Tensile Behavior of PVC-Coated Woven Membrane Materials Under Uni- and Bi-Axial Loads

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ABSTRACT: Tensile characteristics are the most significant mechanical properties for coated woven fabrics as membrane materials used in lightweight constructions. Factors that might affect test results of the material under uni- and bi-axial tensile loads are examined. After series of tensile tests on PVC-coated membrane materials, it is demonstrated that (1) to measure the strains in the two perpendicular directions, the contact method by the needle extensometer does not interfere the correct data recording; (2) the positions where the strains are measured on specimens have a great influence on the test results of the stiffness and Poisson's ratio in warp direction under uni-axial load; (3) to perform bi-axial tensile tests the size of the cruciform specimen in bi-axial tensile test can be much smaller than those suggested in the literature. The tensile behavior of coated membrane materials under bi-axial loads are affected dramatically by the stress ratio in the warp and fill directions. Besides the residual strains of coated membrane materials are affected not only by the properties of the constituent yarns and woven structure but also by loading conditions during the coating process. © 2007 Wiley Periodicals, Inc. J Appl Polym Sci 107: 2038–2044, 2008

Key words: poly(vinyl chloride) (PVC); mechanical properties; uniaxial; biaxial; coated woven materials

INTRODUCTION

In the past two decades, the application of coated fabrics as architectural membrane material for lightweight structures has grown dramatically. As a kind of flexible materials, coated membrane materials have virtually little bending stiffness, and therefore can only resist in tensile. To sustain a shape, the membrane material must be in tension. Tensile behaviors are therefore vital to establish the material properties for structural design.[1]

To test the tensile behaviors of coated membrane materials under uni-axial load there are several international standards. However, it is known that membrane materials are under complex loading conditions when used as architecture structures. Uni-axial test, although simple to undertake, is less favorable in evaluating the service performance of the material. Thus, the bi-axial tensile test is recommended. However, presently there is no common recognized testing method on bi-axial tensile test for membrane materials. Neither the configurations of specimen shape nor the testing procedures have been identified. So far, as a matter of fact, various test methods have been suggested by manufacturers.

To perform bi-axial tensile test on membrane material, three methods have been referred in the literature, i.e., the bursting test, the cylinder test and the in-plane bi-axial test.[2–4] Among them, the in-plane bi-axial test, especially with a cruciform specimen, represents the best results for stress-strain relation of the material. Therefore, it has been used more popularly since 1980s.

For the specifications of the cruciform specimen, there are a number of examples and suggestions in the published literature. The dimensions of the cruciform specimen, particularly the cross area, varied from 160×160 mm^2 to 300×300 mm^2.[5–9] The slits in the arms were reported helpful for a uniform stress distribution in the cross area of the specimen.[2,5] The transfer efficiency of the stress from the holding clamp to the cross area would be greatly improved with the assistant of these slits. In addition, the shape of the cross corners of the specimen meant certain effect on the stress distribution. Compared to the straight corner or triangular corner, the rounded corner, with a radius of 5–15 mm, had shown its benefit to the transmission of stress.[2,6]

For bi-axial tensile test on coated membrane materials, a large deformation could be expected. To measure the tensile strain of the material there are two kinds of method, that is, contact and noncontact

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TABLE I
Specifications of PVC-Coated Polyester Fabrics

Sample code	Weave pattern	Yarn count (Tex)	Yarns density (warp/fill) (ends/cm)	Mass (g/m^2)	Thickness of coated fabric (mm)	Average thickness of PVC layer (mm)	Breaking strength (warp/fill) (N/5 cm)
S1	Basket	111.11	12/12	900	0.74	0.31	3900/3500
S2	Basket	144.44	13/13	1100	1.00	0.42	5500/5000
S3	Basket	111.11	12/12	1000	0.90	0.40	4400/4000

method. Needle method is one of the contact methods.[6,8] The strain is measured with an extensometer attached to the center of the test sample with two needles. With this method, the needles have to penetrate the specimen, which might interfere the correct tests. To overcome the possible interferences of the contact method, noncontact methods, such as photograph method[2,10,11] and laser method,[12] have been used widely. Because of the availability a pair of needle extensometers was used in the present study. Therefore, before conducting bi-axial strains test, it would be interesting to know the performance of the needle extensometer.

