$$C_{sys} = \frac{1}{m_{cal}} - C_{cal} \tag{9}$$

where:

m_{cal} = slope of calibration curve, P/δ, N/mm [lbf/in.], and
C_{sys} = system compliance, δ/P, mm/N [in./lbf].

The compliance of the MMB loading system must be determined at each setting of lever length, *c*, to be used.

11.6 Mount the MMB specimen in the apparatus. The specimen must be centered in the apparatus and aligned so that no more than a 0.05 mm [0.002 in.] gap is left on one side of the specimen when contact is first made on the opposite side of the specimen. This applies to both rollers contacting the specimen and to the contact made to load the lever. (An alignment procedure for the example MMB apparatus provided in Appendix X2 is provided in Appendix X3.)

11.7 *(Propagation Option Only)*—Set an optical microscope (see 7.6), or an equivalent magnifying device, in a position to observe delamination growth. This device shall be capable of pinpointing the delamination front with an accuracy of at least ±0.5 mm [±0.02 in.].

11.8 The specimen is loaded continuously in displacement control. Apply load to the specimen at a crosshead (or servohydraulic ram) displacement rate of 0.5 mm/min [0.02 in./min] and record the load versus displacement trace as seen in Fig. 4. This may be accomplished with an *x*-*y* chart recorder or by electronic means.

11.9 *(Propagation Option Only)*—Visually observe the delamination front at the end of the insert on either edge. When the delamination grows from the end of the insert, mark the location as VIS on the plot of load versus opening displacement (Fig. 4). The corresponding load value at this point is P_{vis}. Make additional marks on the load displacement plot as the delamination grows past each of the marks placed on the specimen as described in 11.3.

11.10 When the delamination has extended far enough that the load begins to decrease (for the propagation option when the delamination has extended past the last mark or to a crack length of $a = L - 3\ h$), unload the specimen and stop the test machine. Load and displacement are recorded throughout the test, including the unloading cycle. The unloading may be performed more quickly.

11.11 *(Propagation Option Only)*—If an alternative method for monitoring delamination growth is used, such as crack growth gauges bonded to the specimen edges, it should collect data according to the principles, accuracy, and magnification as set out in detail above.

11.12 After the test is finished remove the test specimen from the MMB apparatus and wedge the specimen open so that the delamination extends the length of the specimen. Take one half of the specimen and measure from the center of the loading pin in the applied tab to the delamination insert. Measure three locations across the face to an accuracy of ±0.25 mm [0.01 in.] and record the average as a_o, the initial delamination length. If the delamination insert shows any tears, folds, or irregular shape (that is, the insert is not straight and parallel where the delamination initiated), then no valid toughness value may be reported.

11.13 Inspect the delaminated surface for lines indicating instantaneous delamination front growth. If they are present on the specimen surface, the marks should indicate that the delamination grew uniformly from the delamination insert and did not favor one side or the other. If the distance from the growth line to the delamination insert at the two edges of the specimen differ by more than 2 mm [1⁄16 in.], the test must be rejected because of nonuniform growth.

11.14 *(Propagation Option Only)*—Measure the distance from the center of the hinge pin to each of the marks made on the specimen edge to track delamination propagation.

11.15 Take the load displacement curve and mark the slope of the initial portion of the load displacement curve (as seen in Fig. 4), but neglecting any initial nonlinearities that may occur in the first 20 % of the loading curve. Determine the slope of this marked line and record it as *m*. Determine the point along the load displacement curve where the loading curve and the marked slope line deviate and mark this point as the nonlinear point, NL (the load at this point is P_{NL}). Mark a second line that intercepts the first marked line at zero load and has a slope that is reduced by 5 %. Find where the second marked line intersects the loading curve. If this intersection occurs before the maximum point, mark the intersection as *5%/max*, otherwise mark the maximum load point as *5%/max* (the corresponding load at this point is $P_{5\%/max}$).

11.16 *Interpretation of Test Results*—Several G_c values may be determined from the load-displacement plots.

