NISTIR 6288

NIST Workshop on Standards Development for the Use of Fiber Reinforced Polymers for the Rehabilitation of Concrete and Masonry Structures, January 7-8, 1998, Tucson, Arizona. Proceedings

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NIST

United States Department of Commerce
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Technology Administration
Cheryl L. Shavers, *Under Secretary for Technology*
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Raymond G. Kammer, *Director*

INDUSTRY PERSPECTIVE ON COMPOSITE RETROFIT SPECIFICATIONS

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State and federal governments have invested millions of dollars in developing and validating composite materials for infrastructure renewal. This effort is a strategic part of the diversification of defense materials and technologies via the California Trade and Commerce Agency, Advanced Research Project Agency, National Institute of Standards and Technology and Federal Highway Administration. In a report to Congress by the Federal Highway Administration in 1995, about 18 % of our Nation's bridges are classified as structurally deficient, with a cost to fix these deficiencies estimated at $80 billion. Similar deficiencies exist in Europe, Asia and the Middle East. The global market for infrastructure renewal is enormous. We know that composites, when properly applied, can provide cost effective solutions due to their high strength-to-weight ratios, non-corrosive properties and speed and ease of application. The success of these government-funded programs equates to global competitiveness and increased tax revenues for years and even decades to come. Consequently, we all have a vested common interest in the successful implementation of these technologies and materials.

Infrastructure renewal has been under way for several years, and of particular interest has been the retrofit of bridge piers with high performance composite casings. Current specifications for composite casings have been in development for several years and are still somewhat fragmented. Considering the enormous potential application of composite casings, it becomes very apparent that these specifications need to be reviewed and improved.

Improvements can be made to the Caltrans Pre-Qualification Requirements, Durability Testing Procedures, and Column Casing Specifications (see Appendix 3.1b of Roberts's paper in this volume). For example, the material property aspects of the pre-qualification requirements presently in use by Caltrans contain several test procedures which do not correspond to actual modes of material resistance and failure found in the field. This paper discusses some of the more important issues in this regard.

PRE-QUALIFICATION REQUIREMENTS:

Ring versus Flat Specimens: Pre-qualification for existing materials requires that testing be performed on specimens derived from flat laminate samples of the composite system. In all cases of pre-qualification of composite column casings to date, flat laminate plates have been used for material qualification, durability testing and residual strength determination. The flat plates are cut into specimens, which are tested in accordance with ASTM standards such as D 3039, D 3165 and D 2344. Yet, the flat laminate specimen is not representative of either the manufacturing process or the structural loading condition in the field. In fact, the use of flat specimens introduces errors and distortions to the data for the following reasons:

(a) The process of making flat test specimens for the continuous carbon fiber filament winding system involves using a machine to wrap tows around a circular column or mandrel, then cutting and removing these circular plies and laying them up on a flat surface to form a flat specimen before curing. We have two concerns about this method: first, this specimen preparation procedure is not the actual process that is used in making the column casing; second, a flat specimen made by this procedure will result in wrinkles, distortions, and uneven tensions in the fibers of the flat test coupon, leading to a reduction in the strength and stiffness of the flat laminate.

(b) For the case of bonded shells, the bond thickness is uniformly controlled in the flat test specimens, but is quite variable in the large, circular shell assembly bonded in the field. Since the structural strength of adhesive bonds depends on the uniformity of adhesive thickness and mechanical properties, as well as on proper surface preparation of the adherents, a flat specimen introduces errors in the measured bond strength of the bonded shell system.

(c) A flat coupon is tested under uniform tension, whereas a ring test stresses the outside surface more than the inside, a situation closer to the actual loading in a circular casing.

For these reasons, we recommend that all materials properties for pre-qualification of any composite column casing system, for design purposes or strength retention assessment, should be obtained from a ring test. We recommend 508 mm (20 in) diameter ring specimens loaded by internal pressure (Figs. 1 and 2).

Thickness Measurement: Casing thickness is used as a measure of the amount of fibers used in the casing construction. This assumes certain wrapping procedures and material parameters. These parameters are used in the following formula to obtain the structural thickness t:

$$t = \frac{A_t}{V_f} * \frac{N}{P} * C$$

where,

A_t = cross sectional area of a tow or strand,
V_f = fiber volume fraction,
N = number of tows per pitch,
P = pitch, and
C = number of plies.