In the present study, several factors that might interfere correct tensile tests were examined. In addition to the performance evaluation of the needle extensometer, the influence of the positions on specimen where strains were detected was investigated. The possibility of using small size cruciform specimens was examined. Besides, the effect of loading conditions, such as tensile cycles and stress ratios between the warp and fill directions were also discussed. It hopes that the study would provide additional information for those who want to evaluate the tensile performances of coated membrane materials by means of bi-axial tensile tests.

EXPERIMENTAL

A bi-axial tensile tester, model Z010/TH2A by Zwick GmbH, was used. The tester consists of two load frames crosswise connected. The load frame consists of two guide profiles, two moving crossheads and a head plate. The head screws have tow counter rotation threads so that the moving crossheads move synchronously in opposite directions.[13] Two pairs of specimen holders are controlled by compressed air so that specimens can be held as rigorously as possible.

PVC-coated polyester fabrics with a surface treatment of polyvinylidene fluoride (PVDF) were used in the current research. Table I lists the specifications of the samples.

The configuration of the specimen for bi-axial tensile tests is shown in Figure 1. The cross area of the specimen is 60×60 mm^2 and the shape of the cross corner is rounded with a radius of 15 mm. There are three long slits in each tensile arm. For the reason of comparison, uni-axial tensile tests were also conducted on the same tester. The dimensions of the specimen for uni-axial tests as a strip shape are compatible with those of bi-axial tests.

In the bi-axial tests, the loading speed in one direction was set 1.0 N/s and that in the perpendicular direction followed the stress ratios determined. For example, for the stress ratio 1:2 (warp:fill), the loading speed in warp and fill direction was set at 0.5 and 1.0 N/s, respectively. For uni-axial tensile tests the loading speed was kept at 2.0 N/s.

Three cycles of loading-unloading were conducted, according to the usual practice of bi-axial tensile tests for coated membrane materials.[5,7,9,14] There was no suspension between the loading cycles. The maximum stress in the loading cycle was 15% of the ultimate tensile strength of the corresponding specimen. For samples S1, S2, and S3 listed in Table I, the maximum stress was set at 125, 140, and 150 N/cm, respectively.

For each test, three specimens were tested.

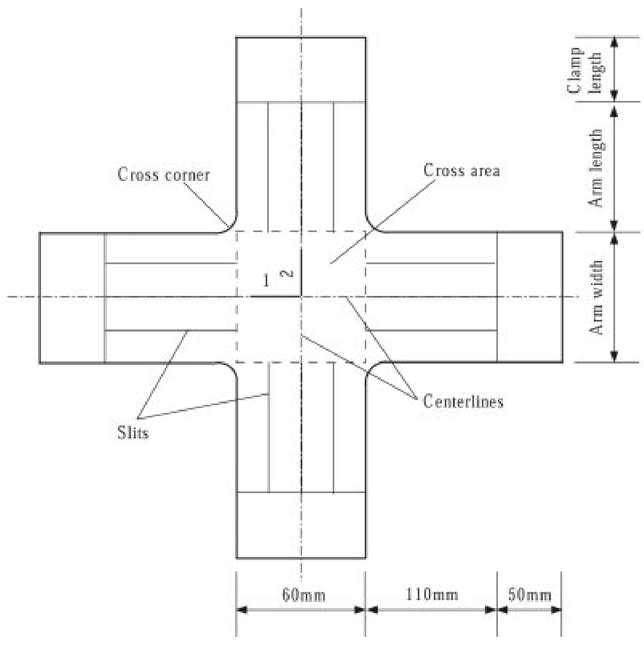

Figure 1 Dimensions of specimens for bi-axial tensile tests.

