IDENTIFICATION, SELECTION, AND DEVELOPMENT OF COMPOSITE TEST STANDARDS – A CASE STUDY FROM THE DEVELOPMENT OF A DESIGN STANDARD FOR COMPOSITES

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Abstract

The development of design standards is a critical need for the expanded use of composites in new applications. One aspect of the development of design standards that is often not fully appreciated is the need for the identification, selection, and development of appropriate composite test standards. While advances in standardization of test methods for composites have been made, many cases still exist where there are numerous variations for a given test technique. The large number of test standards and the variations for a given test technique leads to confusion and often hinders the adoption of composites for new applications. This situation can also hinder the development of design standards for composites.

This paper examines the identification, selection, and development of appropriate composite test methods as required in the composites design process. Examples from the development of a load and resistance factor design (LRFD) standard for pultruded composites are presented. The issues addressed for this case study discussion would be applicable to any segment of the composites market that is looking to establish design procedures or develop design standards.

Introduction

As polymeric composites are used in more demanding applications and in varied environmental conditions, the understanding of mechanical properties of composites becomes even more important. The uniform utilization and adoption of standardized test methods help simplify the design process for composites. In turn, this facilitates the marketing and adoption of composite materials for new applications. Overdesign makes the use of composites too costly in many cases, but accurate property data is necessary to avoid overdesign. The development of statistical based design procedures also highlights the need for robust test methods so that measured property data gives a true representation of the material being used in the design. If scatter in the data is a consequence of the test method used and not a true representation of the material properties, the true potential for polymeric composites will not be reached in many applications. When overdesign was an acceptable approach to design with polymeric composite materials, the use of test methods that gave property data within a general range was a viable approach, and extensive time and thought were not given to the selection of the test methods used. However, efficient designs require more attention to all aspects of the process including the selection of appropriate test methods.

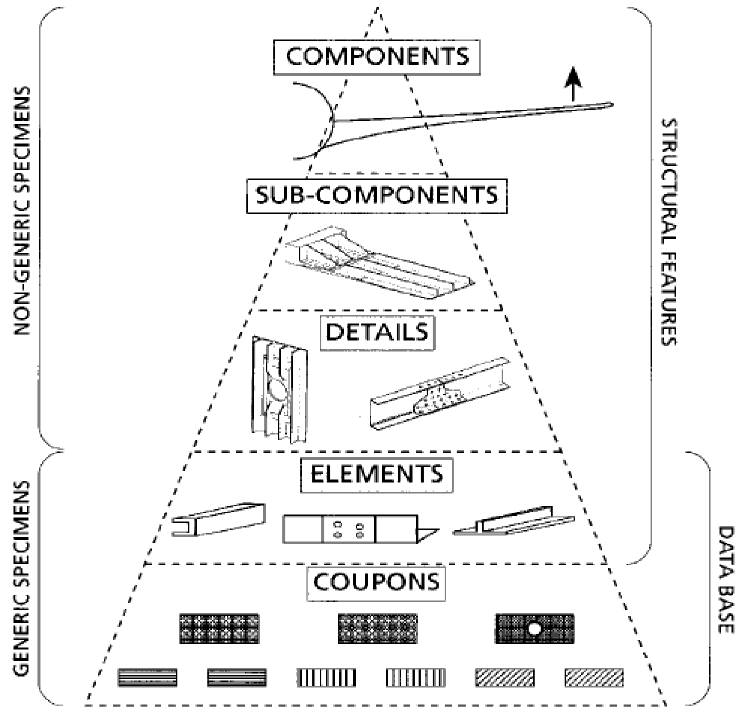

Figure 1. The pyramid of tests for the building block approach to design presented in MIL-HDBK-17 [1].

Even as virtual prototyping and virtual testing become more common in the design process, coupon testing of specimens to establish basic laminate properties of stiffness, strength, and toughness used in the models is still a necessity. As seen in Figure 1, the utilization of consistent, standardized coupon level test methods is a key feature of the building block approach to composite design advocated in MIL-HDBK-17 (now called Composite Materials Handbook (CMH-17)) commonly used in the aerospace industry [1]. Even as more virtual testing is incorporated into this design process, Figure 2 illustrates that researchers still anticipate that coupon testing will provide the basis for the evaluations needed for a successful design [2]. Without reliable property data on which to build this base, all subsequent test and model data is unreliable. While it is obvious that extensive testing and property data are required for critical designs such as those in the aerospace industry, applications in other industries also share many characteristics with this design approach. The uniform utilization and adoption of standardized test methods help facilitate the use of composites in the design process in any industry. For example, the adoption of consistent test methods has been cited as a key factor in the development process of a load resistance factor design (LRFD) code for pultruded composites [3, 4].