11.16.1 *Deviation from Linearity (NL)*—The calculation of G_c using the marked NL point (that is, P_c=P_{NL}) assumes that the delamination starts to grow from the insert in the interior of the specimen at this point **(9)**. The NL value represents a lower bound value for G_c. For brittle matrix composites, this is typically the same point at which the delamination is observed to grow from the insert at the specimen edges. For tough matrix composites, however, a region of nonlinear behavior may precede the visual observation of delamination onset at the specimen edges, even if the unloading curve is linear.

11.16.2 *5 % Offset/Maximum Load (5%/max)*—The calculation of G_c using the marked *5%/max* point (that is, P_c=$P_{5\%/max}$) normally produces the most reproducible values, but since these values are also normally the highest, they may be nonconservative.

11.16.3 *Visual Observation (VIS) (Propagation Option Only)*—The calculation of G_c using the marked VIS point (that is, P_c=P_{vis}) gives the fracture toughness for the first point at which the delamination is visually observed to grow from the insert on either edge using the microscope described in 7.6 and is usually an intermediate value between the NL and the *5%/max* values.

11.16.4 *Propagation (Propagation Option Only)*—The G_c values calculated from the load and displacement, and crack length measured as the delamination is growing is often artificially high as a result of fiber bridging (see 5.3.2), but falling propagation values may be an indication of a poor delamination insert. In the high Mode II region, a few materials have exhibited lower propagation values than insert values even for thin inserts. Because bridging is not expected to be effective in increasing the fracture toughness in the high Mode II region, propagation toughness values may at times be the more conservative for this type of loading.

12. Validation

12.1 Values for toughness shall not be calculated for any specimen that fails by breaking in some manner other than delamination advance, such as breaking at some obvious flaw, unless such flaw constitutes a variable being studied. Retests shall be performed for any specimen on which values are not calculated.

13. Calculations

13.1 *Bending Modulus, E_{1f}*—The stiffness of the laminate is used in the subsequent calculation of the fracture toughness and mode mixture.

$$E_{1f}=\frac{8(a_o+\chi h)^3(3c-L)^2+\left[6(a_o+0.42h\chi)^3+4L^3\right](c+L)^2}{16L^2bh^3\left(\frac{1}{m}-C_{sys}\right)} \tag{10}$$

where:

E_{1f} = modulus of elasticity in the fiber direction measured in flexure, MPa [psi],
a_o = initial delamination length, mm [in.], and
m = slope of the load displacement curve, N/mm [lbf/in.].

Since the E_{1f} and subsequent G calculations are weak functions of E_{11}, E_{22}, and G_{13}, published values for the material or class of material are acceptable. The preceding equation calls for the out-of-plane shear modulus, G_{13}, which may be assumed equal to the inplane shear modulus, G_{12}, for a unidirectional composite.

13.2 *Check for Geometric Nonlinear Error*—The fracture toughness calculations that follow assume a linear elastic behavior of the test specimen. If the applied displacement becomes too large, this assumption will be violated and significant errors can result due to geometric nonlinearity. It has been shown that this geometric nonlinear error will be less than 5 % if the applied displacement is less than δ_{max} **(2)**.

$$\delta_{max}=L\left(0.27-0.06\frac{G_{II}}{G}\right) \tag{11}$$

where:

δ_{max} = maximum allowable applied displacement, mm [in.].

The applied load will normally remain below δ_{max} except when testing very tough materials or when using especially thin specimens. No permissible fracture toughness value may be calculated when the applied displacement becomes larger than δ_{max}. If the applied displacement is larger than δ_{max}, the specimen can be redesigned to avoid the problem by using the equations in 8.4. Note that the applied displacement increases with delamination length; therefore the specimen should be sized so that the delamination length can reach the longest value where toughness is to be calculated without δ_{est} becoming greater than δ_{max}.

