1 Introduction

Bearing strength is often a critical design property for polymer matrix composite structures, as it frequently defines the sizing required for regions containing bolted attachments. Over the past three decades, stakeholders in the composites industry have participated in the development of standard test methods for bearing strength. However, diverse requirements have resulted in a proliferation of test methods and specimen configurations. The number of published “industry standard” test configurations now stands in the double-digits.

Understandably, the large number of standards often leads to confusion among novice users. The primary purpose of this paper is to provide guidance when selecting an industry standard bearing strength method for testing polymer matrix composites. This will be accomplished by:

- Reviewing the history and current state of industry standard tests for composite bearing strength determination.
- Comparing and contrasting important specimen attributes and sensitivities.
- Providing guidance on the use of particular tests for specific applications, such as generic vs. design-specific data generation.

It is the desire of the author that this paper will facilitate discussion and lead to improvements in the industry standard tests, as well as to the development of improved industry guides covering test selection for bearing and composite bolted joints in general.

2 Standard Tests for Bearing Strength

The development of industry standard test methods has facilitated the expanded use of polymer matrix composites in aerospace, marine, automotive, energy and civil infrastructure structural applications. In the case of composite bearing strength, the first standard tests utilized were those which evolved from the plastics industry, such as ASTM D953 [1] which was first published in 1948. Specific standards for high-modulus fiber reinforced composites were first developed in the late 1980s, and included SACMA SRM 9-89 [2], ASTM D5961 [3] and prEN 6037 [4]. A plain-pin bearing strength test, ISO 12815 [5], was recently published by ISO/TC 61/SC 13.

2.1 ASTM D953

ASTM D953 is under the jurisdiction of ASTM Committee D20 on Plastics, and covers bearing strength determination for rigid plastics. This standard was widely used in composites testing prior to the development of SACMA SRM 9-89 and ASTM D5961, which were intentionally developed for continuous fiber composites. It is still utilized for composites testing within historical material specifications, especially for low modulus materials such as fiberglass-reinforced composites.

D953 includes two test procedures with unique specimen and fixture configurations, as shown in Fig. 1. Procedure A loads the specimen in double shear tension bearing. The test utilizes a fixture assembly composed of three steel loading plates. Shims must be used to accommodate variations in specimen thickness.

Procedure B loads the specimen in compression bearing. The test uses a clevis fixture which contains thrust bushings to align the specimen and resist lateral displacement of the specimen under compression loading.

Both procedures determine to the pin bearing strength of the composite, as no out-of-plane clamp-up forces are applied to the specimen. Both procedures cover testing with either 3.18 mm (0.125 in.) or 6.35 mm (0.250 in.) diameter bearing pins as standard.
2.2 SACMA SRM 9-89

In the late 1980s, the Suppliers of Advanced Composite Materials Association (SACMA) developed a series of standard composite test methods to support material qualification and acceptance testing. A double shear bearing test method, SRM 9-89, was developed but never formally published as a SACMA standard. Nonetheless, the specimen and fixture configuration have found use within the composites industry.

The SRM 9-89 fixture is similar to that of ASTM D953 Procedure A with a 6.35 mm (0.250 in.) diameter bearing pin, but integrates the three plates into a one-piece loading fixture for ease of handling. Sleeved bushings interface between the loading pin and the fixture, which permit clamping forces to be imparted to the test specimen. Use of the bushings also accommodates variations in specimen thickness without the need for shims.

2.3 ASTM D5961

ASTM D5961 is under the jurisdiction of ASTM Committee D30 on Composite Materials. When first published in 1996, the standard contained two test procedures (for double and single shear testing, respectively). As shown in Fig. 2, Procedure A is a single fastener, tension-loaded test using one composite and two metallic loading straps. A composite spacer is placed between the two straps, which are then gripped using tension wedge grips. The standard fastener diameter is 6 mm (0.250 in.).

Each Procedure A loading strap is machined with a 13 mm (0.50 in.) diameter, 2 mm (0.06 in.) high boss at the fastener hole. The function of the boss is to simulate a representative fastener head or collar surface area on the test specimen, over which out-of-plane clamp-up forces are reacted. This tends to reduce the bearing strengths obtained using this procedure in comparison to double shear tests with flat load plates, and better simulates the composite bearing capability in typical structural joints.