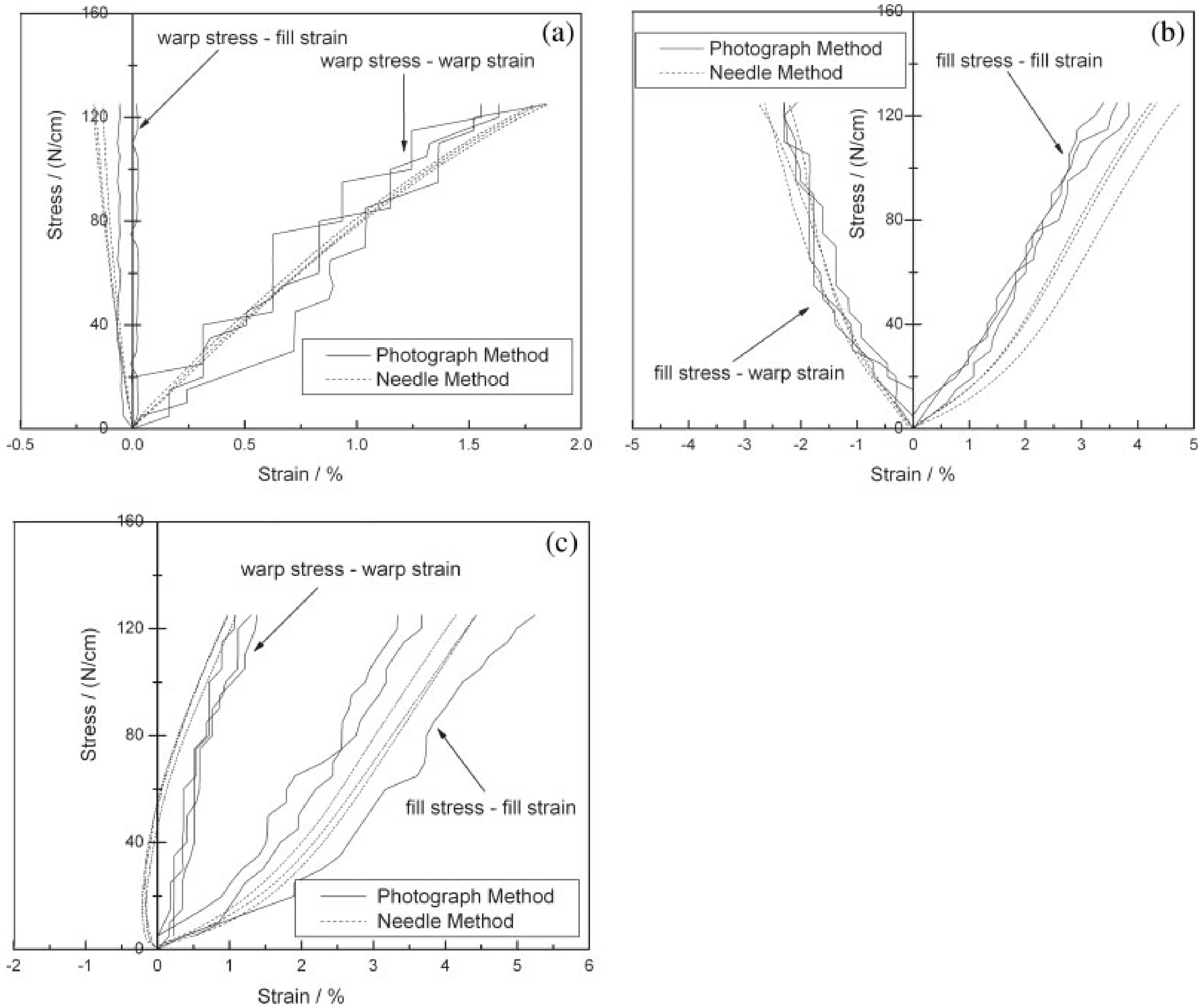

Figure 2 Tensile strains recorded by both needle and photograph methods. (a) Uni-axial tests in warp direction. (b) Uni-axial tests in fill direction. (c) Bi-axial tests with a stress ratio 1 : 1 (warp: fill).