Direct measurements of the very thin casing thickness can produce large relative errors. For example, a small measurement error of 0.76 mm (0.030 in) in a 1.78 mm (0.070 in) thick casing represents a relative error of 43 %. Errors of this magnitude are common, and caused by minute surface irregularities and waviness, microscopic voids, surface resin migration, filament cross-over and twist, weave pattern, concrete adhering to sample surfaces, etc. Cored casing samples used for thickness measurements with a micrometer, as required by some specifications, incorporate all of the errors mentioned above and provide only an upper bound of the thickness. This is illustrated in Figure 3. On the other hand, the structural property that matters is the thickness specified in the above formula and controlled by five parameters. We recommend that casing thickness be deduced from the above equation and knowledge of the five parameters involved.

Glass Transition Temperature: This issue concerns both the adhesives used to bond shells and the resin matrix of the shells. Some ambient cured adhesive systems have glass transition temperatures (T_g) much lower than would be expected to provide adequate jacket strength over the expected operational temperature range. It is well known that the mechanical properties of thermoplastic and thermoset materials change dramatically above their T_g . Usually, the change is a significant reduction in stiffness and strength. Because of this, the composites industry requires that the T_g of a thermoplastic or thermoset material (in this case, the adhesive) should be at least 15 °C to 30 °C (27 °F to 54 °F) higher than its maximum expected operating temperature. (Note that in aerospace, the requirement is usually 40 °C (72 °F) above the operating temperature.) This rule of thumb can only be ignored if specific data have been generated to show that it does not apply in a particular situation. Given that some specifications state that the maximum required operating temperature for composite jackets is 60 °C (140 °F), the T_g of **all** the materials used in a composite column casing should be at least 75 °C (167 °F). As shown in the table below, most of the systems proposed do not meet this requirement, a very risky situation indeed.

	System 1	System 2	System 3	System 4
T_g composite, min.	63 °C (145 °F)	104 °C (220 °F)	104 °C (220 °F)	104 °C (220 °F)
T_g adhesive, min.	not used	not used	65 °C (150 °F)	20 °C (68 °F)

Performance of a composite casing depends on the entire system. Thus, when a composite column casing system incorporates adhesive bonded joints, the adhesives should meet the performance requirements of the operating environment as well. For a successful application, maximum and minimum service temperatures must be considered in the selection of an adhesive. As stated above, the performance of adhesives is temperature dependent and their operating range is limited. On hot days, the operating temperature for columns can be expected to be greater than 20 °C (68 °F).

An example of the dramatic effect of T_g on performance is given by the strength of aluminum lap joints made with a common epoxide-polyamide adhesive (FM-100). Strength dropped by 50 % to 75 % between 0 °C (32 °F), which is below the T_g of the adhesive, and 65 °C (150 °F), which is above the T_g. This level of strength loss is not uncommon for adhesively bonded joints.

We recommend that casing materials be verified to perform at the maximum expected exposure temperature by testing them to at least this maximum temperature. It is critical that this be done in pressurized ring specimens made from the "as-built" jacket system (no post-cure of the adhesive). Given the high probability of reduced adhesive strength at elevated temperatures, we recommend that existing specifications be modified.

Positive results from the above recommended testing at the maximum expected operating temperature might still not be adequate. Environmental exposure, particularly exposure to moisture, can further depress the actual T_g of the material and its adhesion in the field. In addition, it is well known that moisture up-take by a thermoplastic or thermoset material can be greatly accelerated if exposure occurs above the T_g of the material. This should be especially acute when composites are used in underwater casing applications. Users have already carried out some durability tests to address this issue.

Sampling of Field Specimens and Acceptance of Test Data: Current specifications do not specify a data evaluation method for either laboratory qualification or field quality verification. We recommend that the procedures of ASTM E 178 be adopted for this purpose. In particular, the values of concern in all acceptance test data should be the mean and standard deviation of several test points. It should be recognized that outliers are common in testing of any materials. Test data having standard deviations exceeding a certain ratio of the mean should be retested using double the original number of specimens.

DURABILITY TESTING:

Environmental Conditioning: Some of the environmental exposure conditions specified in current durability test programs are not representative of the operating environment in the field, and therefore give misleading results. They are:

(a) High temperature resistance: Currently the specimens are subjected to a continuous temperature of 60 °C (140 °F) for 1 000 h, 3 000 h and 10 000 h before testing. The specimens are returned to room temperature and tested. The high temperature exposure of 60 °C (140 °F) for the selected durations will undoubtedly post-cure some the composite systems, particularly ambient cured systems, thereby artificially increasing the test specimen strength and stiffness. In actual column casing applications, high temperature exposures last a short time (a couple of hours in the middle of the day) and the casing is most vulnerable to failure then.

