicted from the available material data (shear stiffness and strength) and easily measured imperfection parameters (misalignment), thus reducing the number of structural tests required to substantiate the design process. Since laminate compressive strength is controlled by the unidirectional layers,[2] the proposed methodology applies to laminated composites.

Compressive Strength Formula

Compression failure of a unidirectional PMC is triggered by buckling of the fibres. The effect of initial shear stiffness on the compression strength has been studied experimentally, concluding that higher initial shear stiffness and strength correlates with higher compression strength. The detrimental influence of fibre misalignment has been experimentally demonstrated. The experimental evidence suggests that fibre buckling of perfectly aligned fibres (Rosen's model) is an imperfection-sensitive problem if the shear response of the composite is nonlinear.[3] These observations were incorporated into a model[4], where it was assumed that all the fibres have the same value of misalignment, α. The value of this empirical parameter, called 'effective misalignment' is set by practitioners so that the model predictions match experimental data. Unfortunately, experimental data must be available before the model can be used.

1. *A Dobyns*, RAH-66 Comanche Building Block Structural Qualification Program, *ASTM Symposium on Composite Structures: Theory and Practice, STP 1383, 17–18 May, Seattle, WA, 1999.*
2. *E J Barbero, S Makkapati and J S Tomblin, Experimental Determination of Compressive Strength of Pultruded Structural Shapes,* Composite Science and Technology, *59, 2,047–2,054, 1999.*
3. *J S Tomblin, E J Barbero and L A Godoy, "Imperfection Sensitivity of Fiber Micro-Buckling in Elastic-Nonlinear Polymer-Matrix Composites",* Int. J. Solid Structures, *34(13), 1,667–1,679, 1997.*
4. *A S D Wang*, A Non-Linear Microbuckling Model Predicting the Compressive Strength of Unidirectional Composites, *ASME Winter Annual Meeting. ASME Paper 78-WA/Aero-1, 1978.*

Since it is well known that a Gaussian distribution of fibre misalignment angles exists in real composites[5], a new model is summarised here, following the developments presented in other sources.[6-8] Basically, it is assumed that the fibres with large misalignment buckle first and the stress is redistributed to the remaining fibres. This phenomenon continues until the remaining fibres are no longer capable of sustaining the load, thus defining the compressive strength of the material.

Since the shear stress-strain plot of the PMC is nonlinear, the bundle stress $\sigma(\alpha,\gamma)$ of a fibre bundle with all the fibres having the same misalignment α has a maximum with respect to shear strain γ. The following equation fits shear experimental data very well.[9]

$$\tau=F_6\tanh(G_{12}\gamma/F_6)$$

(1)

However, the following, simpler equation is accurate enough for the prediction of compressive strength

$$\tau=G_6\gamma+C_2\gamma^2$$

(2)

provided C_2 is adjusted to fit the data in the interval of shear strain over which compression failure takes place.[7]

$$C_2=-\frac{G_{12}^2}{4F_6}$$

(3)

Following the procedure used above[3] but, using Equation 2 instead of Equation 1, the bundle stress is obtained as

$$\sigma(\alpha,\gamma)=\frac{\gamma G_{12}}{\gamma+\alpha}+\frac{8}{3}\frac{C_2\gamma^2}{3(\gamma+\alpha)\pi}$$

(4)

The bundle stress versus shear-strain plot has a maximum for each misalignment value α, as shown in *Figure 1*. The loci of maxima represent the bundle strength $\alpha_{eff}(\alpha)$ of a fibre bundle of a composite with all fibres equally misaligned at angle α. Therefore, the bundle strength is given by the red line in *Figure 1*, reproduced in *Figure 2* as a function of the misalignment angle.