RESULTS AND DISCUSSION

Strain testing by needle method

Before actual tests, the recording performance of needle methods was examined by comparing the testing results with those by photograph method. For comparison, three groups of experiments, under both uni- and bi-axial tests, were arranged on sample S1. They were uni-axial tests in both warp and fill directions and bi-axial tests with a stress ratio 1 : 1 (warp: fill).

As a photograph method, a digital camera was fixed above the center area of the specimen. Photos were taken in every 75 s during the whole test period to record the displacement of prearranged marks on the surface of specimen.

By penetrating needles, a pair of resistance extensometers was attached on the top and bottom sides of specimens, respectively, to record the strains in perpendicular loading directions. The recorded data were then transmitted to a data acquisition system for further processing.

The testing results, by both photograph and needle methods, are shown in Figure 2. For easy identification, only the third uploading curves are displayed. It is noticed that the data recorded from the two methods are in general agreement. The needled method does not introduce unacceptable errors in the present range of measurement. In fact, the data recorded by the needle method are more consistent and accurate than the photograph one.

Positions of strain measurement on specimen

To study the effect of the position where tensile strains were measured on a specimen, experiments were arranged on sample S2 at three positions: A, B, and C, as illustrated in Figure 3.

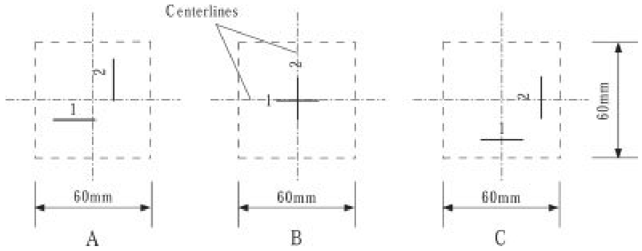

Figure 3 Positions of tensile strain measurement on specimen.

Figure 4 shows the tensile stiffness and Poisson's ratio measured at different positions on specimen in uni-axial tests. Differences are observed when the measurement is at different positions when loading in warp direction. At position A, the tensile stiffness is much higher than that in position B or C. Similar variations of Poisson ratio can also be observed. It indicates that the stress distribution perpendicular to the loading direction is not as uniform as one may expect. It is therefore recommended that, to obtain a consistent recording, the position of measurement should be along the centerline of loading to avoid any possible position effects.

In Figure 4 it may also be noticed that the position effect is less sensitive when loading in fill direction. The reason for the different behaviors of position sensitivity can be attributed to the different levels of yarn crimps due mainly to the coating process, in which warp direction is tensioned resulting in a great degree of fill crimp because of crimp interchange of woven structure.

Unlike those in uni-axial tests, the tensile behaviors of specimen under bi-axial tests are less sensitive to the position of strain measurement, as shown in Figure 5. This can be expected by referring to Figure 6 by Bridgens[12] that there is a range within the cross area of the cruciform specimen, in which the stress distribution is rather uniform. When the measurement position is outside this range, a significant decrease of tensile stress would be expected.

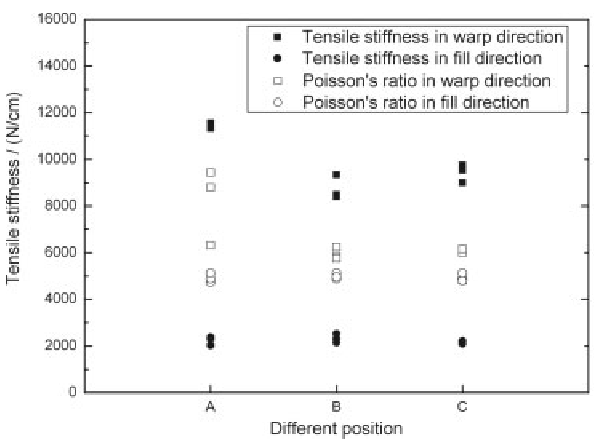

Figure 4 Testing results of sample S2 with different measurement positions in uni-axial tests.