13.3 *Fracture Toughness, G_c and Mode Mixture, G_{II}/G*—The fracture toughness and mode mixture will be calculated using the following equations. These equations rely on delamination length corrections **(10-12)** for laminate rotation at the delamination front which has been shown to agree well with finite element results **(13)**.

$$G_I=\frac{12P^2(3c-L)^2}{16b^2h^3L^2E_{1f}}(a+\chi h)^2 \tag{12}$$

$$G_{II}=\frac{9P^2(c+L)^2}{16b^2h^3L^2E_{1f}}(a+0.42\chi h)^2 \tag{13}$$

$$G=G_I+G_{II} \tag{14}$$

$$\frac{G_{II}}{G}=\frac{G_{II}}{G_I+G_{II}} \tag{15}$$

where:

G_I = mode I component of strain energy release rate, kJ/m^2 [in.-lbf/in.^{2}],
G_{II} = mode II component of strain energy release rate, kJ/m^2 [in.-lbf/in.^{2}], and
G = total mixed-mode strain energy release rate, kJ/m^2 [in.-lbf/in.^{2}].

Although strain energy release rate and mode mixity can be calculated for any loading condition, when a critical load condition associated with delamination growth is used in Eq 12-15, the strain energy release rate equals the fracture toughness.

$$G_c=G\big|_{P_c,\,a_o}\ or\ G\big|_{P_{1-25},\,a_{1-25}} \tag{16}$$

where:

P_c = either P_{NL}, $P_{5\%max}$, or P_{vis}, N [lbf],
P_{NL} = critical load at nonlinear point of loading curve, N [lbf],
$P_{5\%/max}$ = critical load at 5%/max point of loading curve, N [lbf],
P_{vis} = critical load when delamination is observed to grow, N [lbf],
a_o = initial delamination length, mm [in.], and
$a_{1\text{-}25}$ = propagation delamination lengths, mm [in.].

The initial delamination length, a_o, shall be measured from the face of the delaminated specimen while the propagation delamination lengths, $a_{1\text{-}25}$, are measured to the marks on the specimen edge which were associated with loads and displacements identified as the delamination was propagating.

13.3.1 *Lever Weight Corrections*—The lever and loading apparatus should be made of lightweight material such as aluminum. Occasionally, when testing low toughness material, the weight of the lever may cause a significant loading of the MMB specimen therefore affecting the measured toughness. This should be accounted for whenever the weight of the lever and attached loading apparatus (P_g) weigh more than 3 % of the applied load (P). The following equation may be used to account for the lever weight accurately. c_g is the distance from the center of gravity to the center roller as seen in Fig. 1 (c_g will change with the lever load position). If any test in a series of tests on a material requires the correction for lever weight the correction should be made for all tests.

$$G_{I} = \frac{12[P(3c-L)+P_{g}(3c_{g}-L)]^{2}}{16b^{2}h^{3}L^{2}E_{1f}}(a+\chi h)^{2} \tag{17}$$

$$G_{II} = \frac{9[P(c+L)+P_{g}(c_{g}+L)]^{2}}{16b^{2}h^{3}L^{2}E_{1f}}(a+0.42\chi h)^{2} \tag{18}$$

Adding the correction for lever weight will of course cause the lever length for a given mode mixture to deviate from that predicted by Eq 5. Once the critical applied load can be estimated, the lever length can be set with Eq 19.

$$c = \left(1+\frac{P_{g}}{P_{est}}\right)\frac{12\beta^{2}+3\alpha+8\beta\sqrt{3\alpha}}{36\beta^{2}-3\alpha}L-\frac{P_{g}}{P_{est}}c_{g} \tag{19}$$

13.4 *Statistics*—For each series of tests calculate the average value, standard deviation, and coefficient of variation (in percent) for each property determined:

$$\bar{x} = \frac{\left(\sum_{i=1}^{n} x_{i}\right)}{n} \tag{20}$$

$$S_{n-1} = \sqrt{\frac{\left(\sum_{i=1}^{n} x_{i}^{2} - n(\bar{x})^{2}\right)}{(n-1)}} \tag{21}$$

$$CV = \frac{100\, S_{n-1}}{\bar{x}} \tag{22}$$

where:

$\bar{x}$ = sample mean (average),
S_{n-1} = sample standard deviation,
CV = sample coefficient of variation, in percent,
n = number of specimens, and
x_i = measured or derived property.