Continuous damage mechanics (CDM) is now used to combine the distribution of misalignment with Equation 4. The misalignment distribution is Gaussian, with a zero mean value and standard deviation Ω. Since fibre microbuckling is indifferent to the sign of the misalignment, the folded Gaussian

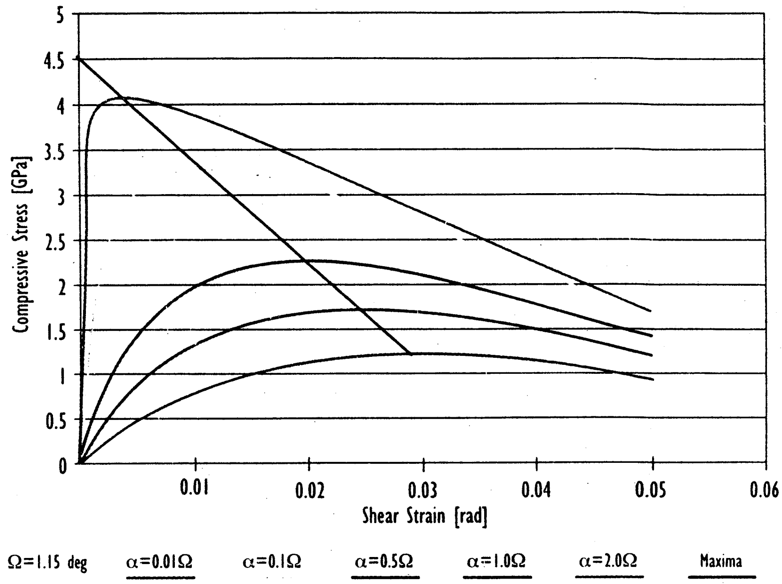

Figure 1: Bundle Stress versus Shear Strain in 949/M30GC

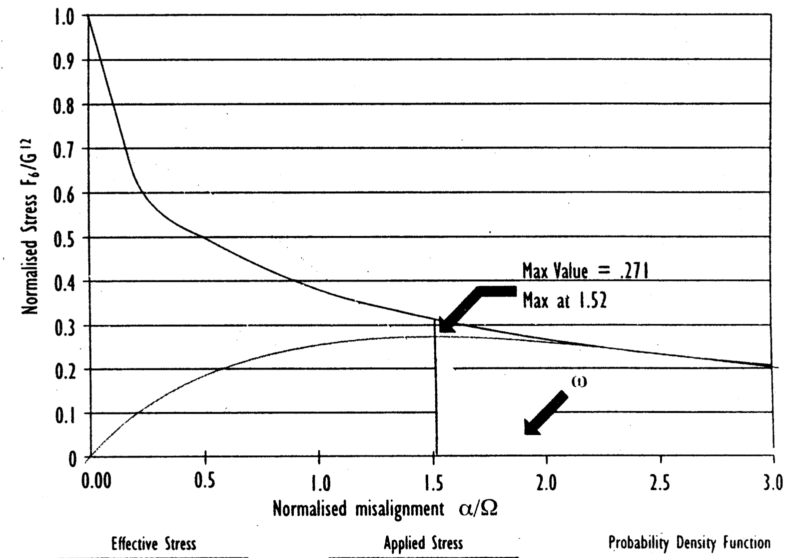

Figure 2: Combined Buckling/Misalignment Plot for 949/M30GC

distribution $f(\text{abs}|\alpha|)$ is used. Then, the area fraction of composite that has fibre misalignment in excess of $\text{abs}|\alpha|$ is given by

$$\omega=\int_{\alpha}^{\infty}\frac{1}{\Omega}\sqrt{\frac{2}{\pi}}\exp\left(\frac{-(x')^2}{2\Omega^2}\right)x'dx'\ ;\ 0\leq\omega\leq1$$

(5)

which corresponds to the shaded area under the folded probability density of fibre misalignment in *Figure 2*. Since the integral above is transcendental, it

5. *S W Yurgartis, "Measurement of Small Angle Fiber Misalignment In Continuous Fiber Composites,"* Composite Science and Technology, *30:279–293, 1987.*
6. *E J Barbero and J S Tomblin, "A Damage Mechanics Model for Compression Strength of Composites"*, Int. J. Solid Structures, *33(29):4,379–4,393, 1996.*
7. *E J Barbero, "Prediction of Compression Strength of Unidirectional Polymer Matrix Composites"*, Journal of Composite Materials, *32(5):483–502, 1998.*
8. *E J Barbero and E Wen, "Compressive Strength of Production Parts without Compression Testing"*, ASTM STP 1383 Composite Structures: Theory and Practice, *ASTM, PA, 1999.*
9. *E J Barbero*, Introduction to Composite Materials Design, *Taylor and Francis, Philadelphia, PA, 1998.*

