AN ALTERNATE COMPRESSION TEST METHOD FOR NOTCHED AND UNNOTCHED COMPOSITES

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ABSTRACT

An alternate compression fixture that can be used for compression and open hole compression (OHC) testing is introduced and discussed. This UCSB fixture has several features that set it apart from others, including the well-established Suppliers of Advanced Composite Materials Association (SACMA) fixture. Some of the UCSB fixture's features are:

i) Supportive extensions on the ends of the fixture act as self-contained bearing surfaces for the specimen.
ii) The specimen is end- and side-loaded.
iii) A reduced combined thickness of the specimen and the fixture allows the use of most standard hydraulic grips.
iv) A lighter, smaller fixture facilitates testing.

Compressive strength data for notched and unnotched carbon fiber reinforced polymer matrix composites (PMC) are presented and compare favorably to results obtained using different fixtures, including the SACMA fixture. In the experimental series of OHC tests discussed herein, maximum stress values were all grouped within 6% of the highest value for each test group.

1. INTRODUCTION

The UCSB compression fixture was designed for an advanced aging study on carbon fiber reinforced PMCs. The experimental program concerned the aging effects on the structural characteristics of these composites by exposing specimens to sustained periods at elevated pressure and temperature (1, 2). OHC test data of quasi-isotropic laminates conducted as part of this aging investigation, and based on the UCSB fixture, are included herein. OHC specimens with alternate materials and layups, as well as unnotched laminate specimens, were also tested with the UCSB fixture to establish baseline laminate properties, to study the versatility of the fixture, and to compare results with those obtained with different fixtures (3-5).

Based on a review of the literature on this type of test, it was determined that the most common fixture for compression/OHC utilized by researchers was the SACMA SRM3R-94 (also listed as SACMA SRM3-88) fixture (6-12). An overview of this fixture and a discussion of its drawbacks are given in the next section. Because of the disadvantages discussed below, the new UCSB fixture was created to facilitate the experiments and allow the use of existing test facilities at UCSB (1, 2). The test data derived from the UCSB fixture and the interpretation thereof is addressed in this paper.

2. SACMA FIXTURE

An illustration of the SACMA SRM 3R-94 fixture used in most OHC tests is in Fig. 1.

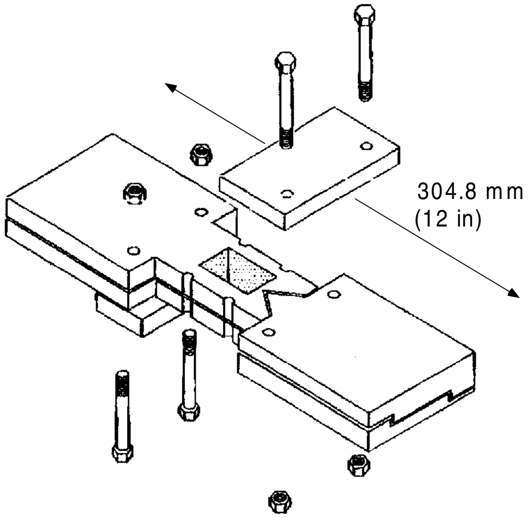

**FIG. 1 — SACMA SRM 3R-94 OHC Test Fixture.
(image courtesy of SACMA)**

This SACMA fixture is composed of four main pieces which are bolted together to hold the specimen at the desired gripping position between roughened faces. Two outer support plates are bolted to the fixture to constrain the main pieces, guiding the sample into pure compression. The openings near the center of the fixture are present to allow for the placement of strain gauges or to give a clear view of the specimen's hole.

The SACMA fixture has various disadvantages, including its relatively large specimen size, bulky overall size, and high required clamping pressure of test grips. Each of these points is discussed in detail in the following paragraphs. While these aspects may be detrimental to testing, the SACMA fixture does offer excellent stiffness for its test specimens, is well-established with a proven record by many users, and has the versatility to be used in grips or between platens.

2.1 SACMA Specimen Size The SACMA OHC test specimens are fairly large because they are designed to have the same geometry as open hole tension (OHT) specimens, which, due to the nature of that test, require extra gripping area. This is undesirable if the material being tested is expensive or difficult to acquire or manufacture. The SACMA test specifies 304.8 x 38.1 x 2.54 mm (12 x 1.5 x 0.1 in) specimens, while the 127 x 38.1 x 2.29 mm (5 x 1.5 x 0.09 in) specimen size in the new UCSB fixture is less than half this size. SACMA dictates 16-ply specimens or, if constructed from fabrics, 2.54 mm (0.1 in) thick.