The selection and utilization of basic coupon test methods that are to provide the property data that forms the base of the building block approach to design are not as straightforward as this might initially seem. Further complicating the selection of appropriate test methods are the facts that 1) numerous test standards often exist for the determination of a given property and 2) appropriate test methods may not exist or methods that have traditionally been used may not be appropriate for the composite being examined. This paper will discuss examples of each of these complicating factors related to the selection of composite test methods as part of the design process.

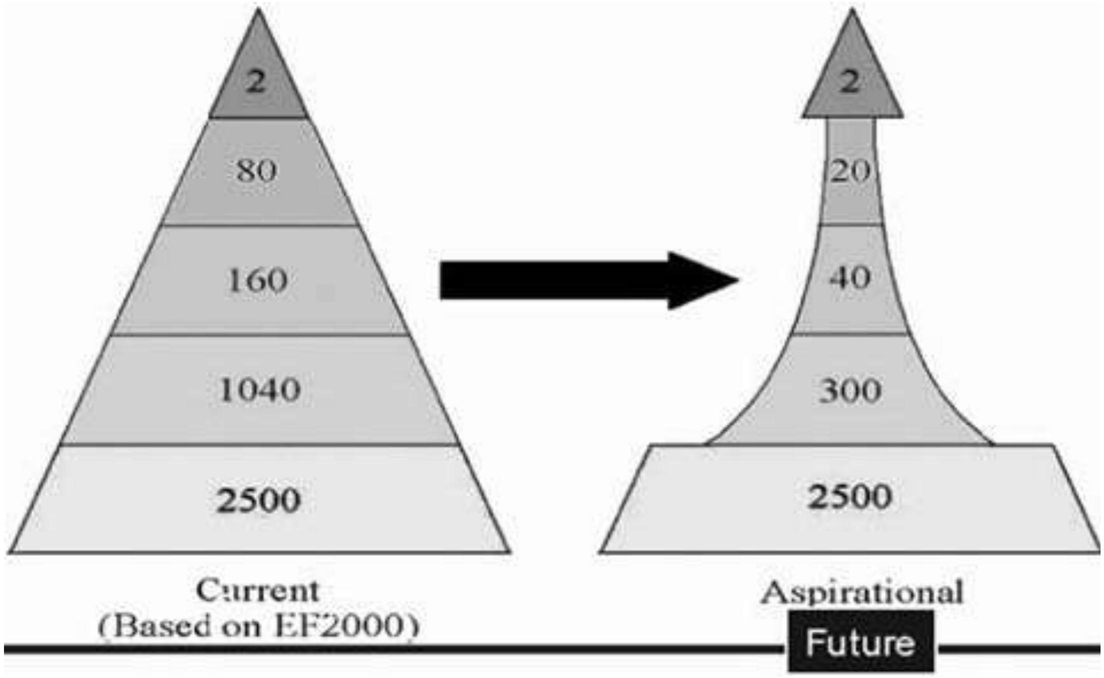

Figure 2. Desired progression of the testing requirements for the aerospace design process as the utilization of virtual testing increases. [2]

Historically, the field of mechanical testing of polymeric composites has not strictly followed a unified set of testing standards. The variety of constituent materials and the corresponding range of properties for the many different possibilities of composites makes the adoption of "one" set of standards more difficult for composites than for metals. Also, as newer composite materials with increased toughness, strength, and stiffness are developed, test methods have to evolve in order to successfully characterize these materials. Historically, many of the early composite test methods were adapted from methods that were originally developed for metals or unreinforced plastics. While many of these methods are able to successfully characterize some composites, the special characteristics associated with polymeric composites make these methods inadequate for many of today's more advanced composites. Just as improvements in constituent materials and manufacturing have been the focus of composites research in recent years, similarly the improvement of composites test methods has also been an active area of research.

Selection of Appropriate Test Methods - Navigating the Composites Testing Jungle

Significant research related to the development of test methods for polymeric composites has been ongoing since the 1960's. During this time, numerous test methods have been developed, and many of these methods have been standardized or adopted by specific industry segments. In some cases, numerous test methods have been developed for the determination of a given property; however, in other cases, appropriate test methods have not been developed. For example, well over 17 coupon compression testing methods have been developed, but to date, no universally accepted test method has been identified [6, 7, 8, 9]. In addition to the numerous standard coupon test methods that have been developed for compression testing of polymeric composites, some researchers have investigated specialized compression test methods for particular types of composites; two such compression methods have been investigated for pultruded composites [10, 11]. Of the numerous compression test methods that have been developed, literature reports indicate that at least 5 of these methods are commonly used by the U. S. composites community [6, 7, 8, 9, 12, 13]. With this number of different tests in use, the questions facing a designer include 1) which test method should be selected for use and 2) how do results from one method compare to results from another method. Answers to these questions must be determined as design procedures are standardized, but answers to these questions require an understanding of the test methods and the factors that affect each method. An in-depth discussion of compression test methods is provided in this paper as a case study of the type of issues that must be considered when selecting a particular test method for use in a design process. Also, a discussion of test method needs identified during the development of the LRFD standard for pultruded composites is presented.

