IN-PLANE TESTING OF FULLY-ADHERED MODIFIED BITUMEN ROOF MEMBRANES

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This paper discusses the in-plane testing of fully-adhered, modified bitumen roof membranes and their performance characteristics. The in-plane testing process is done parallel to the plane of the roof. The main objectives are to distinguish between testing for quality control and testing to predict in-service performance, and to show that the multi-ply membrane as well as the individual plies need to be tested if in-plane performance is to be assessed. Results from the testing of two different proprietary membranes are used for illustration. For each membrane, the individual plies and the membrane system (i.e., cap sheet and base sheet bonded together) were subjected to the standard tension test and the nonstandard, joint-bridge test at various temperatures.

The results clearly show that to track membrane performance adequately, the entire load-deflection history must be considered. Recording only the maximum load and the corresponding elongation is not adequate.

With fully-adhered systems, the tension testing of the individual plies provides a means of quality control during manufacturing. To assess in-plane performance during its service life, the membrane system, rather than the individual plies, should be subjected to the joint-bridge test over a temperature range representative of conditions that might occur.

KEYWORDS

Behavioral chacteristics, fully-adhered, in-plane performance, joint-bridge test, load-deflection, membrane system, modified bitumen, roofing, tension test, testing.

INTRODUCTION

According to recent surveys, fabric-reinforced, polymer-modified bitumen roofing membranes account for about 20 percent of the U.S. market for low-slope roofs on commercial and industrial buildings.[1] The article also states that within the U.S. the market share for modified bitumen membranes is the fastest growing. Comparable market figures for Canada are not known.

During the last five years, the Building Engineering Group (BEG) at the University of Waterloo has been involved in a variety of research and development projects related to roofing. Most of the support and much of the effort has been directed at the mechanical properties and in-service performance of modified bitumen membranes. A great deal of standard and nonstandard testing has been done on individual materials (mainly nonwoven fabric reinforcements), and on base sheets, cap sheets and multi-ply roofing membranes or membrane systems. Joint university and industry round-robin testing has also been conducted. In general, BEG has focused on short- to medium-term mechanical properties, while the industry collaborators have looked after durability testing and chemical analysis.

One purpose of this paper is to discuss testing techniques and experiences. The main objective is, however, to address two concerns:

- A need to distinguish between testing for the purpose of quality control and testing to predict in-service performance.
- A need to show that both the multi-ply membrane as well as the individual plies need to be tested if in-plane performance is to be assessed.

This paper will identify and discuss some of the basic test procedures, use test results to demonstrate certain points qualitatively and argue for some changes in the way tests and their results are used. The paper will not identify the products tested nor will it attempt to pass judgment as to developmental strategies, since the work is of a proprietary nature.

PHYSICAL TESTING FOR IN-PLANE MECHANICAL PROPERTIES

A test procedure that appears to be universally accepted is the tension test. Our testing followed the procedures outlined in the Canadian General Standards Board (CGSB) standard 37-GP-56M, with some exceptions. Following are details of the test specimens and procedures for the tension test.

A rectangular 200mm x 50mm sample was used. Fifty millimeters of the sample was inserted into each jaw or grip of the test machine, leaving an unconstrained span between the jaws of 100mm. Figure 1 shows the type of jaws used. The samples were conditioned for a minimum of 12 hours. The jaws were separated under displacement control at a rate of 50mm/min. A load-deflection plot was generated for each sample tested. Focal behavioral characteristics were selected from the plot and recorded (both load per unit width (N/mm) and elongation (mm)). Tensile elongation was based on the measured separation of the jaws. An attempt was also made to assess the slope (relative tensile stiffness) of the initial linear segment, if applicable.

On a roof, modified bitumen membranes are fully adhered to a substrate that usually consists of sections of board insulation. During service, the roof is subjected to thermal cycling and other forms of loading. Thermally induced volumetric changes cause cycles of in-plane deformations at the substrate joints, and these in turn work the membrane above the joint.

It follows that, if a realistic test for in-plane performance of fully-adhered roof membranes is to be developed, then these in-service conditions should be properly simulated. The BEG has developed a nonstandard test procedure that has been named the joint-bridge test. Details of the specimens and the testing procedure for the joint-bridge test have been previously published.[2] Subsequently, an extensive amount of testing has been conducted. Following is a brief summary of the nature of this test.