2.2 SACMA Fixture Size The SACMA OHC test fixture is quite thick in the through-the-thickness direction; it measures 33.02 mm (1.3 in) while holding a 2.29 mm (0.09 in) thick specimen. This dimension is too large to fit in many standard hydraulic grips. Therefore, many test labs will resort to the alternate SACMA test method: the fixture may be end-loaded between two parallel platens instead of gripped. However, this arrangement has several drawbacks, including fixture stability (During testing, the fixture has the potential to actually shift laterally in the test machine if it is not constrained properly.), specimen alignment in the fixture, and fixture positioning in the test machine.

When assembled, because the bolts clamp the fixture around the specimen approximately 89.0 mm (3.5 in) from the coupon's ends, the fixture is not truly supporting or clamping the sample near the ends. Therefore, while testing between platens, the ends may experience a local brooming failure, a common occurrence when testing stiff or unnotched specimens (The UCSB fixture has proven itself to be more forgiving, producing consistent results despite operator variances, as discussed in section 6.). In tests where both ends of the sample fail in brooming before the gauge section fails, the upper and lower pieces of the fixture may actually contact each other before the specimen has failed properly, forcing the operator to abort the test. Brooming failures also create non-monotonic loading on the gauge section and create peaks and valleys in the load-displacement curves generated in the test. Fig. 2 shows a sample load-displacement curve from an end-loaded OHC test with the SACMA fixture.

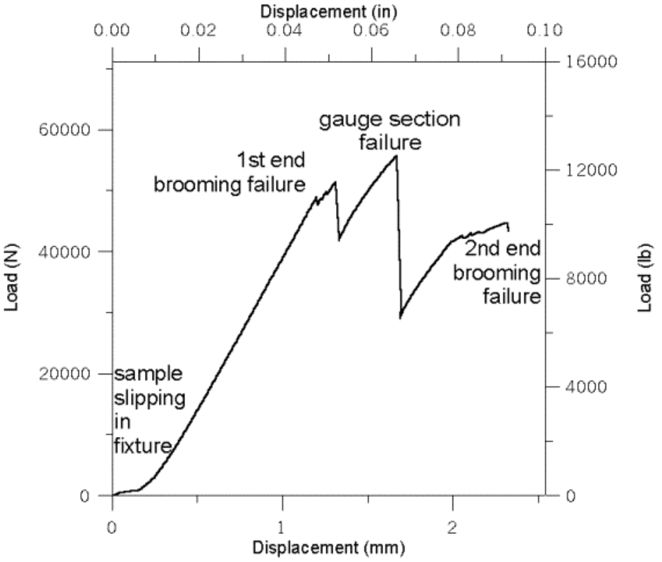

FIG. 2 — Sample SACMA end-loaded test data for M40J/949 $[0]_{14}$ material.

In every SACMA OHC test (held between platens) at UCSB in the fixture comparison, the test machine recorded significant displacement before the load began to increase, no matter how carefully the specimen was loaded (Fig. 2). This was due to the difficulty in loading the specimen so that its ends were perfectly flush with the ends of the fixture. When clamping the specimen into the fixture, the test operator must carefully align the specimen end with the fixture end, a fairly difficult task, given the size and weight of the fixture. Additionally, while the 4.5 kg (10 lb) weight of the SACMA fixture does not directly affect the test results, it can pose a threat to the integrity of the specimen and complicate handling of the apparatus during both specimen loading and fixture placement.

2.3 SACMA Test Grip Pressure Test machine grips must be not only large enough to hold the 33.02 mm (1.3 in) thick assembled SACMA OHC fixture but strong enough to grip the fixture to prevent the test coupon from slipping through friction alone. Roughening the interior surface of the fixture, where the sample is located, helps prevent slipping. However, this adds an extra step in the fixture construction and may not be adequate to prevent the slippage. If the surface is roughened too coarsely, then compression of the fixture on the sample may possibly cause localized crushing and give poor test results.

3. UCSB Fixture

The UCSB compression fixture is somewhat similar to the SACMA OHC fixture, but it features some key improvements. Illustrations and technical drawings of the fixture are shown in Figs. 3 and 4.

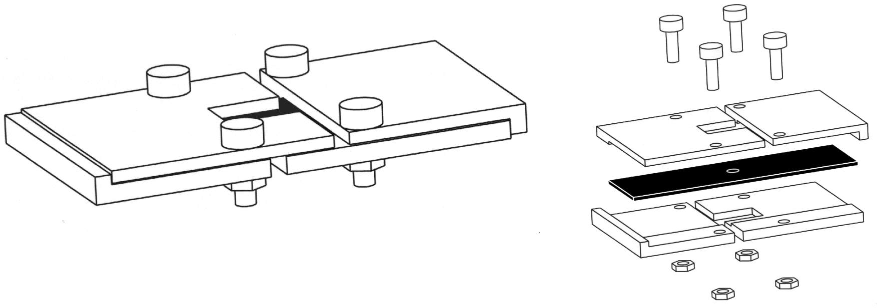

FIG. 3 — UCSB compression test fixture.