To adequately assess temperature resistance, we therefore recommend that he specimens be tested in extreme conditions, i.e., the exposure duration should be very short to minimize any post curing, and the test should be conducted at 60 °C (140 °F) or some appropriate maximum temperature of service.

(b) Freeze-Thaw Resistance: Current specifications require that specimens be subjected to 24 freeze-thaw cycles, then returned to room temperature and tested. The number of cycles should be higher and the temperature should be related to the low temperatures in the field. Composite laminates have higher strengths and stiffness at colder temperatures. However, in most bonded shell systems, the strength of adhesive bonded joints can be significantly reduced at low temperatures. Most adhesives become stiffer and more brittle as temperatures decrease. This condition is detrimental to adhesive bonds, and makes them very susceptible to shear failure. For bonded systems, it is critical that testing be conducted at the cold temperatures expected in use, e.g., -25 °C (-13 °F) and not at room temperature of 24 °C ± 2 °C (75 °F ± 3 °F) as required in current specifications. We recommend that specimens be tested at cold temperatures and that the number of freeze-thaw cycles be increased to at least 100 cycles.

Durability Assessment of Adhesive Bonds/Joints: Current pre-qualification tests do not cover adequately adhesive bonds / joints. Currently, bond durability specimens are constructed with the adhesives being sandwiched between two composite laminates having edges sealed with a waterproof sealant prior to exposure, hence they are completely protected from the environment rather than being exposed to it as in the field. These bond durability test specimens remain uncut during simulated environmental exposure, and are then cut (with lateral staggered grooves that form the shear area) just prior to testing. In so doing, the environmental exposure medium does not reach the bond area as it would in field installed casings. We have two concerns: first, bonds/joints are critical parts, being zones of high normal (peel) and shear stresses, and the likely points of failure initiation; second, the lateral staggered grooves forming the shear area in the flat test specimen should be cut before environmental exposure to allow for proper simulation of exposure.

Material Safety Factor: Another concern centers on the durability of some composites in high moisture environments and the absence of material safety factors in the design of the composite casings. Nearly all polymers and adhesives and some glass fibers are adversely affected by moisture, which can reduce service life dramatically in some cases. Some columns sit in water for several months of the year. This environment may not be at all suitable for some composite casing systems and their adhesive bonded joints. While certain durability programs have produced data after 10 000 hours of exposure to some of these environments, these data have not yet been used to develop material safety factors in the design of current column casings. "Degradation of composites typically used in civil infrastructure, when it occurs, usually affects strength, rather than stiffness, and hence care should be taken to apply strength reduction coefficients to designs to account for drop-offs in short-term and long-term performance levels" (Seible and Karbhari 1997).

COLUMN CASING SPECIFICATION:

Concrete Surface and Casing Surface Resin Coating: The Illinois Department of Transportation has data showing the deleterious effects of entrapped moisture on the concrete of a column. A resin coating on the concrete surface inhibits "breathing", i.e., the transport of moisture into and out of the column. This coating is not necessary if the column is wrapped, since wrapped casings provide adequate permeability, while a homogeneous coating is significantly less permeable and adds considerable cost.

The application of a resin coating on the outside surface of a casing is redundant. Where required, coatings should be properly selected to provide adequate permeability as well as protection against ultraviolet radiation and other surface effects. In general, resin coating of an FRP casing is an unnecessary additional expense.

Field Quality Assurance: Certain materials tests, process control tests and finished column casing tests should be performed to validate manufacturing process control and to verify the quality and long term reliability of the casing installation. In this regard, current specifications are either inadequate or unnecessary for the following reasons:

(a) Currently, material testing for all composite casing systems is done on a daily basis on field coupons. For hand-wrapped casing systems where the mixing of resin and hardener, as well as the impregnation process, occur in the field, this is necessary to verify manufacturing process control. However, for casing utilizing prepreg materials, **daily** field coupons are an excessive demand, since the material properties are certified by the supplier. In this case, verification of the manufacturing process control should be done primarily to ensure the degree of cure. The excessive testing on prepreg systems imposes cost penalties and creates an uneven playing field for the competitive systems. Current column casing specifications should differentiate between manufacturing processes and specify a frequency of materials conformance testing tailored to each type of material, field manufacturing process and supplier batch sizes. In most cases certification of material properties by the suppliers should suffice. If field testing of materials is mandatory, then one test series for each supplier batch is more than adequate and would apply to all materials entering the construction site including coatings, resin and adhesive components, dry fibers and fabric, pre-impregnated fibers and fabric, paint, etc.