14. Report

14.1 *Data Sheet*—A recommended data reporting sheet is provided in Appendix X1. The report shall include the following information. (Reporting of items beyond the control of a given testing laboratory, such as might occur with material details or panel fabrication parameters, shall be the responsibility of the requester.)

14.1.1 *Material*—Complete identification of the material tested including prepreg manufacturer, material designation, manufacturing process, fiber volume fraction, and void content. Include the method used to determine fiber volume fraction and void content. Also include the transverse and shear modulus values.

14.1.2 *Coupon Data*—Average nominal thickness and width of each specimen and maximum thickness variation down the length of the beam, type, and thickness of insert.

14.1.3 *Test Setup*—Type of loading system. Compliance of loading system, C_{sys}, length of lever arm, c, and half span length, L.

14.1.4 *Test Procedure*—Drying procedure, relative humidity, test temperature, and loading rate.

14.2 *Test Results:*

14.2.1 Load-displacement curves indicating load, displacement, and the critical points: first deviation from nonlinearity (NL), 5 % offset (5 %), and max load (max). (Curves recorded using the propagation option should also indicate the visual onset point (VIS) as well as the points at which the delamination was observed to grow past each mark on the specimen edge (1-25).) Upon unloading, if the load does not return to zero, damage may have been induced in the beam arms. Note this on the data reduction sheet.

14.2.2 Measured results including slope, m, load associated with each of the critical points, and delamination length(s).

14.2.3 Calculated results including correction factors, Γ and χ; bending modulus, E_{1f}; area moment of inertia, I; and toughness values, G_c and G_{II}/G, for each critical point.

14.3 Report summary of tests including the number of specimens tested and the mean, standard deviation, and coefficient of variation (standard deviation divided by the mean) of quantities in G_c and G_{II}/G.

14.4 If several mode mixtures are tested results should be presented as shown in Fig. 3 where G_c is plotted versus mode mixture G_{II}/G.

15. Precision and Bias

15.1 *Precision*—The data required for the development of a precision statement is not available for this test method.

15.2 *Bias*—No other standard test method exists for determining the mixed-mode interlaminar fracture toughness of composite laminates. Hence, no determination of the bias inherent in the MMB test is available.

16. Keywords

16.1 composite materials; delamination; interlaminar fracture toughness; mixed-mode bending; Mode I–Mode II

APPENDIXES

(Nonmandatory Information)

X1. MMB DATA SHEETS

MMB STANDARD DATA REPORTING SHEET	Lab:	Date:

Material	Mat. Property Source		Adhesive:	Test:
	Max cure	V_f %	Material	Temp °C
Producer	Temp °C	FAW	Surf Prep	Load Rate
	E_{11} MPa	Γ	Insert:	N/min
Panel No.	E_{22} MPa	χ	Material	Rel Humidity
	G_{13} MPa		Thickness mm	%

Specimen No.	G_{II}/G nominal	α β	c mm	P_g N
Avg. b mm	Ave 2h mm	h mm	L mm	c_g mm
m N/mm	C_{sys} mm/N	E_{1f} MPa	δ_{Max} mm	lever weight correction used ☐

a (mm)	P (N)	G_I (kJ/m²)	G_{II} (kJ/m²)	G_C (kJ/m²)	G_{II}/G (%)
a_0	NL				
	5%/Max				
Propagation Option					
a_0	Vis				
a_1	1				
a_2	2				
a_3	3				
a_4	4				
a_5	5				
a_{10}	10				
a_{15}	15				
a_{20}	20				
a_{25}	25				
Comments:					

FIG. X1.1 MMB Standard Data Reporting Sheet (SI Units)

MMB STANDARD DATA REPORTING SHEET	Lab:	Date:

Material	Mat. Property Source		Adhesive:	Test:
	Max cure	V_f %	Material	Temp °F
Producer	Temp °F	FAW	Surf Prep	Load Rate
	E_{11} psi	Γ	Insert:	lbf/min
Panel No.	E_{22} psi	χ	Material	Rel Humidity
	G_{13} psi		Thickness in.	%