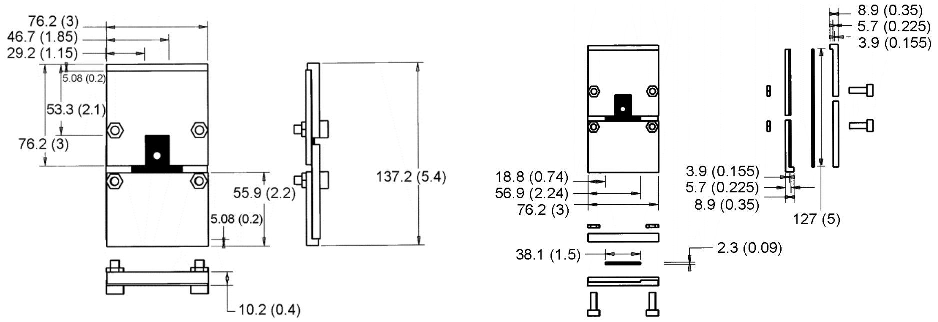

FIG. 4 — 3-view dimensioned drawings of UCSB compression fixture. All dimensions are in mm (in).

3.1 UCSB Test Specimen Size The UCSB fixture was designed around a 127 x 38.1 x 2.29 mm (5 x 1.5 x 0.09 in) test coupon with a 6.35 mm (0.25 in) diameter hole in its center (Fig.5). Despite the smaller sample size for the new fixture, the applied test load is still sufficiently far from the specimen hole to obtain accurate test results, as confirmed by a series of ANSYS (13) finite element analyses, discussed below.

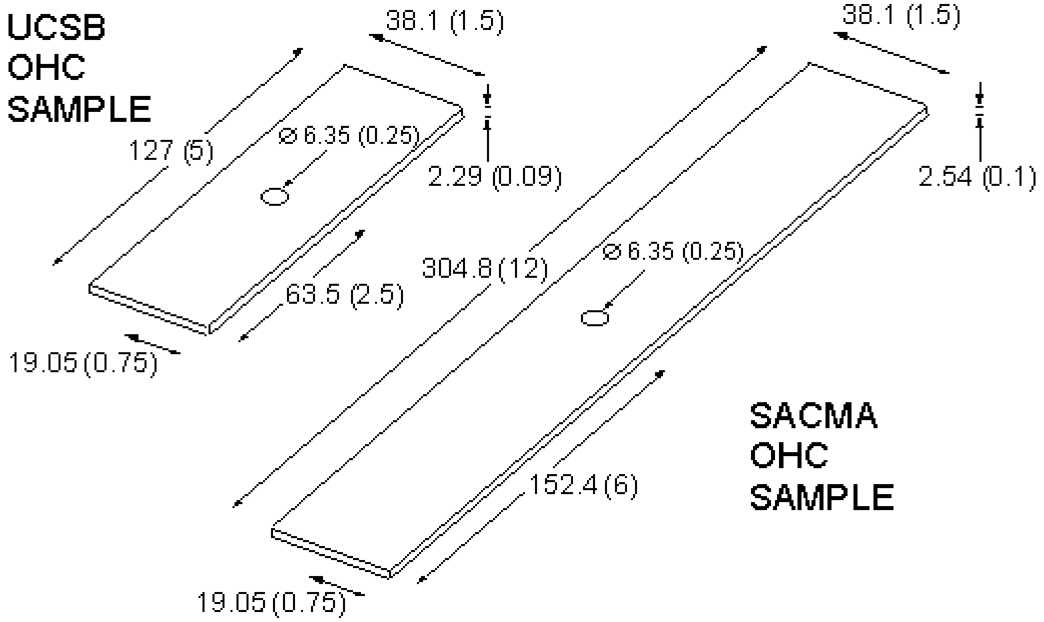

FIG. 5 — Comparison of UCSB and SACMA OHC test specimens. All dimensions are in mm (in), drawing not to scale.