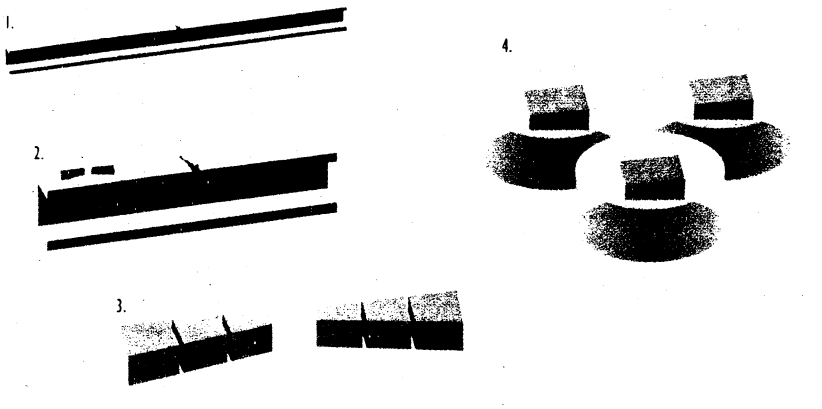

Figure 3: Beam Sample Polishing Procedure

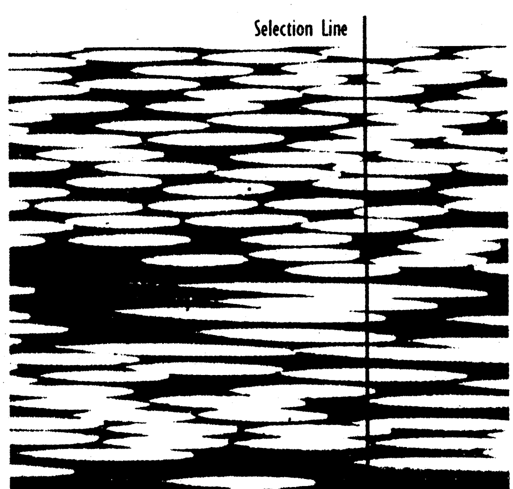

Figure 4: Microscope View of Fibres as Ellipses

is approximated by

$$F(\alpha)=0.8341342\frac{\alpha}{\Omega}-0.1727790\left(\frac{\alpha}{\Omega}\right)^2 \quad (6)$$

For a given value of applied stress σ_{app}, a number of fibres buckle because they have sufficiently high misalignment. The load is redistributed to the unbuckled fibres, having area $(1-\omega)$. Therefore, the applied stress is

$$\sigma_{app}=\sigma_{eff}(\alpha)[1-\omega(\alpha)] \quad (7)$$

which is shown by the Effective Stress line in *Figure 2*. The maximum of the applied stress is the compressive strength, given by

$$F_{1c}=G_{12}\left(\frac{\chi}{p}+1\right)^q,\ p=0.21,\ q=-0.69 \quad (8)$$

in terms of the dimensionless number

$$\chi=\frac{G_{12}\Omega}{F_6} \quad (9)$$

Equation 8 does not contain empirically adjustable factors and is simple enough to be used in practice. The parameters p and q are not set to fit any empirical data – they are obtained as the result of finding the maximum of Equation 7 using the procedure used above[7]. It will be shown that predictions using Equation 8 compare well with compression strength

Experimental Validation

Next, the accuracy of the formula presented in the previous section is checked against experimental data from the literature and from an in-house study of two carbon/epoxy prepregs used in the construction of an unmanned aerial vehicle (UAV). The first material – Cytec Fibreite, using 949-HYE epoxy and M30GC carbon fibres – has a standard modulus fibre with a tough resin. The second material – Cytec Fiberite, using 948A1-HYE epoxy and M40J carbon fibres – has an intermediate modulus fibre and a relatively stiff matrix. The prepregs were laid up by hand and cured in an oven at 135°C for 90 minutes with an approximately 1.04mmHg vacuum bag pressure. The compression, shear strength and shear modulus tests for the specimens were conducted at 82°C, room-temperature-ambient (RTA) and -87°C for both materials.[8]