(b) Manufacturing process controls need to be checked for every mix (for multiple component field mixtures); and every column for column specific operations such as surface preparation, filling, profiling, thickness control and cure. Present specifications are inadequate.

(c) There is a critical need for visual inspection criteria of finished casing for abnormalities, and standards for acceptable corrections. Such things as delaminations, debonding, and surface irregularities (crazings, cracks, loose fibers, dry areas, resin rich areas) need to be addressed. Again, present specifications are inadequate. The paper by Hawkins, Johnson and Nokes in this volume presents a promising method.

The extent and frequency of testing, checking and visual examination need to be specified in advance and incorporated in bid specifications to avoid misunderstanding and excessive cost and to maintain expected quality levels.

RECOMMENDATIONS AND CONCLUSIONS:

For the continual improvement of bridge retrofit specifications, we recommend the institution of a suppliers' alliance which would participate in the improvement of specifications for materials, job qualification and construction. This alliance would work closely with standards writing organizations, such as AASHTO, in the continual development of highway bridge standards. For the development of standards for the structural retrofit of **buildings** using FRP, we recommend using research results, experiences and standards for **bridges** as a starting point.

For both bridge and building retrofit with FRP, we recommend that the National Institute of Standards and Technology (NIST) play a strategic role in leading the technological progress for standards improvements. NIST contribution will provide leadership to both the research needed in formulating new approaches to retrofit design and construction and the development of standards needed to implement this new field of technology. Standards development would encompass both the evaluation of existing specifications and the development of new, national standards for all retrofit applications. In conclusion, we advocate standards development by a partnership among government, industry, and academia.

Reference

(1) Seible, F., Karbhari, V., (1997), "Seismic Retrofit of Bridge Columns Using Advanced Composite Materials", National Seminar on Advanced Composite Material Bridges (FHWA), Arlington, Virginia, May 5-7, 1997.

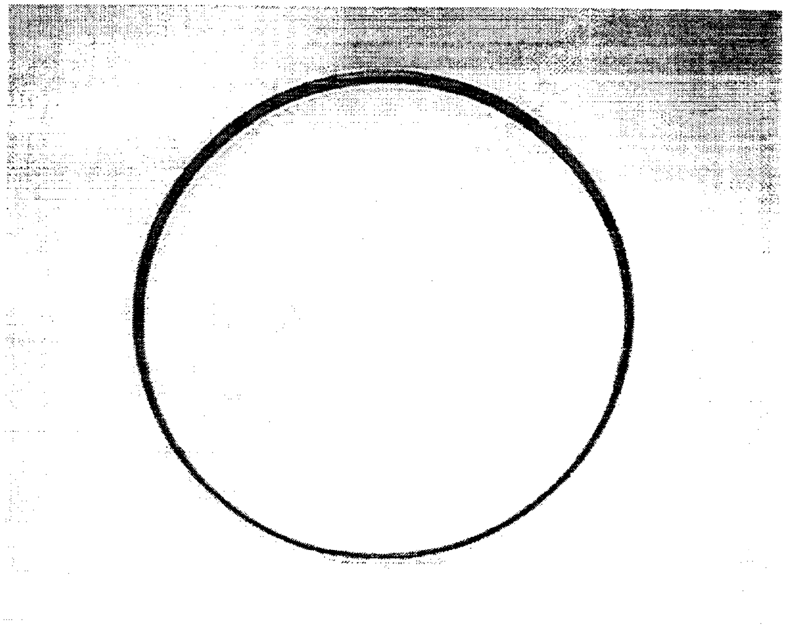

Figure 1A: Untested Naval Ordnance Laboratory (NOL) ring made with automated carbon jacketing process.

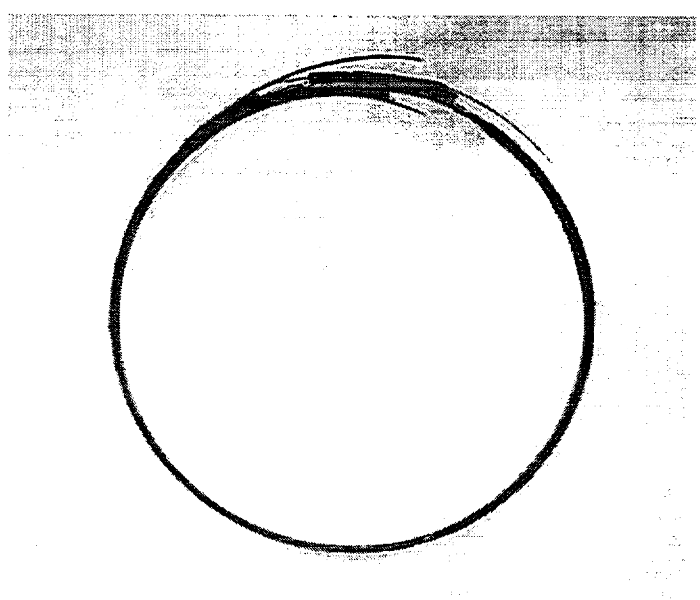

Figure 1B: Naval Ordnance Laboratory (NOL) ring after internal pressurization testing.