Specimen No.	G_{II}/G nominal	α β	c in.	P_g lbf
Avg.b in.	Ave 2h in.	h in.	L in.	c_g in.
m lbf/in.	C_{sys} in./lbf	E_{1f} psi	δ_{Max} in.	lever weight correction used ☐

a (in.)	P (lbf)	G_I (in-lbf/in^2)	G_{II} (in-lbf/in^2)	G_C (in-lbf/in^2)	G_{II}/G (%)
a_0	NL				
	5% Max				
Propagation Option					
a_0	Vis				
a_1	1				
a_2	2				
a_3	3				
a_4	4				
a_5	5				
a_{10}	10				
a_{15}	15				
a_{20}	20				
a_{25}	25				
Comments:					

FIG. X1.2 MMB Standard Data Reporting Sheet (Inch-Pound Units)

X2. DRAWINGS OF EXAMPLE MMB APPARATUS

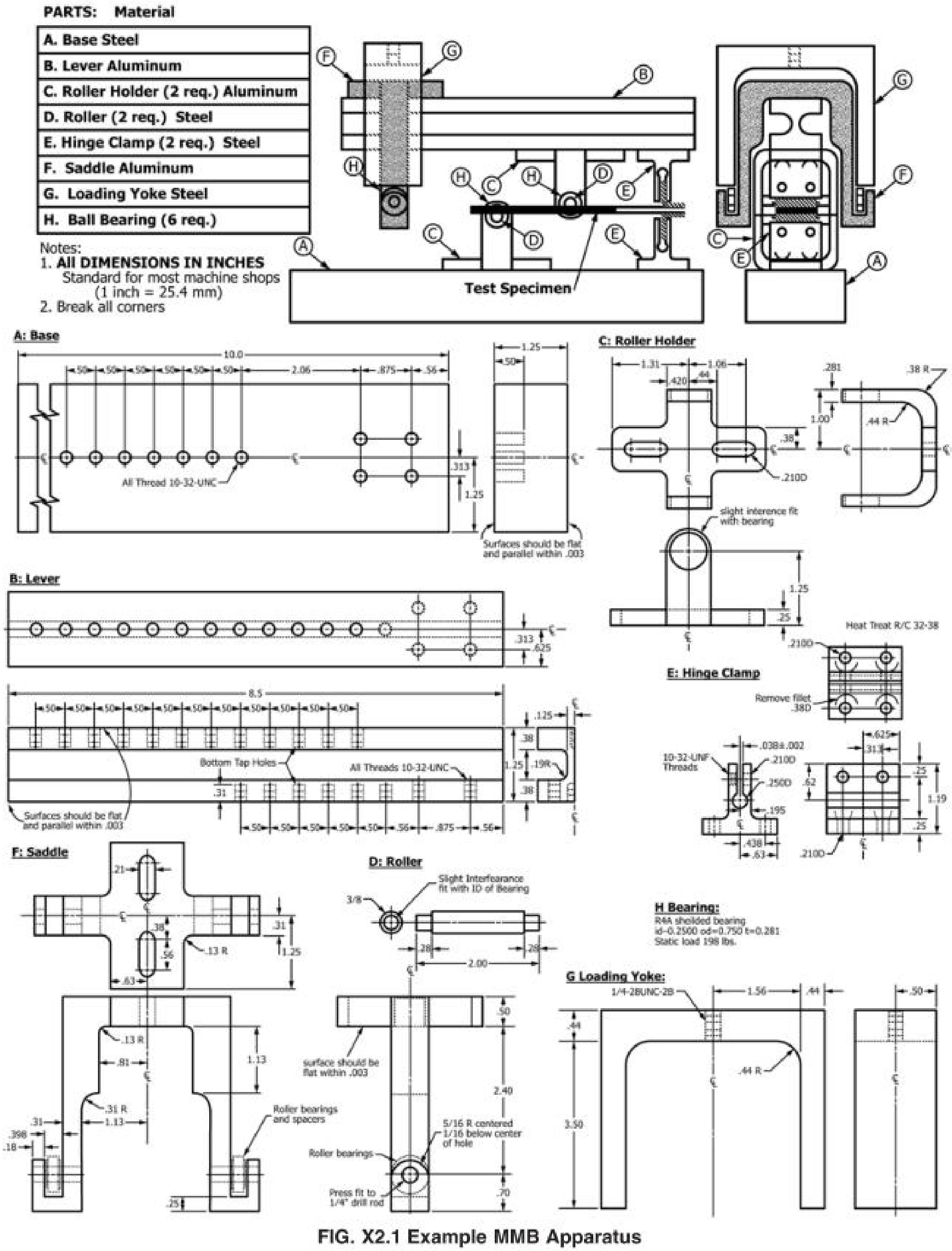

FIG. X2.1 Example MMB Apparatus

X3. ALIGNMENT PROCEDURE FOR THE EXAMPLE MMB APPARATUS SHOWN IN APPENDIX 2

X3.1 Attach the lower roller holder and hinge clamp to the base, setting the span length, 2*L*, to the desired value (span length is the lateral distance between the center of the roller to the center of the pin of a hinge held in the hinge clamp). Make sure that the roller axis is parallel to the axis of the hinge clamp (referring to the drawings in Appendix X2 may help in understanding this section).

X3.2 Attach the upper roller holder and upper hinge clamp to the lever such that the lateral distance between the center of the hinge pin and the center of the roller is half the span length set in X3.1. This attachment should be made such that the center line of the roller is parallel to the axis of the hinge clamp and that both are perpendicular to the longitudinal axis of the lever.

X3.3 Attach the saddle to the lever so that the length along the line of the lever between the upper roller and the center line of the saddle roller equals the desired lever length, *c*. The center line of the saddle roller bearings and the center line of the upper roller must also be parallel. This can be accomplished by making sure that they are both perpendicular to the length of the lever.

X3.4 Mount the test specimen to the base by holding the specimen flush against the lower roller while tightening the hinge in the lower hinge clamp. The hinge should be inserted into the hinge clamp far enough so that the longitudinal axis of the specimen is parallel to the top plane of the base.