Coupon and Prototype Beam Tests

The SACMA SRM-1R-94 procedure was selected for the longitudinal compression because it is most commonly used by airframe manufacturers and prepreg producers, etc. The ASTM D5379 method was used to measure shear strength and modulus. Micro-Measurements shear gauges were used since they average the shear strain over the entire region between the notches of the Iosipescu specimen. Modulus G_{12} data were taken between 1,000 and 6,000 microstrains from back-to-back shear gauges and the results from each side were averaged together. The in-plane shear strength, F_6, was taken where there was a significant change in the slope of the load-displacement plot.

Two C-section beams were tested at room temperature in four-point bending. These beams were made of 949 HYE/M30GC and were relatively thick hand lay-ups cured at 135°C with 1.04mmHg vacuum pressure. In Beam 1, the gauge section consisted of 60 ply of zero degrees and one ply ±45 degrees on top and bottom. In Beam 2, the gauge section had 56 ply with one ±45 degree ply every 8 ply of zero degree.

The t-distribution was used to establish the confidence intervals for the actual compression strengths, shear strengths and shear moduli at the three test temperatures. The confidence interval is at the 95% confidence level, based on four replicates (n=4).

Misalignment Characterisation

Samples were cut from the compression cap of the beams close to the location of the failure, as shown in *Figure 3*. These samples had two faces that were reference surfaces when grinding the specimens. A +5 degree cut and -5 degree cut were made and then polished until the fibres could be viewed as complete ellipses, as in *Figure 4*.

The two halves of the tested SACMA specimens were carefully ground to regain parallel edges by using the end of the specimen as a reference surface. A +5 degree cut and a -5 degree cut were then made. The specimens were then in acrylic with the ±5 degree surfaces on top. These surfaces were then polished using the Buehler Ecomet 2 Polishing Machine at 240, 400, 600 and 800 grit sandpaper and with 1 micron alumina polishing compound.

To quantify fibre misalignment, the major and minor axes of the fibre ellipse were measured using a metalographic microscope and video acquisition software. The major axis was measured at 200x magnification for 1,512 fibres on each specimen and the minor axis of the fibre was measured at 500x magnification for 40 points on each specimen.

The misalignment angle is computed from the major axis length, the fibre diameter and the angle of the cutting plane using the following equation, as depicted in *Figure 5*

$$\sin\omega = \frac{d_f}{b}$$

(10)

The misalignment data are represented by just two parameters: the standard deviation of fibre misalignment Ω and the mean value, which is the global misalignment.

Considering only one side of the specimen, the misalignment distributions are slightly skewed from a perfectly normal distribution because of a bias in the measurement technique. For example, the +5 degree side (right side) usually has a distribution with more negative angles and, therefore, a negative skew, while the -5 degree side has the opposite. To cancel the bias, which is introduced by the measurement technique, it is proposed to combine the data from the +5 and the -5 degree sides of the specimen. The combined data are normal (Gaussian), with negligible skew.

Confidence intervals on the standard deviation Ω at the 95% confidence level were constructed for each set of four replicates (n=4) using the t-distribution as given below

$$\sqrt{V - \frac{t_{\alpha/2,n-1}S_V}{\sqrt{n}}} \leq \Omega \leq \sqrt{V - \frac{t_{\alpha/2,n-1}S_V}{\sqrt{n}}}$$

(11)

Ω = population standard deviation
V = sample variance
S_V = standard deviation of sample variance