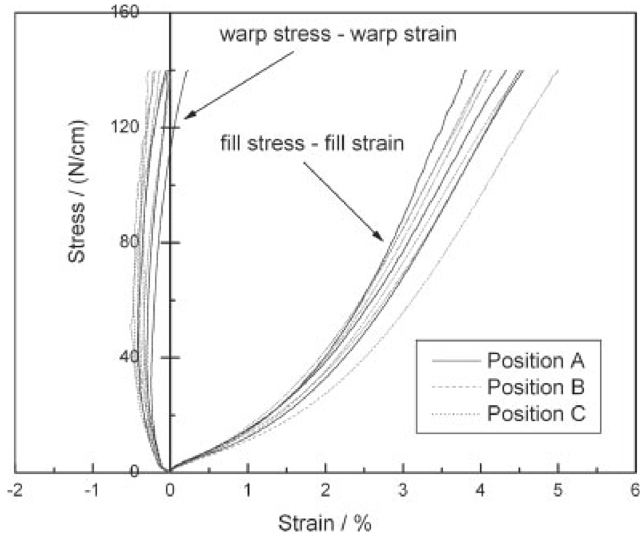

Figure 5 Tensile behavior of sample S2 in bi-axial tests with different measurement positions (stress ratio 1 : 1).

Tensile behaviors under uni- and bi-axial loads

Samples S2 and S3 were tested under both uni- and bi-axial loads. For all tests the strains were measured by the needle method at position B identified in Figure 3. The results of the third uploading curves are shown in Figure 7. W and F represent the bi-axial tensile curve in warp and fill directions, respectively, followed by the stress ratio between warp and fill directions. W-uni and F-uni are the uni-axial tensile

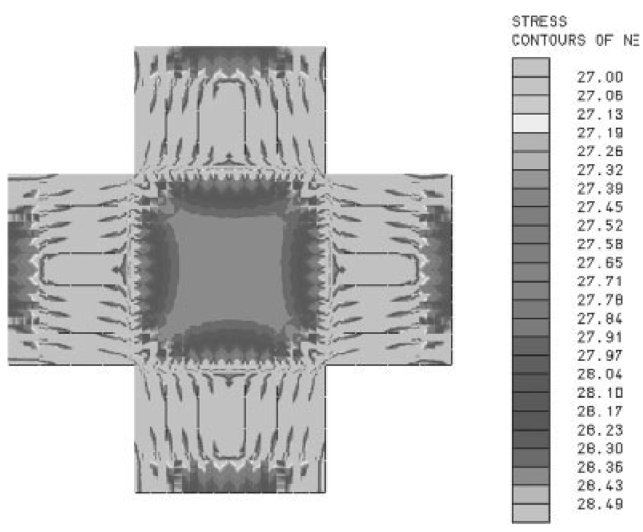

Figure 6 Stress distribution of cruciform specimen, with 30 N/cm loads in both of loading direction.[12]