As shown in Fig. 3, Procedure B utilizes two composite straps and spacers. Two specimen configurations are standard, permitting the test to be performed with either one or two fasteners. The composite spacers are secured to the ends of the straps, and are used to minimize the eccentricity of applied force at the bolted joint. The standard fastener diameter is 6 mm (0.250 in.).
Procedure B tests can be performed under tension loading when the specimen is gripped directly using tension wedge grips (unstabilized configuration). The test can also be performed with the specimen placed within a stabilization fixture (shown in Fig. 4), which restricts bending deformation induced by the single shear loading eccentricity. Use of the fixture permits the specimens to be loaded under either tensile or compressive forces.

While not strictly a pure bearing test, the two-fastener specimen exhibits reduced fastener bending and joint rotation in comparison to the single fastener specimen. As such, its deformation more closely approximates that of typical structural joints. Use of the two-fastener specimen does add complexity to the test in regard to force distribution, stresses and strains local to the fastener holes, and observed failure modes. These are discussed in greater detail in the subsequent comparative assessment of test methods.

The 2008 revision of D5961 standardized two additional test configurations. As shown in Fig. 5, Procedure C is a single fastener, tension-loaded test using one composite strap and a metallic fixture. Like Procedure B it approximates fastener deformation in structural joints, but requires less composite material than the Procedure B test. The specimen and fixture are both gripped using tension wedge grips. The standard fastener diameter is 6 mm (0.250 in.).

The Procedure D configuration (also shown in Fig. 5) is similar to that of D953 Procedure A, but is designed to permit double shear compression testing without a complex stabilization fixture. The test utilizes a fixture assembly composed of three steel loading plates, and utilizes shims to accommodate variations in specimen thickness. The specimen and fixture are both gripped using wedge grips. The standard fastener diameter is 6 mm (0.250 in.).

2.4 prEN 6037

Prestandard prEN 6037 was developed in 1995 by the European Association of Aerospace Industries (AECMA). This document covers bearing strength of multidirectional fiber-reinforced composites, including laminates manufactured from
unidirectional tape or woven fabric reinforcement. The test utilizes a double shear configuration with two hardened steel loading plates. The standard fastener diameter is 6.35 mm (0.250 in.), and a 0.1 mm (0.004 in.) clearance between the specimen and each loading plate is specified.

2.5 ISO 12815

ISO 12815 was published in 2013 by Technical Committee ISO/TC 61, Subcommittee SC 13. This standard covers plain-pin bearing strength of fiber-reinforced composites with either thermoset or thermoplastic matrices. The test assembly is similar to that of D953 Procedure A, utilizing three steel loading plates and shims to accommodate variations in specimen thickness. Hardened bushes interface between the loading pin and the fixture to improve durability of the loading plates; no clamping forces are imparted to the test specimen. The standard fastener diameter is 6 mm.

3 Comparison of Test Specimen Attributes

Standardization of the bearing strength test methods described herein resulted from the needs and requirements of the composite community. The standards are intended to support the application of diverse composite bolted joint configurations under a variety of applied loadings. The need for so many tests, rather than one or two, resulted from the difficulty associated with translating bearing strength results from one configuration to another. For example, even the relatively minor addition of through-thickness preload (e.g. fastener torque) in a double shear configuration can influence ultimate bearing strength, force vs. deflection response, failure modes and failure progression of the composite.

The following paragraphs compare and contrast important test specimen attributes, and discuss bearing strength and failure mode sensitivities to various test parameters.

3.1 Double vs. Single Shear

The most significant difference amongst the test methods is the general specimen configuration, i.e. double shear versus single shear. Single and double shear tests can exhibit differences in the following aspects:

- **Fastener rotation and bending** - single shear tests generally exhibit greater fastener rotation than double shear tests, due to the moment induced by loading eccentricity. The rigid steel loading plates and fixtures used in double shear testing also aid in resisting the rotation of the fastener head and collar. Single shear tests exhibit greater fastener bending than double shear tests which achieve equivalent bearing stress levels, as the entire test loading is carried through a single fastener shear plane.