Fig. 6 shows the meshed and loaded 2-D finite element analysis (FEA) models for the SACMA-sized and UCSB-sized quasi-isotropic OHC samples used in the comparison analysis. The triangles on the left sides of the models represent the applied load of a constant compressive displacement on the end of the sample. The triangles on the right sides indicate that the right side's displacement is fixed horizontally. Finally, the triangles on top of the upper right corners of both models represent that corner node's displacement being fixed in the vertical direction. The UCSB specimen model is made of 2,203 plane stress, 8-node elements that are 2.29 mm (0.09 in) thick. For ease and speed of numerical analyses, and because the specimens being studied were quasi-isotropic, an isotropic material was used in the ANSYS model.

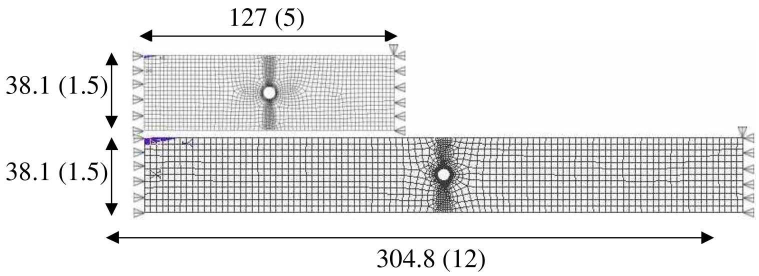

FIG. 6 — ANSYS finite element analysis models of SACMA and UCSB OHC samples. All dimensions are in mm (in).

Fig. 7 displays the longitudinal stress (in the direction of load), across the mid-plane of the quasi-isotropic specimen (bisecting the hole). One can see that the stress distribution for the 127mm (5 in) sample is coincident with that of the 304.8 mm (12 in) sample, confirming that, near the hole, the stresses are equivalent, despite the UCSB fixture's smaller specimen size.

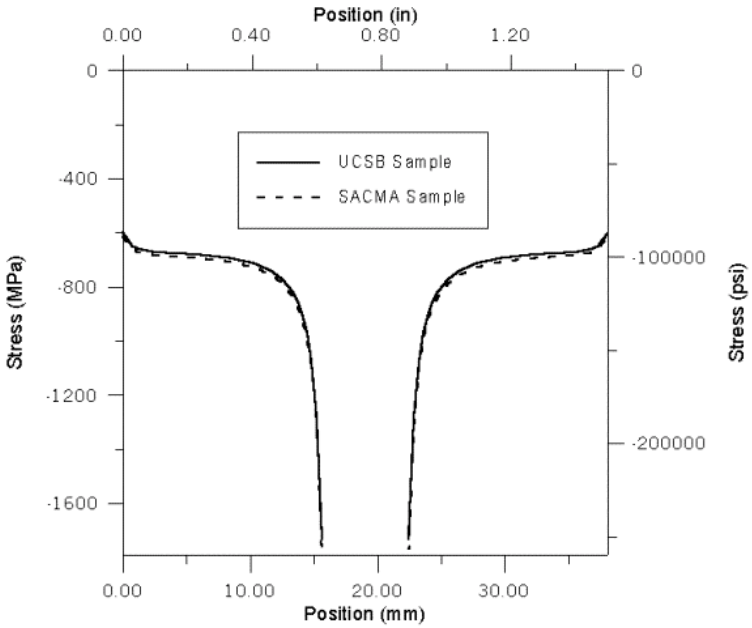

FIG. 7 — ANSYS Comparison of mid-line longitudinal stress in SACMA and UCSB OHC samples.

A similar FEA model was analyzed to confirm that the UCSB test's specimen is adequately long even for highly orthotropic materials. A $[0/45/0/-45/0/90/0_2]_s$ sample (with $E_1 = 2.87\ E_2$) was modeled and the longitudinal stress across the specimen at a distance of three hole diameters away from the hole is plotted in Fig. 8. It can be seen in the plot that the longitudinal stress varies by only 2.4% across the width of the sample, confirming that the UCSB specimen is of adequate length for highly orthotropic layups.

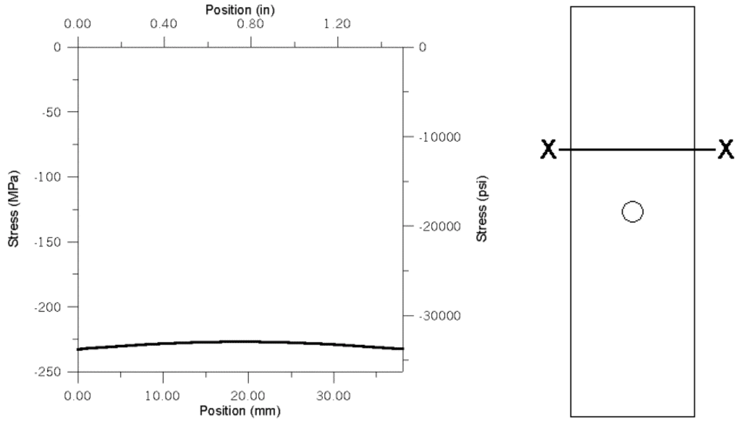

FIG. 8 — Modeled longitudinal stress in a $[0/45/0/-45/0/90/0_2]_s$ OHC specimen at section X-X, a distance of three hole diameters away from the hole.