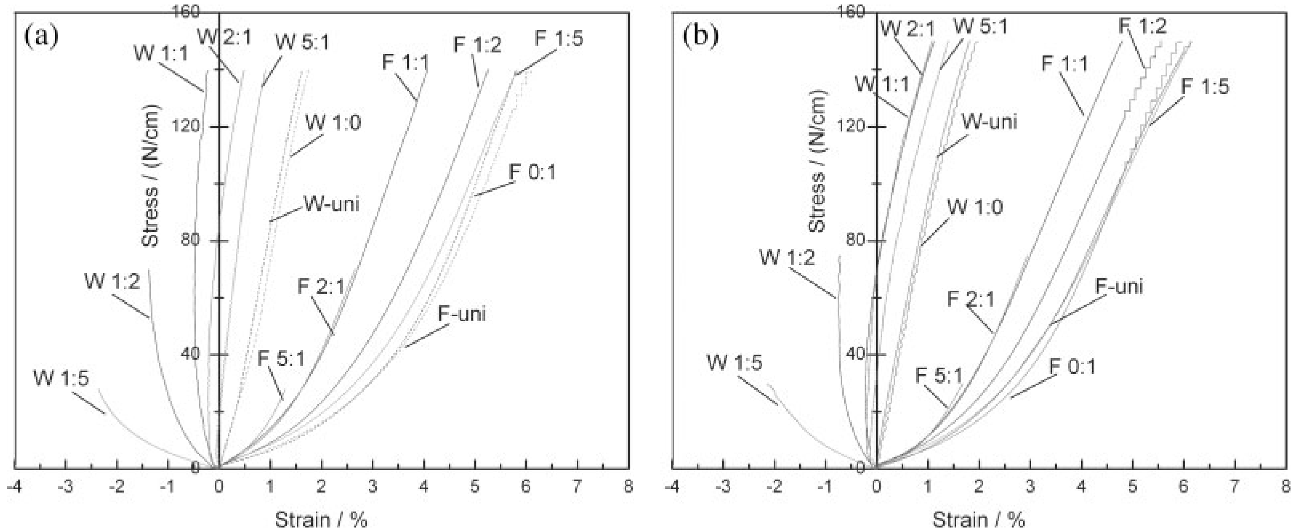

Figure 7 Tensile behaviors under uni- and bi-axial loads. (a) Sample S2 and (b) Sample S3.

curves when loading in the warp and the fill direction, respectively.

Referring to the tests reported in the literature with larger size of cruciform specimens, such as Itoh's[9] with a cross area of 160 $\times$ 160 mm^2 and Kato's[7] with 300 $\times$ 300 mm^2, it could be found that the tensile behaviors with different stress ratios were compatible. This indicates that the cross area of the specimen for bi-axial tensile tests could be reduced, such as 60 $\times$ 60 mm^2 in the present study.

In coated membrane materials, since the Young's modulus of the pure PVC membrane is as low as 6.7 Mpa, the polyester fabrics play a more important role in the tensile characters of the coated membrane materials under bi-axial loads especially under higher stresses.[7] Then the difference between the tensile behavior of S2 and S3 under bi-axial loading (see in Fig. 7) is mostly resulting from the yarns and the fabric structures (see in Table I).

Because of the different level of the crimp and the looseness in the warp and the fill directions in the coated membrane materials resulting from the producing of woven fabric and coating process, the unbalanced deformations in the warp and fill directions happen according to different stress ratios (see in Fig. 7). When the stress ratio is less than or equal to 1 (for sample S3 or S2), negative strains happen in the warp direction and positive strains happen in the fill direction due to the unbalanced structure of the materials. The state of the shrinkage in the warp direction and the state of the extension in the fill direction can result in the situation of unbalanced deformations of the structure membrane. Besides, because of the decrease of the Young's modulus in the warp direction with stress ratios less than 1, the use efficiency of the materials especially in the warp direction will be reduced dramatically. Therefore, in the design and the application of the membrane structures, the potential damage (for example, the shrinkage of the surface) resulting from the special stress distributions should be avoided.

Residual strains after bi-axial loading cycles

Figure 8 shows the residual strains after each loading cycle in bi-axial tests with different stress ratios for sample S2 and S3, respectively. To make the figure much clear, each value is the mean value from three specimens since the percent errors are as small as less than 5%. The stress ratio of 10 represents the bi-axial test with a stress ratio of 1:0 (warp: fill).

Compared to the results of S3, the residual strains (positive and negative ones) of S2 are much smaller in both the warp and the fill directions. By referring to the sample's specifications in Table I, it is known that, with higher-strength yarns and tighter woven structure, sample S2 shows better elastic recovery with cycle-loads than sample S3.

From Figure 8, it can be noticed that for sample S2 and S3 during the three loading cycles, when the stress ratio is less than 1 the residual strains in warp direction are still negative. However, in the fill direction the residual strains are positive. This phenomenon emphasizes that the stress distribution with stress ratios less than 1 should be avoided in the application of the structure membrane.