Compression Test Method Evaluation and Selection Example

The compressive test standards most commonly used by the composites community in the United States for coupon testing include the following: ASTM D3410, ASTM D695, SACMA SRM 1R (modified D695), and ASTM D6641 (CLC). The first ASTM standard established for the measurement of compressive properties of polymer-matrix composite materials was ASTM D3410, which was first standardized in 1975. Through the years, advances in understanding of compression testing and other factors have lead to the modification of this original standard and the development of new methods. Today, there is still not universal agreement concerning the "best" compression test method. The only issue that people completely agree on concerning compression test methods is that all of the available methods have some drawbacks associated with them.

Composite Compression Test Method Overview: Compression testing is significantly influenced by the fixturing used for the test method. Compression test methods for polymeric composites can be categorized according to loading method -- 1) shear loading, 2) end loading, or 3) combination of shear and end loading. The amount of support and restraint provided by the fixture in an effort to avoid certain failure modes also influences the compressive properties measured by a given method. The appropriate amount of restraint provided by a compression fixture is determined based on the objective of the testing program. A testing program intended to produce data for structural design will have the goal of reproducibly measuring compressive failure properties that are representative of real world behavior. However, this data may not be representative of the theoretical maximum compressive properties of a material that could be achieved under perfect conditions. Euler buckling should be avoided for all, but microbuckling is expected to be present in real world failure situations. Microbuckling must be avoided to achieve the theoretical maximum compressive strength. Thus, desired compression testing fixturing should provide the proper balance of sample support and restraint without producing artificially high compressive properties that will not be achieved in real life loading situations [1, 14]. Common failure modes encountered in compression testing include the following: shear failure (in-plane or through-thickness), local fiber buckling, longitudinal splitting, delamination, end crushing (brooming), and global Euler buckling. As shown in Figure 3, all of these modes except end crushing (brooming) and global Euler buckling are considered to be acceptable failure modes for valid compression testing according to ISO 14126:1999(E) [7].

In addition to the influence of fixturing on the measured compressive properties of polymeric composites, additional factors including the ruggedness of the test method, specimen preparation, test equipment, and material variations have also been shown to significantly affect compressive properties. Studies have shown that compressive strength and, to a lesser degree, compressive modulus are very sensitive to material processing quality and consistency, damage induced during test specimen fabrication, test specimen surface finish, test specimen alignment, and the use of tabs [1, 14, 15, 16, 17, 18]. Test ruggedness is related to the experimental factors that strongly influence the measurements provided by the test method and the degree to which these variables need to be controlled for the method to produce valid test results [19]. Ideally, a test method will not be extremely sensitive to a large number of variables. Squires et al recommend a surface roughness of < 5 µm for cut surfaces of compression samples. Squires reported that the compressive strength of a sample with a surface roughness of 22 µm for the cut edges was 60% lower than for the same material with cut surfaces having a surface roughness of 4 µm [16]. Fiber misalignment has also been shown to have a significant effect on compressive strength. Wisnom reported that a misalignment of only 0.25º leads to a reduction in the predicted theoretical compressive strength of a particular unidirectional carbon/epoxy composite from 2723 MPa (395 ksi) to 1848 MPa (268 ksi), and a 3º misalignment equates to a 70% reduction in compressive strength [17]. While these values are a theoretical prediction, misalignment effects could help explain some of the low compressive

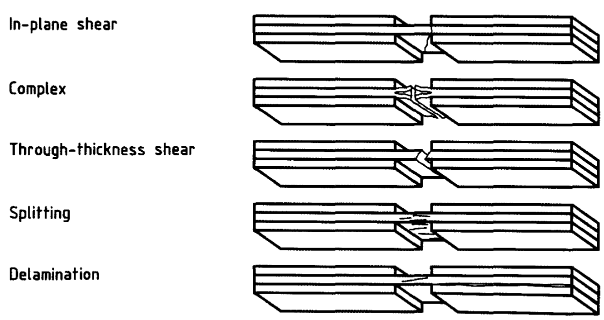

Figure 3. Acceptable compressive failure modes from BS EN ISO 14126:1999 [7].

strengths and high variability often seen for compressive strength data. Although tabs are necessary in order to provide sufficient bearing area or to protect the test specimen for some test methods, tabs are known to create stress concentrations. While some research has been done to evaluate the effects of tab configurations on compression testing and to identify configurations that reduce the stress concentration effects, the best way to minimize this effect is to use a test method that does not require the use of tabs [18].