The UCSB fixture can accommodate specimens as thin as 1.78 mm (0.07 in). If a specimen thinner than 1.78 mm (0.07 in) is inserted, then the fixture will not clamp down on the sample—the inner faces of the opposing fixture pieces will contact, leaving the specimen unsupported. In the other extreme, the protrusions on the ends of the fixture extend 4.95 mm (0.195 in). Therefore, the maximum specimen thickness that is geometrically feasible, while keeping its ends fully supported by these surfaces, is 4.95 mm (0.195 in). Specimens thicker than 4.95 mm (0.195 in) are not recommended for testing, as the ends will not be fully supported and may crush locally. The dimensions on this fixture may be altered to accommodate other sample sizes—for larger specimens, the length and thickness of the two supporting lips on the ends of the fixture may be increased. And, because the material and fabrication costs of the UCSB fixture are low, construction of additional fixtures for different-sized specimens is more feasible than for most other fixtures.

3.2 UCSB Fixture Features The most significant change from the SACMA design to the UCSB fixture is the addition of small protrusions on the ends of two of the four main fixture parts (Figs. 3 and 4). These ledges prevent the sample from slipping out of the fixture and provide a flat, hardened bearing support surface. There are many benefits to this system including:

i) The test specimen is subjected to combined end- and side-loading.
ii) The fixture's inner surfaces need not be roughened.
iii) The test machine grip pressure need not be set high enough to prevent coupon slippage through friction alone.
iv) It facilitates proper sample loading.

The side support plates as seen on the SACMA OHC fixture (Fig. 1) are optional on the UCSB fixture and need be used only if the test machine grips are not in perfect alignment. If the test machine grips are aligned properly, the specimen should experience nearly pure compression, since the grips are only approximately 76 mm (3 in) apart. The overall UCSB fixture weighs only 0.68 kg (1.5 lb), approximately 3.86 kg (8.5 lb) less than the SACMA fixture. This smaller mass facilitates handling, specimen loading, and testing, and shortens the soak time for elevated temperature compression tests, which can hinder testing with heavier fixtures like SACMA and ASTM D3410 (14).

The overall thickness, in the through-the-thickness direction (normal to the plane of the sample), is only 10.2 mm (0.4 in) when fully assembled with a 2.29 mm (0.09 in) thick specimen, as opposed to 33 mm (1.3 in) for the SACMA setup. This allows the use of standard hydraulic grips without the necessity of purchasing larger, more expensive grips. Typical 11,364 kg (25,000 lb) rated grips from major manufacturers can not open beyond approximately 12.7 mm (0.5 in). To hold the 33 mm (1.3 in) SACMA fixture, large, expensive grips rated at 22,727 kg (50,000 lb) are required.

3.3 Unnotched Compression Testing with UCSB Fixture The UCSB fixture has also been used to test unnotched IM7/8552 $[45/0/-45/90]_{2s}$ and M40J/954-3 $[0/45/90/-45]_{2s}$ specimens. When an unnotched specimen is installed, the window in the center of the fixture can be used to accommodate strain gauges to determine elastic modulus and failure strain. The use of the UCSB fixture is preferable to other unnotched compression methods like SACMA SRM-1-88 and ASTM D3410 because the UCSB method does not require bonding tabs to the specimen. Tabs require extra time, expense, and the possibility for error should the tabs be misaligned or flawed (14). Additionally, the tab material and construction (stacking sequence) variations, as well as the adhesive material selected, have been shown to influence compression test results significantly (11, 15). For composite materials that are difficult to obtain, creating composite tabs from the same material can increase testing time and cost. Furthermore, special care must be taken when choosing tab adhesive for testing on moisture-conditioned or elevated temperature samples. Moreover, the ASTM D3410's conical wedge grips compress the tabbed ends of the sample with increasing grip load as more test load is applied, effectively changing the specimen's thickness (15). The ASTM D695 unnotched compression test method uses samples smaller than the UCSB fixture's, but its samples need to be machined to have a necked gauge section.