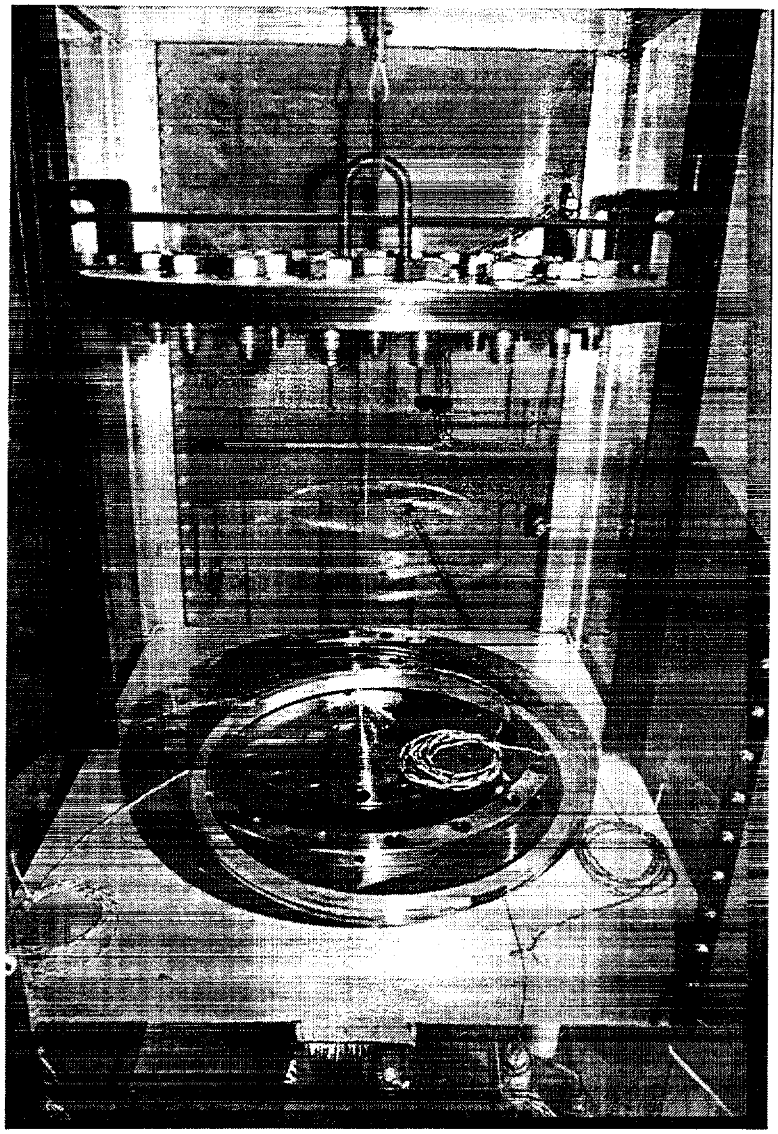

Figure 2: Test fixture for NOL ring internal pressurization testing.

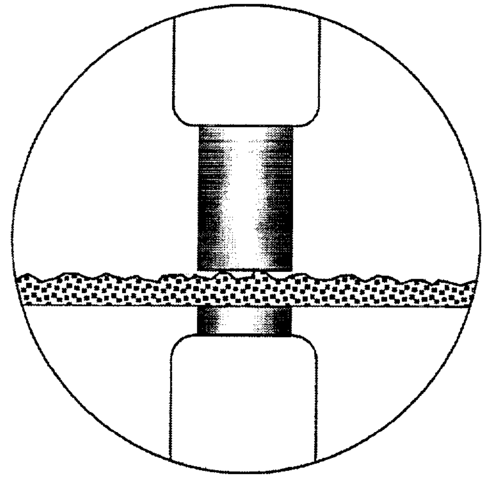

Figure 3: Illustration of Thickness Measurement Error with Cored Casing Sample.