ASTM D 3410 is entitled “Compressive Properties of Polymer-Matrix Composite Materials with Unsupported Gage Section by Shear Loading.” The original test method described by ASTM D3410 was developed by the Celanese Corporation. The Celanese method (Method A) was not a rugged test method. It had numerous shortcomings including intense sample preparation, restrictive sample geometry limitations, and other extensive test setup procedures. Tabs were typically necessary for the samples. If everything was done correctly, the method was thought to give valid results, but obtaining valid test data was problematic at best with reported test results showing “severe scatter” [6]. Due to difficulties associated with the

Celanese method, a new method was standardized in 1987 as part of D3410. This new method, known as the IITRI method (Method B), was developed by the Illinois Institute of Technology Research Institute. The IITRI method is a more user-friendly variation of the Celanese method. For the IITRI method, the load is also applied through shear loading and tabs are typically used. Strain gages or extensometers are used to measure strain data. A three letter code system with corresponding failure modes and locations is provided for description of the failure of the sample. Failures at the end of the tab near the gage section are noted to be less desirable than failure completely within the gage section, but failures at the end of the tab are cited to be an acceptable failure mode. Although the IITRI fixture is complicated and heavy (about 43 Kg (95 lb)), the test method is more forgiving than the Celanese method and is generally considered to produce valid results. The Celanese method (Method A) was removed from D3410 in 2003 [1, 6, 20, 21]. This evolution of the ASTM D3410 standard illustrates the point that in addition to simply naming the standard that was used for testing, for example ASTM D3410, it is important to provide a full description including the issue date of the standard (for example ASTM D3410-03) and the specific method or other options described in the standard that were used to obtain the test data.

In an effort to develop a simpler method for compression testing of polymeric composites, some people began examining the use of ASTM D695 – Standard Test Method for Compressive Properties of Rigid Plastics, an end loading method that was originally developed in 1942 for use with unreinforced plastics [6, 22]. ASTM D695-02a now includes "Section 6.7 - Reinforced Plastics, Including High-Strength Composites and High-Strength Composites and Highly Orthotropic Laminates" which describes the specimen details for use of this method with fiber reinforced polymeric composites. The D695 method is specified in standards for ladder rail and is commonly employed by pultruders.

In the D695-02a standard, this method is described as useful for unreinforced, rigid plastic and reinforced plastics. For composites, ASTM D695-02a specifies the use of an untabbed, dog-bone shaped sample held within a support jig to avoid buckling. This specimen configuration often results in end crushing prior to valid compression failure for high strength composites, and stress concentrations are present at the radii [23]. The dogbone shape also requires accurate machining. For unidirectional composites, the dogbone shape often results in splitting in the area where the reduced gage area transitions to the enlarged end section, which is an invalid failure mode. ASTM D695-02a discusses the use of a compressometer to determine modulus, but the use of strain gages is not mentioned and would not be possible with the presence of the support jig [22]. An ASTM D-30 round robin evaluation of this method for [0] AS/3501 and [0] E-Glass/1002 laminates concluded that this test method is not adequate for determining compressive strength of high-modulus composites similar to the form studied, but it is recognized that some composites with other reinforcements can be successfully tested using this method [1, 24]. However, when data from the D695 method is compared to compression data for similar materials tested by other methods, the D695 results are often reported to be lower than results produced using other methods [13, 25, 26]. "Section 12 – Report" in ASTM D695-02a does not require the failure mode to be reported for the testing; therefore, it is possible that data from this method is being reported as compressive strength even when other failure modes such as end crushing occur [22].

The desire for the simplicity of the ASTM D695 method without the problems associated with the end crushing of the dog-boned sample lead numerous researchers to examine modifications of this method. In general, these test methods are referred to as a modified D695 method. Numerous groups including Boeing, Union Carbide, and Hercules developed their own modified versions of ASTM D695 using an end-loaded straight-sided sample with tabs. Although commonly used by the composites community, especially those in the aerospace community, the modified D695 method was never standardized by ASTM. However, the