To date, no compression tests have been conducted on unnotched unidirectional composites with the UCSB fixture. In part, this is due to the authors' awareness of the current position regarding the questionable value of such data, which is known to produce data scatter even for tests that utilize more specialized fixtures like ASTM D3410. A position regarding the determination of design values for composite compressive strength was presented recently by Adams (12). Briefly, the mean, standard deviation, and most significantly, failure mechanism of unidirectional compression test data is not considered to be representative of the equivalent levels and type found for in-situ unidirectional plies contained within practical laminates.

4. Experimental Results of Notched Samples

A summary of the aging study's control group results obtained from OHC tests with the UCSB fixture is presented in Table 1 (1, 2). The tight grouping of the failure stresses of the samples can be observed, showing that the fixture held specimens consistently from test to test so that they failed by the same desired mode of horizontal cracking through the hole, as displayed in Fig. 9. The observed failure strengths correlate well with previous experimental data on IM7 fiber-based materials (9). Table 1 compares UCSB's results with those found in the literature.

TABLE 1 — Failure stresses of quasi-isotropic $[45/0/-45/90]_{2s}$ OHC IM7 specimens

IM7/8552, UCSB fixture Failure Stress, MPa	IM7/3501-6 (reference 9) Failure Stress, MPa	IM7/8551-7 (reference 9) Failure Stress, MPa
300.73	data not available	data not available
305.83		
302.81		
295.75		
303.90		
303.42		
306.22		
294.31		
279.05		
Average: 299.11	Average: 287	Average: 280
Standard Deviation: 8.59	Standard Deviation: N/A	Standard Deviation: N/A

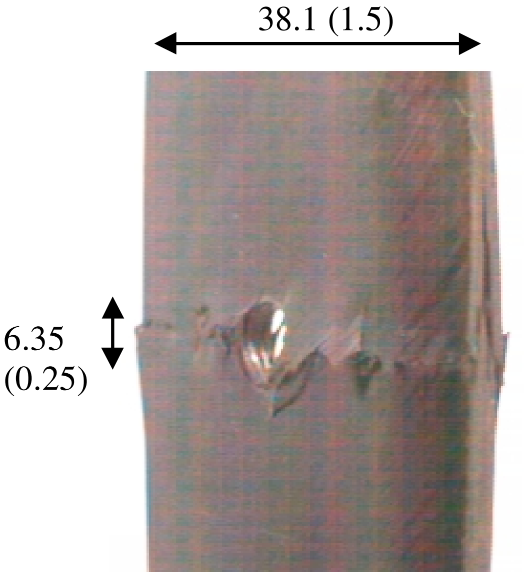

**FIG. 9 — Mode of failure for all tested OHC specimens, 45° side view.
All dimensions are in mm (in)**

A series of M40J/SP1 quasi-isotropic $[0/45/90/-45]_{2s}$ OHC specimens was run in both the UCSB and SACMA fixtures to compare the test results (Table 2). Note that while both fixtures produced the same average failure stress, the UCSB fixture's results were grouped more tightly.

TABLE 2 – USCB vs. SACMA fixture OHC test results, M40J/SP1 $[0/45/90/-45]_{2s}$

UCSB fixture (held in grips) Failure Stress, MPa	**SACMA fixture (held between platens) Failure Stress, MPa**
237.30	236.74
238.26	238.64
238.30	246.83
228.29	215.75
233.58	
229.21	
225.57	
231.86	
228.13	
231.86	
Average: 232.24	Average: 234.59
Standard Deviation: 4.56	Standard Deviation: 13.24

The UCSB fixture was loaned to the University of Wyoming for a series of OHC tests. A set of AS4/3501-6 $[45/0/-45/90]_{2s}$ samples were tested (Table 3). As in the UCSB tests, the failure stresses in this set were all grouped very tightly and matched results found in the literature, which were conducted on samples of size 114.3 x 38.1 mm (4.5 x 1.5 in), as opposed to the UCSB test's specimen size of 127 x 38.1 mm (5 x 1.5 in) (8).

TABLE 3 — Failure stresses of quasi-isotropic OHC AS4/3501-6 specimens

AS4/3501-6, UCSB fixture, tested at U of Wyoming $[45/0/-45/90]_{2s}$, 56% fiber volume Failure Stress, MPa	AS4/3501-6 (reference 8) $[45/90/-45/0]_{2s}$, 60% fiber volume Failure Stress, MPa
300.9	|
308.0	|
295.7	data not available
302.1	|
313.9	|
Average: 304.1	Average: 319
Standard Deviation: 7.017	Standard Deviation: N/A

Two series of M40J/954-3 OHC specimens were tested to study the UCSB fixture's performance with orthotropic samples. Open hole compression failure strengths for a set of 10 $[0_2/45/0_2/-45/0/\underline{0}]_s$ and 10 $[90_2/-45/90_2/45/90/\underline{90}]_s$ samples are found in Table 4. Although these test results were not compared with those in the literature or those obtained with another test method, the tight grouping of the data further reinforces the UCSB fixture's versatility and consistency.