- **Head and collar deformation** - single shear tests generally exhibit greater deformation of the fastener head and collar, which react the bending moment induced at the joint.

- **Specimen bending** - single shear tests exhibit specimen bending at the joint due to the moment induced by loading eccentricity.

- **Bearing stress distribution** - single shear tests generally exhibit greater through-thickness variation in local contact force and resultant bearing stress distribution, due to the greater degree of fastener rotation, fastener bending and composite specimen bending observed in single shear tests.

- **Failure modes** - single shear tests generally exhibit a greater frequency of failures influenced by the fastener head and collar, due to contact of the specimen surface with these features. Specimen surface damage induced by contact with the head and/or collar is not uncommon in single shear testing.

Comparisons of double and single shear bearing strengths have been published in the literature. Garbo and Ogonowski [6] tested a variety of AS/3501-6 Type II composite layups using single and double shear bearing specimens. They found single shear bearing properties (initial nonlinearity bearing stresses and ultimate bearing strengths) to be 10-25% lower than double shear properties due to the greater joint loading eccentricity.

Grant and Sawicki [7] discussed stabilization factors used in strength analysis, which were derived from testing a variety of bolted joint configurations. Strength factors for stabilized and unstabilized single shear bearing were set to 85% and 70% of
double shear strength, respectively. These values are similar to those observed by Garbo and Ogonowski.

Parida et al [8] reported mean quasi-isotropic T300/914C unidirectional tape single shear bearing strengths (2% offset strength) to be approximately 65% of comparable double shear strengths in both room temperature and hot/wet conditions. The observed single shear strength factors were likely lower than those previously discussed due to the use of flat loading plates in double shear tests, instead of ASTM D5961 loading plates with machined bosses.

3.2 Through-thickness Restraint and Preload

Pin bearing tests can exhibit differences in bearing strength and failure modes when compared to tests conducted with representative structural fasteners. For example, both Collings [9] and Hart-Smith [10] observed that double shear bearing strengths with finger-tight fasteners present were approximately twice those achieved in comparable pin bearing tests. The addition of normal fastener installation torque further increased bearing strengths by 15% to 30% depending upon the laminate configuration. Similar increases due to torque application were reported by Garbo and Ogonowski [6].

These differences are associated with the effects of through-thickness restraint and fastener preload forces, which are manifested through their influence upon bearing damage formation and propagation:

- **Damage initiation** – damage initiation is associated with the formation of small matrix cracks, including transverse cracks, shear cracks and interlaminar cracks. Compressive preload forces contribute to a more benign stress state that suppresses matrix crack initiation.

- **Damage propagation** – initial bearing damage tends to progress into macroscopic shear cracks, which swell the composite in the through-thickness direction. As observed by Sun, Chang and Qing [11], when pure pin conditions are present the swelling progresses unabated and no additional bearing force can be carried by the joint. Conversely, when through-thickness constraint exists, swelling is restricted until the applied force is sufficient to propagate the damage outside of the constrained area. Preload forces serve to further retard damage growth, especially in single shear joints where preload helps maintain through-thickness constraint while the fastener bends and rotates.

3.3 Tension vs. Compression-Reacted Bearing

Bearing strengths may vary depending upon the loading applied to the bolted joint, as tension-reacted bearing produces a different global stress state in the specimen than is present under compression-reacted bearing. Additionally, most tension-reacted bearing tests are affected by the closer proximity of the specimen end to the fastener hole than exists in compression-reacted bearing tests. As demonstrated by Crews and Naik [12], bearing damage initiation and ultimate strength are both affected by the distance between the fastener hole and the end of the specimen. For this reason, tension-reacted bearing strengths tend to be lower than those achieved in compression-reacted tests.

Compression-reacted tests can be adversely affected by specimen bending and instability when testing low-stiffness composites, or if requirements on fixture and specimen geometry are not carefully adhered to.