Suppliers of Advanced Composite Materials Association (SACMA) did standardize a modified D695 method as SACMA SRM-1R-94. SACMA disbanded as of June 1, 2000, so this method is no longer reviewed and maintained. A support jig similar to the fixture for ASTM D695 is used for the strength testing in SRM-1R-94. Tabs are bonded to the sample so that a very short 0.188 inch gage section remains between the tabs. Because of the lack of space for the attachment of strain gages to the tabbed sample used for strength measurements, a second sample without tabs is required for modulus measurement. The modulus sample is not tabbed, and the support jig for this sample has a cutout to accommodate the strain gages. This untabbed sample is to be loaded only up to 5000 microstrain instead of to failure to avoid crushing the untabbed sample. SRM-1R-94 specifies that the testing report should include a description of the type and location of the failure. The SRM-1R-94 method usually provides slightly higher compression strength average value data than the ASTM D3410 standard. Possible reasons for this include the fact that end loading creates a more uniform stress in the gage section, the very short gage section tends to inhibit Euler buckling, and the possibility of establishment of a redundant load path. As with ASTM D695, the support jig can set up a redundant load path if the clamping forces are too high. SRM-1R-94 specifies that 0.68 - 1.1 newton-meter (6-10 in-lb) of torque should be used for the clamping screws on the support jig [1, 27]. Although the SRM-1R-94 modified D695 method is a relatively simple method that uses a simple fixture and produces data comparable to ASTM D3410, it still has drawbacks. Possible end crushing is still an issue with the end-loaded sample, and the need for tabs and separate modulus samples are not desirable.

As part of the continuing efforts to develop improved compression test methods, the Wyoming combined loading compression (CLC) test method was developed [26]. In 2001, this method was standardized as ASTM D6641-01 – Standard Test Method for Determining the Compressive Properties of Polymer Matrix Composite Laminates Using a Combined Loading Compression (CLC) Test Fixture. The CLC method, is a combination loading method that takes the best features from end loading methods, such as ASTM D695, and shear loading methods, such as the ASTM D3410 IITRI method, without the complications of each. Xie and Adams have demonstrated that the stress concentrations created using the combination loading method were lower than those for either end loading alone or shear loading alone [18]. For the CLC testing, shear loading is produced via friction of flame sprayed surfaces against the surface of the sample clamped between blocks of the fixture, and end loading is applied to flat surfaces on the ends of the sample. The desired ratio of shear loading to end loading is achieved by varying the torque applied to the clamping screws of the blocks, with the goal being to apply sufficient torque to provide sufficient shear loading such that end crushing does not occur but no more shear loading than necessary due to the creation of stress concentrations at the end of the gage section. The typical range of recommended torque is 1.1 – 2.8 newton-meter (10-25 in-lb). Most types of composites other than unidirectional composites can be tested without tabs using the CLC method. For testing unidirectional composites, tabs will likely be necessary. As with other methods, the use of tabs is not desirable for the CLC method due to stress concentrations and the added sample preparation difficulties associated with tabbing. Standard sample size for the straight-sided CLC sample is 139.7 millimeter (5.5 in) long and 12.7 millimeter (0.5 in) wide, but samples of other sizes can be accommodated by the fixture. A 12.7 millimeter (0.5 in) gage length is produced for the standard sample size. This gage length is sufficiently large to accommodate strain gages but short enough to avoid Euler buckling for samples of reasonable thickness. If desired, the standard states that transducers other than strain gages may be used to measure strains.

Table I shows the direct comparison of compression data for selected commercial pultruded composites that were tested using ASTM D6641-01, D695-02a, and SACMA SRM-1R-94. As seen in Table I, the ASTM D6641-01 CLC and SACMA SRM-1R-94 methods give very similar results for the ladder rail and sheet piling, with the results from the D695-02a method being somewhat more variable. This observation was confirmed using the k-sample Anderson-Darling statistical test method. Significantly lower average compressive strength data was recorded for the ladder rail material that had a larger percentage of unidirectional fiber when tested using D695-02a. Numerous literature reports indicate that reported D695 data is lower than compressive properties determined using other methods [13, 25, 26], and this was reflected in data from the ladder rail material tested in this study and also in a follow up study conducted by the Pultrusion Industry Council's LRFD Technical Committee that examined the compression strength of commercial pultruded structural composites. Complete data for all sample measurements summarized in Table I are available in reference [28].

Compression Test Method Selection: While there is no consensus as to the "best" compression test method, the relatively new ASTM D6641 CLC method has shown many positive characteristics and has been adopted by many groups. In a report for the Office of Aviation Research, Wegner and Adams compared the CLC test method versus the IITRI method. It was reported that the data produced by each method were similar, but Wegner and Adams identified the CLC as the better test method based on its usefulness, cost, and ease of use [29]. Research has also demonstrated that the IITRI method and CLC methods produce statistically similar compression data for a given population [6]. For submittal of in-plane compressive strength and modulus data, only the ASTM D3410 and D6641 compression test methods are approved by Mil-HDBK-17-1F for laminate properties [1]. Recently the ASTM D6641 CLC method has been adopted as the compression test method to be utilized with the load resistance factor design (LRFD) for pultruded composites.