TABLE 4 – OHC failure stresses of orthotropic M40J/954-3 specimens

$[0_2/45/0_2/-45/0/\underline{0}]_s$ Failure Stress, MPa	$[90_2/-45/90_2/45/90/\underline{90}]_s$ Failure Stress, MPa
313.14	121.20
310.61	120.23
312.63	118.99
311.23	123.58
331.66	120.67
336.98	115.69
310.21	115.44
323.39	122.51
303.48	114.40
320.47	114.04
Average: 317.38	Average: 118.67
Standard Deviation: 10.554	Standard Deviation: 3.5077

Additionally, experimental results have illustrated that the method of gripping and supporting the specimens is sound. Fig. 10 shows sample load-displacement curves with the UCSB fixture, one from each of the five groups of samples after 1000 hours of soaking at 121.1 °C (250 °F) in the aging study. The increase in load is linear with the increase in displacement, indicating that neither the fixture nor the sample was slipping or otherwise shifting under the applied test load. Load-displacement curves obtained from testing with the SACMA fixture between platens always produced a "flat spot" on the lower end of the graph, demonstrating that the test machine was displacing and the specimen was shifting and settling in the fixture without bearing load. Fig. 2 shows this non-linearity in the SACMA test, as well as plot features resulting from brooming failures.

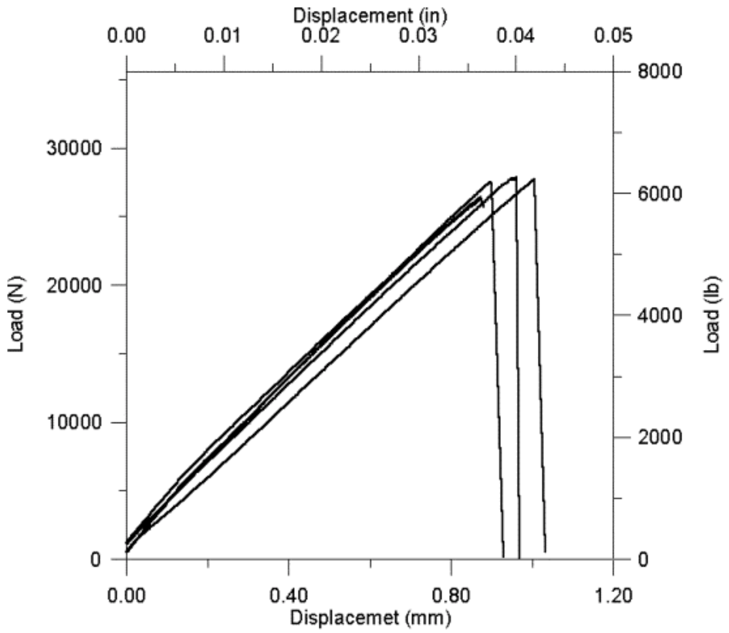

FIG. 10 — Sample UCSB fixture test data, 1 OHC sample from each aging study group: control, 0.101 MPa (14.7 psi), 0.345 MPa (50 psi), 1.03 MPa (150 psi), 1.72 MPa (250 psi).

5. Experimental Results of Unnotched Samples

Failure stress values for specimens with no hole were grouped as tightly as those of the OHC specimens above. Two series of unnotched specimens, IM7/8552 $[45/0/-45/90]_{2s}$ 127 x 38.1 x 2.29 mm (5 x 1.5 x 0.09 in) and M40J/954-3 $[0/45/90/-45]_{2s}$ 127 x 38.1 x 3.05 mm (5 x 1.5 x 0.12 in), were conducted to determine material properties and to confirm that the UCSB fixture can produce consistent results for unnotched samples. Table 5 shows failure stress data from the 5-sample IM7/8552 series. All unnotched specimens failed in the exposed gauge section, where the fixture was not supporting them. As mentioned above, this study did not include tests of unidirectional unnotched laminates, as these specimens give scattered test results and are not typical of real-world layups. The results are compared with a predicted failure stress approximation based on IM7/PETI's unidirectional compressive strength of 1298.3 MPa (4). Using Hart-Smith's 10% rule for the given layup of 25% 0°, 50% 45°, 25% 90°, the stress factor = (0.25) 1 + 0.5 (0.1) + 0.25 (0.1) = 32.5% of 1298.3 MPa = 422 MPa (16).