3.4 One vs. Two Fasteners

As previously noted, ASTM D5961 Procedure B may be conducted using a two-fastener joint specimen, which reduces fastener rotation and bending to more closely approximate bearing response within typical structural joints. However, use of two fasteners can affect several aspects of bolted joint response:

- **Fastener force distribution** – the two-fastener Procedure B specimen is designed to achieve an equivalent force distribution between the two fasteners, and specifies that bearing strength be calculated based upon that assumed distribution. The actual force distribution may vary throughout the test, due to the effects of fastener-hole clearances and damage formation. In some circumstances the force level at a damaged hole can be alleviated, resulting in a higher bearing strength being calculated than would be achieved in a comparable single-fastener test.

- **Stress state and failure modes** – the two-fastener Procedure B specimen is designed...
to exercise bearing failure modes. In a two-fastener joint, a complex stress state (referred to as bearing-bypass interaction) exists in the vicinity of the fastener hole furthest from the end of the strap, resulting from the incremental introduction of force into the strap at each fastener. For certain composite architectures and specimen geometries, such stress states may produce undesirable gross-section bypass failures, as exhibited in Fig. 6. ASTM D7248 [13] provides additional guidance on two-fastener joint testing, including bearing-bypass failure mode characterization and specimen geometry.

As currently published, the standards acceptably describe the attributes and sources of variation associated with the particular test configurations and loadings. There is a corresponding need for additional guidance on the application of the individual test types for specific purposes, to aid in test selection for novice users. The following discussion is intended to provide guidance on bearing test selection, and to help stimulate the development of improved industry guides for selection of tests for bearing and composite bolted joints in general.

4 Test Selection

The global composites community is composed of diverse stakeholders who use standard test methods for a variety of purposes. Among these are material qualification and acceptance, quality assurance, structural design and analysis, and research and development. Given the diversity of users, it is not surprising that multiple tests for bearing strength are used to provide optimal assessment methods for specific applications.

As discussed in CMH-17 [15], D953 has several limitations when applied to testing composite materials, which include the following:

- Specimen layup is not specified, and there is no requirement to report the layup when testing composites.
- Specimen geometry is inconsistent in some critical geometric ratios, such as end distance-to-diameter ratio and width-to-diameter ratio, for the two standard thicknesses and hole diameters. This can lead to differences in the bearing strengths obtained using the two specimen geometries.
- The data reduction methodology is tied to a parabolic shape that may not reflect actual force versus displacement response.
Similarly, prEN 6037 has limitations which include a lack of specimen layup definition/reporting as well as the specified loading procedure. The document mandates a force vs. displacement history analogous to that used in metallic bearing tests which is intended to measure stiffness once bearing yield is achieved.

Conversely, ISO 12815 was harmonized with ASTM D5961, and contains requirements on specimen definition, loading procedures and reporting that are consistent with current best practices for composite testing. Standard layups (quasi-isotropic) are specified, and requirements on critical geometric ratios (width/diameter and end distance/diameter) are documented. Repeatability and reproducibility data are provided based upon testing of eight different composite materials, including carbon and glass fiber reinforcements, unidirectional tape and fabric material forms, etc.

As ISO 12815 is currently the most technically rigorous and appropriate method for pin bearing strength of composite laminates, the author considers this standard to be the most appropriate for material qualification and acceptance test purposes, based upon the rationale discussed above. Use of ASTM D953 and prEN 6037 for such purposes should be done with requirements for specimen layup reporting and critical geometric ratios added, and should utilize force vs. displacement procedures and data reduction methods comparable to those of ISO 12815.

4.2 Quality Assurance

Tests used for composite quality assurance can have multiple purposes, and thus may require different test methods to be utilized. For example, some quality assurance tests are focused on composite manufacturing, for which the primary goal is to verify that the processed material is of acceptable quality. In this case, preferable bearing strength tests are those which are sensitive to material variations, and the most appropriate tests are analogous to those used for material qualification and acceptance. Based upon the rationale previously discussed, ISO 12815 would be considered appropriate for these purposes.