X3.5 Next, attach the lever by holding the upper roller flush to the specimen while tightening the hinge in the upper hinge clamp. The hinge should be inserted far enough into the hinge clamp so that the lower plane of the lever is parallel with the longitudinal axis of the specimen.

X3.6 Place the MMB apparatus in the load frame clamping the base firmly to the bottom platen of the machine such that the axis of the bearings on the saddle is parallel to the axis of the loading yoke. (Because the placement of the MMB apparatus may have to be adjusted several times, it may be convenient to place a straight edge against the side of the MMB base. When the straight edge is clamped to the platen, it keeps the axis of the saddle and loading yoke parallel while other adjustments to the MMB apparatus position are being made.)

X3.7 Bring the loading yoke down over the saddle until it just contacts one of the roller bearings. Use a 0.05 mm [0.002 in.] feeler gauge to check the gap between the bearing and the yoke on the opposite side. If the gap is large enough to allow the feeler gauge to slip freely through the gap, the MMB apparatus is not sufficiently aligned with the load frame.

X3.8 If the MMB fixture is not well aligned, remove the fixture from the load frame and reinstall it with a shim placed on one side of the fixture between the load platen and base of the MMB apparatus. Adjust the shim thickness until the feeler gauge in X3.6 can no longer fit through the gap.

X3.9 Often there is some play in the hinge so that lever/saddle assembly can swing from side to side. Place the lever assembly in the center of this arc of movement and check to make sure that the yoke fits over the saddle with clearance on both sides so that they will not touch during loading. The center line of the saddle should also be lined up within 0.1 in. of the centerline of the yoke (along the longitudinal axis of the lever).

X3.10 Repeat X3.4 – X3.9 for each specimen repeating X3.3 – X3.9 each time the mode mixture is changed.

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