Figure 8 also shows that, when the stress ratio is more than 1, the residual strains in both warp and fill directions are less than 2.0% and the difference after each loading cycle is less than 0.5%. It shows a

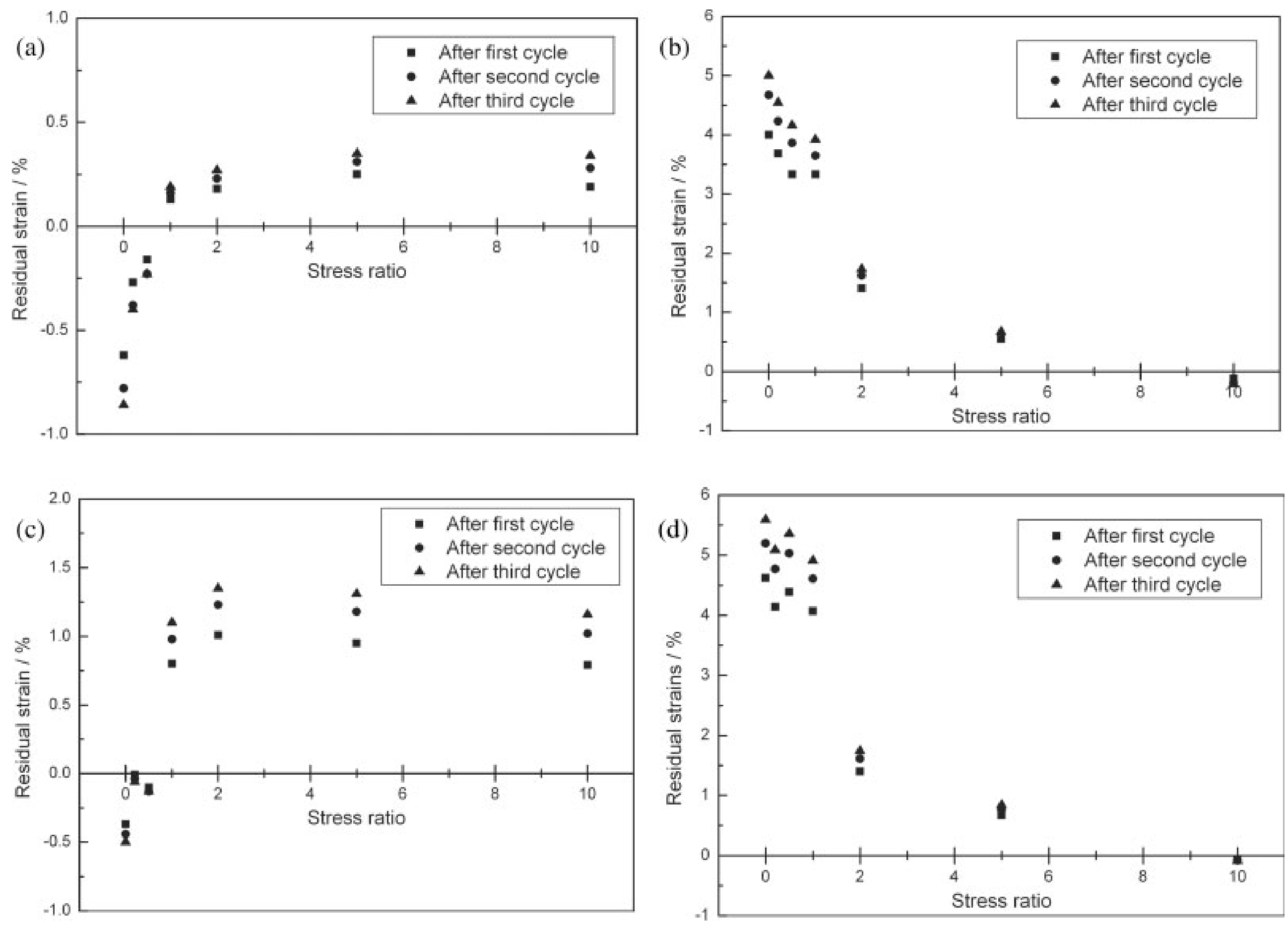

Figure 8 Residual strains after each loading cycle under bi-axial tests. (a) In warp direction for sample S2. (b) In fill direction for sample S2. (c) In warp direction for sample S3. (d) In fill direction for sample S3.

good elastic recovery of the coated membrane materials when loading in warp direction is higher than that in fill direction. However, when the stress ratio is less than 1, the residual strain in fill direction is as great as 5% and the difference after each loading cycle is as large as 1.0%, although the residual strains in warp direction is still less than 1.0%. The different results of the bi-axial tests between a pair of ''symmetrical'' stress ratios, such as 1 : 2 and 2 : 1, should attribute to the inherent unbalanced structure of the coated fabrics,[15] in which the crimp of yarns in fill direction is much higher than that in warp direction. The different residual strains between the warp and fill directions can lead to the difference of relaxation in the two perpendicular directions, and then can result in the difficulty to maintenance of a stable and smooth surface in tensile structures.