Conversely, some quality assurance tests are used to verify acceptable hole quality and fastener installation, in addition to basic composite quality. For these tests, it is desirable to utilize a test which more closely represents structural joints, but still exhibits significant sensitivity to material characteristics. While single shear tests may find applications in quality assurance testing, the use of double shear tests frequently can be preferable because of reduced sensitivity to fastener deformation and failure modes.

ASTM D5961 Procedure A has many attributes which are desirable for quality assurance purposes. The machined loading strap bosses maintain a consistent contact geometry and area over which fastener clamp-up forces are reacted. Standard layups (quasi-isotropic) and specimen geometry are specified, along with procedures for hole geometry measurement, application of fastener torque, and force versus displacement monitoring. Detailed requirements for reporting of these critical items are included in the standard. Compared to ASTM D5961 Procedure D, the test is less sensitive to the effects of gaps and specimen stiffness.

For these reasons, the author considers ASTM D5961 Procedure A to be the most appropriate for quality assurance evaluations when hole quality and fastener installation are parameters under investigation. Alternative methods, such as ASTM D5961 Procedure D, may also be appropriate depending upon criticality of loading scenarios.

4.3 Structural Design and Analysis

Tests used in developing data to support composite structural design and analysis are focused on assessing the performance of specific geometric configurations. In the case of bearing strength, test specimens must be geometrically representative of the as-designed structure in terms of thickness, end distance, edge distance, fastener head style, clamp-up torque, etc. Thus, test specimens are innately less generic in nature, and must be adaptable to permit assessments which support multiple structural configurations.

It is common practice to use single shear bearing specimens to establish strength design properties, as the majority of structural joints are loaded in single shear [14]. However, double shear tests may be appropriate when developing strength data for such joint configurations. Similarly, the usefulness of pin bearing strength data in structural design is limited, as most applications take advantage of the additional bearing strength capability which results from the application of fastener preload.
As previously discussed, ASTM D5961 contains multiple specimen configurations to cover a variety of geometries typical of structural design. A comparison of key D5961 attributes and applications is provided in Table 1. Within D5961, Procedures A and D are double shear tests which may be used to develop bearing design data for tension and compression loaded joints, respectively.

Table 1. ASTM D5961 Test Procedures

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Procedure B</th>
<th>Procedure C</th>
<th>Procedure D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double Shear, One Fastener:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tension Loading</td>
<td>√</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Compression Loading</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Shear, One Fastener:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tension Loading:</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Unstabilized</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stabilized</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compression Loading, Stabilized:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Shear, Two Fasteners:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tension Loading:</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Unstabilized</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stabilized</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compression Loading, Stabilized:</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

D5961 Procedures B and C may be used to develop single shear bearing strength data. Procedure C is limited to tension loading only, but is a simple test that can be conducted rapidly and requires less composite material than Procedure B. Procedure C tests can accommodate a variety of fastener and joint geometries, and provide a representative degree of restraint against joint rotation (which falls intermediate to the unstabilized and stabilized test configurations covered by Procedure B).

As shown in Table 1, Procedure B tests provide the greatest degree of flexibility in terms of joint geometries and loadings covered. Compression bearing strength can be obtained when using the stabilization fixture. Tension bearing strength can also be obtained with a representative degree of rotational restraint through use of the fixture; if such restraint is unrepresentative for a particular application, unstabilized specimens can be tested. Additionally, two-fastener tests may be conducted to better represent the target application, in terms of rotational restraint and force distribution.

ASTM D5961 is currently the most technically rigorous and appropriate standard test method for determination of composite bearing strength with fastener preload present. In particular, Procedure B provides configuration flexibility, can be used to develop both tension and compression bearing data, and provides a structurally representative degree of rotational restraint to single shear joints. For these reasons, the author recommends the use of ASTM D5961 Procedure B with stabilization for general structural design and analysis data generation purposes.

4.4 Research and Development

A common research topic associated with composite materials and structures is the prediction of damage progression and ultimate strength capability. In the case of bolted joints, prediction of strength is complicated by the complex deformation history of the bolted assembly, which is dependent upon multiple parameters including strap stiffness, fastener stiffness, rotational restraint, fastener-to-hole clearance, local deformation at the hole and damage formation.