Table I. Average Compression Test Data Summary

	SACMA SRM-1R-94	ASTM D6641-01	ASTM D695-02a
Ladder Rail Modulus (GPa)	28.3 ± 2.96 (4.1 ± 0.32 Mpsi)	27.9 ± 1.38 (4.05 ± 0.24 Mpsi)	Not measured
Ladder Rail Strength (MPa)	488 ± 54 (70.7 ± 7.83 ksi)	493 ± 35 (71.5 ± 5.06 ksi)	380 ± 53 (55.13 ± 7.71 ksi)
Sheet Piling Modulus (GPa)	25.5 ± 1.79 (3.7 ± 0.26 Mpsi)	25.4 ± 1.72 (3.69 ± 0.25 Mpsi)	Not measured
Sheet Piling Strength (MPa)	431 ± 11 (62.5 ± 1.53 ksi)	422 ± 26 (61.2 ± 3.77 ksi)	406 ± 44 (58.9 ± 6.41 ksi)

Examples Where Appropriate Test Methods May Not Exist

Contrary to the example discussed above where a large number of test methods exist for the determination of a particular property, the development of design procedures often bring to light the need for test methods that do not exist in standardized form or do not address the particular condition under consideration for a given design. For example, during the development of a load and resistance factor design (LRFD) standard for pultruded composites, the need for the development or revision of nine test standards has been identified; these areas are now being considered for new or modified standards. Unfortunately, in some cases, non-standardized test methods are utilized or standardized methods that are not directly applicable to the composite under consideration are employed when lack of appropriate standards are identified. While these unorthodox approaches may provide usable data in some cases, the most prudent approach is to spend the time and effort necessary to develop appropriate standardized test methods for the needed data instead of forcing the use of inappropriate test methods. The development of appropriate standards serves numerous purposes including the following: 1) providing economic incentives as companies share development costs and solve common issues through cooperation and consensus and 2) serving the public interest by helping to ensure that companies fulfill their responsibilities to customers including helping to increase product quality and providing greater user confidence. The positive aspects provided through the development of appropriate standards compensate for the resources required for their development.

One example of an area in which a standardized test method specifically developed for polymeric composites does not exist is characterization of composites in freeze/thaw environments. In 2003, a paper summarizing a gap analysis study undertaken under the aegis of the Civil Engineering Research Foundation and the Federal Highway Administration identified gaps in the effects of freeze/thaw conditions as having a mid-to-high level of criticality as related to civil infrastructure applications [30]. Most research reports concerning the characterization of the effects of freeze/thaw cycling on polymeric composites either do not follow a standardized test method or use ASTM C 666 - Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing. As evidenced by the title, ASTM C666 is intended to determine the effects of variations in both properties and conditioning of concrete in the resistance to freezing and thawing cycles [31]. ASTM C666 was not developed to be applicable to polymeric composites, and procedures developed according to this standard that are appropriate for concrete may not lead to complete freezing or thawing of polymeric composites. An example of a freeze/thaw cycle that conforms to C666 but does not lead to complete thawing of a 25.4 mm x 3.175 (mm 1 in x 1/8 in) cross-section E-Glass/Epoxy pultruded composite is shown in Figure 4. The temperature data shown in Figure 4 was recorded using a thermocouple imbedded at the center of the cross-section of this composite material; unless temperature data is recorded at the interior of the sample being exposed to freeze/thaw cycling, it would not be known that this cycle did not result in complete thawing of the material under test. If thermal cycling that conforms to ASTM C666 for concrete but does not lead to complete freezing or thawing of the polymeric composites under consideration were selected, the use of this standard would lead to incorrect characterization of the effects of this environmental condition on composites. In response to the issues that have been identified with the use of this standard for polymeric composites, efforts are currently underway by the ASTM 20.18.02 subcommittee to develop a freeze/thaw protocol for pultruded composites that could be used with the LRFD for pultruded composites.