Therefore, suitable stress ratios should be determined in the design of tensile structure to obtain uniform tensile behaviors of membrane materials. It is also strongly suggested that proper tension should be applied to the fill direction of woven fabric during the coating process to reduce the degree of fill yarn crimp.

CONCLUSIONS

Factors that might affect tensile testing results of coated woven fabric as membrane materials under uni- and bi-axial tensile loads are examined and some measurement techniques are discussed.

Within the testing range of the present study, the needled method, although two needles penetrating the specimen, does not introduce noticeable errors. It is a preferable method if there is no more sophisticated noncontact method available.

For uni-axial tensile tests with the needle method, the attachment of two penetrating needles on the specimen should be along the centerline of loading to avoid any possible position effects because of the nonuniformity of the stress distribution perpendicular to the loading direction. For bi-axial tensile tests, however, the position effect is less notable because the stress distribution within the cross area of cruciform specimen is rather uniform.

It is shown that in bi-axial tensile tests with small size specimens are in good agreement with those with larger ones suggested in the literature. Further studies are required to identify the most suitable size for the cruciform specimens.

The strains and residual strains of PVC-coated membrane materials under bi-axial cyclic loads are affected greatly by the different degrees of yarn crimp in woven structure. Because of the essential unbalance of yarn crimp in the woven structure, suitable stress ratios should be determined to maintain a stable and smooth surface in tensile structures. However, to obtain a uniform tensile behavior of membrane materials it is strongly suggested that proper tension should be applied to the fill direction of woven fabric during the coating process to reduce the degree of fill yarn crimp.

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References

1. Bridgens, B. N.; Gosling, P. D.; Birchall, M. J. S. Struct Eng 2004, 82, 21.
2. Reinhardt, H. Exp Mech 1976, 16, 71.
3. Mott, R.; Huber, G.; Leewood, A. J Test Eval 1985, 13, 9.
4. Bassett, R. J.; Postle, R.; Pan, N. Polym Compos 1999, 20, 305.
5. Bridgens, B. N.; Gosling, P. D.; Birchall, M. J. S. Struct Eng 2004, 82, 28.
6. Membrane Structures Association of Japan 1995, Testing method for elastic constants of membrane materials, MSAJ/M-02-1995.
7. Kato, S.; Yoshino, T.; Minami, H. Eng Struct 1999, 21, 691.
8. Minami, H.; Motobayashi, S. Trans Japan Soc Compos Mater 1983, 9, 8.
9. Itoh, K.; Tanaka, K.; Ohuchi, Y. An experimental study on tension characteristics of suspension membranes; Shells, Membranes and Space Frames, Proceedings of the IASS Symposium on Membrane Structures and Space Frames. Osaka, Japan, 1986.
10. Mailler, P.; Hamelin, P.; Jarrigeon, M.; Nemoz, G. Annal des Compos 1995, 3, 27.
11. Vysochina, K.; Gabor, A.; Bigaud, D.; Ronel-Idrissi, S. J Ind Text 2005, 35, 137.
12. Bridgens, B. N. Phd thesis, School of Civil Engineering and Geosciences, University of Newcastle, Newcastle 2005.
13. Zwick Technical Documentation Instruction Manual, Instruction and technical manual for the materials testing machine Z010/TH2A, 2003.
14. Minami H.; Toyotaka, H.; Kotera, K.; Segawa, S. Some reviews on methods for performance of membrane materials being used for membrane stuctures; Shells, Membranes and Space Frames, Proceedings of the IASS Symposium on Membrane Structures and Space Frames. Osaka, Japan, 1986.
15. Skelton, J. J Mater 1971, 6, 656.