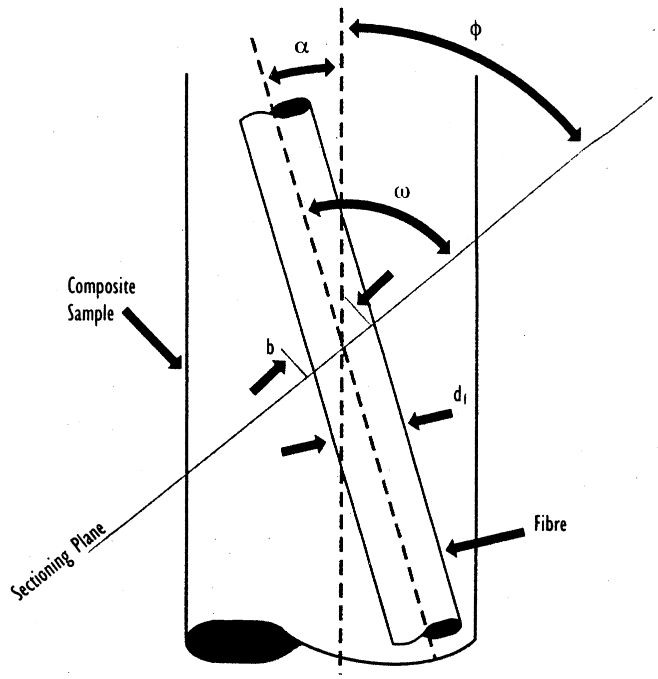

Figure 5: Misalignment Measurement Technique

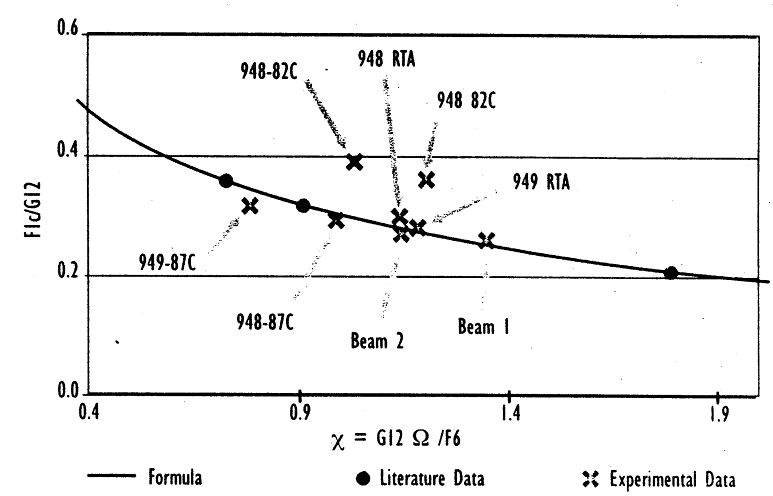

Figure 6: Formula versus Experimental Data

α = probability
n = number of data points
$t_{\alpha/2,n-1}$ = t distribution at α/2, n-1.

Since 1,512 fibre measurements were used in the computation of each of the four Ω values, these can be considered to be exact, with very narrow individual confidence intervals, which were computed using the χ^2 distribution.

Comparison with Experimental Compressive Strength Data

As shown in *Figure 6*, Equation 8 predicts the experimental data from Barbero and Tomblin (1996)[9] and Haberle (1991)[10] very well. In order to further

10. J G Haberle, Strength and Failure Mechanisms of Unidirectional Carbon Fibre-Reinforced Plastics Under Axial Compression, *Ph.D. Thesis, Imperial College, London, UK, 1991.*