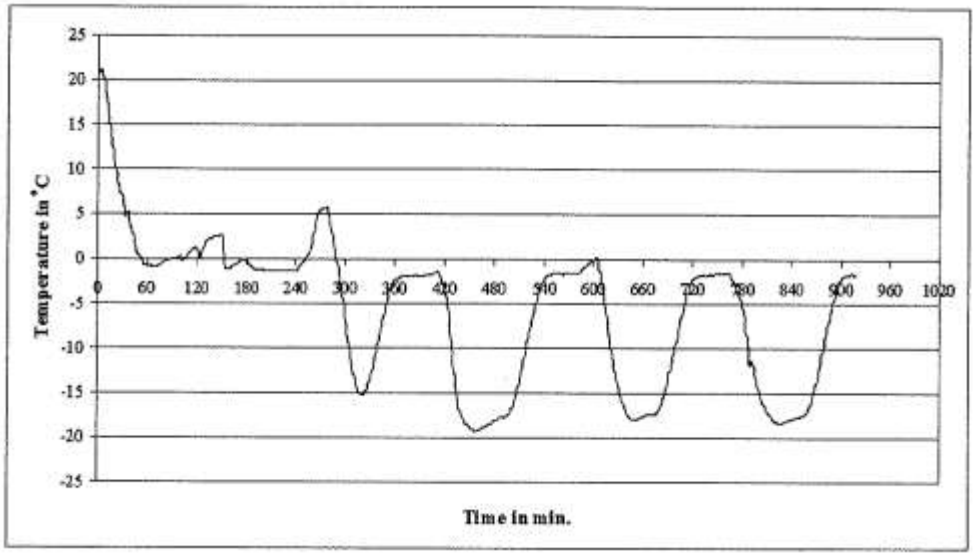

Figure 4. Temperature profile for temperature cycles of -17.7ºC (0ºF) and 4.4ºC (40ºF) measured at the center of an E-Glass/Epoxy composite. Freeze/thaw cycle: 4.4ºC (40ºF) to -17.7ºC (0ºF) in 1 hour, hold at -17.7ºC (0ºF) for 1 hour, return to 4.4ºC (40ºF) in 1 hour

Summary and Conclusions

As discussed in the preceding examples, poor selection of or the lack of appropriate test standards can hinder the development of design standards and the utilization of composites. Even as the utilization of virtual prototyping and virtual testing becomes more common in the design process, coupon testing of specimens to establish basic laminate properties of stiffness, strength, and toughness used in the models is still a necessity. As described by ASTM, "standards provide a way to speak an international language that ensures product consistency and compatibility, enhanced competition, technology diffusion, and the public welfare across international borders" [32]. Further complicating the selection of appropriate test methods are the facts that 1) numerous test standards often exist for the determination of a given property and 2) appropriate test methods may not exist or methods that have traditionally been used may not be appropriate for the composite being examined. Examples of each of these issues have been presented. While the large number of test standards for a given property or the lack of appropriate standards may hinder the development of design standards or the utilization of composites in new applications, the positive aspects provided through the selection or development of appropriate standards compensate for the resources required for the development of these standards. It is in everyone's best interest to understand the appropriate use of composite test standards and to participate in the voluntary, consensus-based process of developing new standards to address areas of need.

References

1. MIL-HNBK-17-1F Volume 1. Polymer Matrix Composites Guidelines for Characterization of Structural Materials, Department of Defense Handbook, 2002.