Given the complexity of analysis predictions for bearing strength, it is often desirable to utilize a phased approach to model validation which addresses particular aspects of the problem one step at a time, leading to an over-arching solution. A typical sequence of validation tests would first address initial damage formation of the composite at the hole, followed by incorporation of representative fastener geometry, followed by incorporation of structurally representative fastener deformation and joint rotation. For such a progression, a recommended sequence of analysis validation tests would be as follows:

- First, conduct pin bearing tests per ISO 12815 to validate predictions for composite bearing damage initiation and propagation.
- Second, use double shear bearing tests per ASTM D5961 Procedure A to validate modeling of fastener preload and head/collar effects upon local deformation and damage initiation/propagation.
Finally, conduct single shear bearing tests per ASTM D5961 Procedure B or C to validate modeling of single shear joint deformation and damage progression.

5 Recommendations for Future Activities

One purpose of this manuscript is to promote discussion amongst the composites community and facilitate development of improved guidance material for composite bolted joint testing. It is the hope of the author that the material provided herein can provide a sound basis for the development of such guidance material, at least in the realm of tests for bearing strength. Additionally, the author has observed opportunities for further improvements and consolidation of standard bearing strength test methods, which will now be discussed.

5.1 Standard Test Method Improvements

While bearing test standards are mature, there remain aspects of particular tests that could be improved. The following are recommended areas for improvement of specific test methods:

- **ASTM D953** – incorporate standard specimen layup and associated reporting requirements, standardize critical specimen geometric ratios, and harmonize data reduction methodology with ASTM D5961.

- **ISO 12815** – permit use of a one-piece double-shear fixture similar to SRM 9-89, and consider adding guidance for test hardware based upon U. S. customary units.

- **ASTM D5961 Procedures A and D** – publish repeatability and reproducibility results from round-robin testing to permit comparison of test variation to the ISO 12815 pin bearing test, and consider incorporation of the SACMA SRM 9-89 one-piece loading fixture to increase test throughput.

- **ASTM D5961 Procedure C** – modify fixture to permit both tension and compression loading of the test specimen, publish repeatability and reproducibility round-robin results for comparison to Procedure B data, and provide guidance on specimen and fixture scaling for tests utilizing alternative fastener diameters.

- **ASTM D5961 Procedure B** – modify stabilization fixtures to decrease assembly and installation time, and provide guidance on specimen and fixture scaling for tests utilizing alternative fastener diameters. It should be noted that there are practical limitations on the maximum fastener diameter that can be tested using this specimen and stabilization fixture arrangement.

5.2 Standard Test Method Consolidation

The composites industry could also benefit from consolidation of overlapping test methods for bearing strength, to avoid duplication of effort and to promote efficiencies at test laboratories. The following are potential areas for consolidation of test methods:

- **Pin bearing** – consolidate to ISO 12815 as best practice. This could be done by incorporating a normative reference within ASTM D953 for high modulus composites. D953 could incorporate guidelines for testing within the U. S. customary unit system.

- **Double shear bearing** – consolidate ASTM D5961 Procedures A and D to permit both tension and compression testing using an individual specimen and fixture configuration.

- **Single shear bearing** – consolidate ASTM D5961 Procedures B and C as these tend to overlap applications. Consolidation to Procedure C would require the capability to perform the test under compressive loading, thus the optimal near-term solution would be consolidation to Procedure B.

6 Acknowledgements

The author is indebted to the efforts of the ASTM Committee D30 membership in the preparation of this manuscript. In particular, the efforts of past and present D30 Committee Chairmen (Carl Rousseau, Richard Fields and Eugene Camponeschi), D30.05 Subcommittee Chairmen (Mark Chris, Peter Grant and Ron Zabora), as well as D30.05 members who served as standards task group chairmen (Stephen Ward, Don Adams, Dan Adams and Paul Lagace)
were instrumental to the compilation of the information provided herein.

The efforts of ISO TC 61 SC 13 in the development of ISO 12815 and in coordinating its efforts with those of ASTM D30 are also acknowledged. The efforts of R. M. Shaw and G. D. Sims in developing repeatability and reproducibility values for ISO 12815 are particularly noteworthy.

References