TABLE 5 — Failure stresses of unnotched IM7/8552 $[45/0/-45/90]_{2s}$ with UCSB fixture

Failure Load, N	Failure Stress, MPa	Predicted Failure Stress
34,820	383.85	|
34,910	390.40	|
35,230	377.35	N/A
32,610	387.90	|
34,350	378.16	|
	Average: 385.53	10% Rule Approximation: 422
	Standard Deviation: 5.77	

6. Experimental Results of Grip Pressure and Specimen Loading Variations

A series of six tests was conducted to determine the optimal gripping pressure of the UCSB fixture for OHC tests. Quasi-isotropic IM7/8552 samples were tested at grip pressures of 13.78, 17.23, 20.67, and 27.56 MPa (2000, 2500, 3000, and 4000 psi), measured as the pressure in the hydraulic line feeding the grips. At 13.78 and 17.23 MPa (2000 and 2500 psi), the fixture slipped grossly in the grips at approximately 23,140 N (5200 lb) of load. At 20.67 MPa (3000 psi), the gripping pressure used for all UCSB compression tests, the fixture did not slip at all and the load-displacement curve was nearly linear (Fig. 10). Gripped at 27.56 MPa (4000 psi), the fixture also did not slip, but the load-displacement curve was slightly straighter than at 3000 psi. This indicates that the specimen does compress somewhat within the fixture's clamped section when tested at 20.67 MPa (3000 psi), thus confirming that the samples are indeed at least partially end-loaded by the fixture's end supports. This proves that the sample is not loaded on its faces through friction alone.

The failure stresses and loads of the samples from grip pressure variation series of tests, all cut from the same panel and subjected to identical aging conditions, are detailed in Table 6. These OHC test results prove that the UCSB fixture can be used successfully in smaller test machines with lower gripping pressure capacity and still achieve consistent results.

TABLE 6 — Failure stress dependence on grip pressure for UCSB Fixture OHC tests

Grip Pressure MPa	Failure Load N	Failure Stress MPa	Fixture Slipped in Grips?
13.78	24,110	273.48	Yes
17.23	24,550	279.63	Yes
17.23	24,650	280.17	Yes
20.67	24,410	274.66	No
27.56	24,730	280.88	No
27.56	24,400	277.33	No
		Average: 277.67	
		Standard Deviation: 3.07	

Another series of three OHC tests was conducted to confirm that the UCSB fixture's end-loading extensions were effective at the desired gripping pressures and that the fixture was tolerant to operator error. These samples were taken from the same panel as those discussed in Table 6. The specimens were intentionally misloaded into the fixture so that the ends of the samples were not resting on fixture's ledges (Table 7). In the two tests with 20.67 MPa (3000 psi) gripping pressure, when the sample was under approximately 20,030 N (4500 lb) of test load, it began to slip in the fixture. The load-deflection curve's slope decreased noticeably, but the specimen continued to hold increasing load until failure. When held under 27.56 MPa (4000 psi) of grip pressure, the misloaded fixture displayed an extremely small decrease in its load-deflection curve's slope. Also note that the ultimate crosshead displacement for this sample is much smaller than that of the two samples gripped at a lower pressure. This further confirms that the UCSB fixture's end-loading extensions do carry load during typical OHC tests at 20.67 MPa (3000 psi) of grip pressure—a fixture without these loading lips that is held in grips may experience specimen slippage. Additionally, the failure stresses are grouped tightly enough to suggest that, even if the operator fails to load the specimen correctly, an accurate failure stress measurement can still be obtained from the test.

TABLE 7 — Failure stress dependence on specimen misloading for UCSB fixture

Grip Pressure MPa	**Failure Load N**	**Failure Stress MPa**	**Crosshead Displacement Mm**
20.67	244.97	278.25	1.0795
20.67	253.61	287.86	1.1278
27.56	250.45	284.27	0.7366

7. Conclusion

The UCSB compression test method provides consistent and accurate experimental results and addresses some of the drawbacks of existing fixtures. While the SACMA fixture can provide valid material strength properties (if it is held in grips), the UCSB fixture is an improvement, especially in usability and functionality. The UCSB fixture can also be used in standard, smaller hydraulic grips. It does not require tabbing or necking specimen preparation that some of the other established test methods do. Its light weight facilitates specimen and fixture loading. The support ledges prevent slipping of the sample and result in secure and accurate placement of the specimen. The small coupon size reduces material costs and preparation time. This fixture is an alternate to existing fixtures that can be utilized by many industrial and university labs without the need for larger, more expensive equipment.

8. Acknowledgements

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