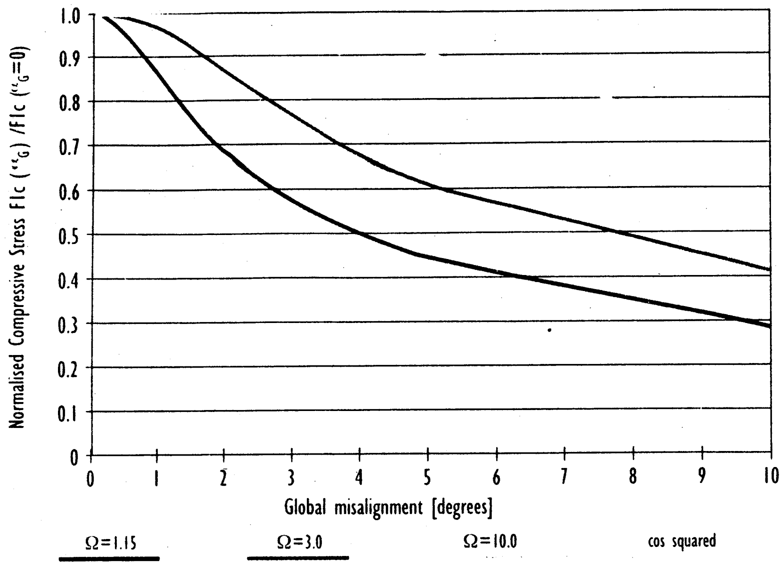

Figure 7: Normalised Compressive Strength versus Global Misalignment

evaluate the merit of the proposed methodology, an experimental programme was designed so that confidence intervals could be established. Not only are they established experimentally on all parameters measured but also on the predicted compressive strength as a function of the experimental confidence intervals on the parameters used in Equation 8, namely G_{12}, F_2, and Ω.

Actual versus predicted compressive strengths of the SACMA specimens and four-point beam bending specimens are shown in *Figure 6*. The formula predicts the compressive strength of the RTA and -87°C compression specimens very well. The predicted strengths of the 82°C specimens are low, even when using the full extent of the confidence interval. This is believed to be caused by residual stresses.

Global Misalignment

When a lay-up has global misalignment α_G, but the misalignment of various layers is balanced and symmetric $|\pm\alpha_G|_s$, the laminate compressive strength can be found by stress transformation (Barbero (1998) page 200"),

$$F_{XC} = F_{1c}\cos^2(\alpha_G)$$

(12)

However, there is no known method for estimating the strength of laminates with unbalanced, global misalignment $|+\alpha_G|_n$ or $|-\alpha_G|_n$. When there is unbalanced global misalignment, the equilibrium Equation 4 still applies, but the distribution of fibre angles is shifted by the average angle α_G to

$$f(\alpha,\alpha_G) = \frac{1}{\Omega\sqrt{2}}\, e\left(\frac{-(\alpha-\alpha_G)^2}{2\Omega^2}\right),\ -\infty<\alpha<\infty$$

(13)

Then, the area fraction of composite with misalignment in excess of abs|α| is given by the integral

$$\omega = F(\alpha) = 2\int_{\alpha}^{\infty} f(\alpha',\alpha_G)\, d\alpha';\ 0\le\omega\le 1$$

(14)

which must be integrated numerically. When multiplied by the effective stress (the Effective Stress line in *Figure 2*), the resulting applied stress curves are similar to the Applied Stress line in *Figure 2*. The maximum of each curve represents the compressive strength at the given global misalignment angle. This technique is informally called the Method of Shifted Distributions. The compressive strength F_{1C}, as a function of global misalignment α_G and standard deviation of fibre misalignment Ω, is shown in *Figure 7*. Each point represents a part fabricated with a prepreg lay-up that has a given value of Ω and is oriented with a global misalignment α_G with respect to the nominal direction (load direction).

Summary

The proposed methodology consists of the following:

a) Measure the global misalignment angle α_G and the standard deviation of fibre misalignment Ω on the actual part. This can be done on witness coupons or on the part itself during post-mortem diagnosis.

b) Use the shear stiffness G_{12} and shear strength F_6 values from coupon data. Since these values are quite insensitive to sample size and preparation, they are representative of the actual part. If in doubt, cut and test ASTM D5379 coupons from the part itself.

c) Estimate the compressive strength of the material using Equation 8 in terms of the dimensionless number χ defined in Equation 9.

d) If the global misalignment is different from zero, use the procedure described above to estimate the off-axis compressive strength.

Conclusions

The proposed methodology accurately predicts the compressive strength prototype beams and coupon samples under various conditions, thus reducing the need for compression testing to substantiate the design possibilities. Shear stiffness and strength coupon data is combined with misalignment data from the prototype part to accurately assess the actual compressive strength of the as-fabricated part. The predictive methodology accounts for both Gaussian misalignment and global misalignment. ■