2. Davies, G. A. O. and E. J. Ankersen, “Virtual Testing of Realistic Aerospace Composite Structures,” *Journal of Materials Science*, Vol 43, pp. 6586–6592, 2008.
3. Zureick Abdul-Hamid, Benett R.M., Ellingwood B.R., “Statistical Characterization of Fiber-Reinforced Polymer Composite Material Properties for Structural Design”, *Journal of Structural Engineering*, Vol. 132, No.8, 2006, pp 1320-1327.
4. Pultrusion Industry Council Load Resistance Factor Design Technical Committee, 2007.
5. ASTM D 6641/D 6641M-01: Standard Test Method for Determining the Compressive Properties of Polymer Matrix Composite Laminates Using a Combined Loading Compression (CLC) Test Fixture, ASTM International, 2001.
6. Chaterjee, S., D. Adams, and D. W. Oplinger, “Test Methods for Composites A Status Report, Volume II: Compression Test Methods,” DOT/FAA/CT-92/17, June 1993.
7. BS EN ISO 14126:1999 - Fibre-Reinforced Plastic Composites. Determination of Compressive Properties in the In-Plane Direction, International Organization for Standardization, 1999.
8. Berg J.S., Adams D.F., “An Evaluation of Composite Material Compression Test Methods”, *Journal of Composites Technology and Research*, 11(2), 1989, pp 41-46.
9. Schoeppner, G. A. and Sierakowski, R. L, “A Review of Compression Test Methods for Organic Matrix Composites,” *Journal of Composites Technology and Research*, Vol. 12, No. 1, Spring 1990, pp. 3-12.
10. Mottram J.T., Compression Strength of Pultruded Sheet Material, *Journal of Materials in Civil Engineering*, Vol 6(2), 1994, pp 185-200.
11. Barbero, E. J., S. Makkapati, and J. S. Tomblin, “Experimental Determination of the Compressive Strength of Pultruded Structural Shapes,” *Composites Science and Technology*, 59, 1999, pp. 2047-2054.
12. Wilson, D. W., et al, “An Analytical and Experimental Evaluation of 0/90 Laminate Tests for Compression Characterization,” Journal of Composites Technology and Research, Vol 16, Issue 2, April 1994, pp. 146-153.
13. Gedney, Christina C., et al, “Comparison of ASTM Standard Compression Test Methods of Graphite/Epoxy Composite Specimens,” *Proceedings of the 32nd International SAMPE Symposium*, April, 1987, pp. 1015-1024.
14. Fields, Richard, “Testing and Certification” in *ASM Handbook: Composites, Volume 21*, Materials Park, OH: ASM International, 2001.
15. Hodgkinson, J. M, editor, *Mechanical Testing of Advanced Fibre Composites*, Boca Raton, FL: CRC Press, 2000.
16. Squires, Charlene A., Keith Netting, and Alan Chambers, “Understanding the Factors Affecting the Compressive Testing of Unidirectional Carbon Fibre Composites, *Composites Part B: Engineering*, Vol. 38, 2007, pp. 481-487.
17. Wisnom, M. R., “The Effect of Fibre Misalignment on the Compressive Strength of Unidirectional Carbon Fibre/Epoxy,” Composites, Vol. 21, No. 5, Sept. 1990, pp. 403 – 407.
18. Xie, Ming, and Donald Adams, “Effect of Loading Method on Compression Testing of Composite Materials.” *Journal of Composite Materials*, Volume 29, No.12, 1995, pp. 1581-1600.
19. E1169-02: Guide for Conducting Ruggedness Tests, ASTM International, 2002.
20. ASTM D 3410-03: Standard Test Method for Compression Properties of Polymer Matrix Composite Materials with Unsupported Gage Section Shear Loading, ASTM International, 2003.
21. Adams, Donald F, May 2005, “Current Compression Test Methods,” *High Performance Composites,* http://www.compositesworld.com/hpc/ issues/2005/May/828, Accessed: March 2007.

22. ASTM D 695-02a: Standard Test Method for Compressive Properties of Rigid Plastics, ASTM International, 2002.
23. ASTM D4762-04: Standard Guide for Testing Polymer Matrix Composite Materials, ASTM International, 2004.
24. Adsit, Norman R., “Compression Testing of Graphite/Epoxy,” *Compression Testing of Homogeneous Materials and Composites, ASTM STP 808*, Richard Chait and Ralph Papirno, Eds., American Society for Testing and Materials, 1983, pp. 175-186.
25. Wolfe, Arthur and Michael Weiner, “Compression Testing - Comparison of Various Test Methods.” *Proceedings of Composites 2004*, American Composites Manufacturers Association, CD-ROM, 2004, pp. 1-4.
26. Adams, Donald and Jeffry S. Welsh, “The Wyoming Combined Loading Compression (CLC) Test Method,” *Journal of Composites Technology and Research*, Volume 19, Issue 3, 1997, pp. 123-133.
27. SACMA SRM-1R-94: SACMA Recommended Test Method for Compressive Properties of Oriented Fiber-Resin Composites, Society of Advanced Composites Manufacturers Association, 1994.
28. Ellen Lackey, James G. Vaughan, Swasti Gupta, Stephen Rawls, Winter Wimbrow, and Clint Smith, "Comparison of Compression Test Methods for Pultruded Product," *Proceedings of COMPOSITES 2007 - American Composites Manufacturers Association*, CD-ROM, pp. 1 – 18, 2007.
29. Wegner, Peter M. and Donald F. Adams, “Verification of the Combined Load Compression (CLC) Test Method,” DOT/FAA/AR-00/26, Washington, D.C.: Office of Aviation Research, August 2000.
30. Karbhari, V. M.; Chin, J. W.; Hunston, D.; Benmokrane, B.; Juska, T.; Morgan, R.; Lesko, J. J.; Sorathia, U.; Reynaud, D., “Durability Gap Analysis for Fiber-Reinforced Polymer Composites in Civil Infrastructure,” *Journal of Composites for Construction*, Vol. 73, 238-247, August 2003.
31. ASTM C666 / C666M - 03(2008) Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, ASTM International, 2008.
32. *The Handbook of Standardization: A Guide to Understanding Standards Development Today*, http://www.astm.org/NEWS/handbook02/images/Handbook02.pdf, ASTM International.