The joint-bridge test utilizes two separate lengths of stiff substrate, usually plywood, that are butted together, to which the membrane sample is bonded using standard roofing techniques. (See Figure 2; note that initially there is no gap.) The samples are thermally conditioned for a minimum of 12 hours. The two pieces of substrate are then separated in a test frame at a rate of 5mm/min. under displacement control. A load-deflection plot is generated for each test sample.

All the test data that follow were derived from an extensive testing program on two different, modified bitumen membranes. For the purposes of this paper, these two membranes are referred to as products A and B. Both systems involve a cap sheet and a base sheet. Both are SBS modified, but use different reinforcement types. The reinforcements in the base sheets of both products A and B are glass fiber mats with similar characteristics. For product A, the cap sheet is reinforced with a polyester scrim and a glass fiber mat. For product B, the cap sheet is reinforced with a polyester mat. Note that during the manufacturing process, the polyester mat used in product B is saturated in blown asphalt prior to being coated in SBS modified asphalt.

Both membranes comply with the same CGSB membrane classification, namely, Type 1a (fully-adhered, exposed roof application), Class A (granule surfaced), Grade 2 (heavy-duty service) and, hence, target the same market. The term "membrane system" refers to the cap and base sheet bonded together.

Both the tension and the joint-bridge tests were conducted on the individual cap and base sheets, and on the two membrane systems. The base sheet was torched to the substrate and the cap sheet was torched to the base sheet. Adhesion by mopping could also have been tested. Testing was conducted at three representative temperature levels; 21°C, −5°C and −18°C. Both the machine direction and the cross-machine direction were tested. A minimum of five test results were obtained for each test condition.

TEST RESULTS

To tabulate and compare the test results, it is necessary to select a series of key parameters or focal behavioral characteristics to represent the behavior of each test specimen. All load values are designated "W," while all elongation values are designated "d." As shown in Figures 3A, 3B, 4A and 4B, there is usually an initial, essentially linear range of behavior with slope K1. The limit of this proportional range is designated "P," hence "Wp" and "dp." For the purposes of this paper, "F" is used to designate the last peak before final downturn of the load-deflection curve. "F" usually coincides with failure of the reinforcement if there is only one layer, or with failure of the last remaining layer of reinforcement in a sample with more than one layer of reinforcement.

Because of limited space and the large amount of data, only the mean values (of usually five tests) are tabulated. For similar reasons, only the machine-direction results are provided. Behavior in the machine and cross-machine direction is, in general, fairly similar except the nonwoven reinforcements strength in the machine direction is higher than in the cross-machine direction.

Tables 1A and 1B contain the tension test results for the machine direction for products A and B. (In all tables, N/A designates the absence of applicable results, while a dash (-) indicates the inability to obtain satisfactory results.) For illustration purposes, only the load-deflection plots for the tension test at −5°C for products A and B, respectively, are shown in Figures 3A and 3B. The focal behavioral points are also identified.

Tables 2A and 2B contain the joint-bridge test results for the machine direction for products A and B. For illustration purposes, only the load-deflection plots for the joint-bridge test at −5°C for products A and B, respectively, are shown in Figures 4A and 4B. Tables 3A, 3B, 4A and 4B summarize the coefficients of variation for each set of tests for the tension and joint-bridge tests, respectively. The coefficient of variation is a statistical parameter for comparing the measure of dispersion between and within data sets. It is used because comparing either the standard deviation or the variance of two or more data sets can be misleading unless the mean values are of approximately the same magnitude.

DISCUSSION

Membrane System vs. Individual Plies

For both products, the shapes of the load-deformation curves for the base sheet and the cap sheet are very different (see Figures 3A through 4B). This is due mainly to the differences in the types of reinforcement used. For instance, a glass mat permits much less elongation than a polyester-based reinforcement, either a mat or a scrim.

It is evident from the test results in Tables 3A, 3B, 4A and 4B that the performance of the membrane system cannot be obtained by summing the load-deformation results from tests on the individual plies, i.e., the base sheet and cap sheet tested individually. This applies to both the tension test and the joint-bridge test, and is evident primarily for the deformation values. This is particularly evident for the joint-bridge test. The load is induced into the specimen at the substrate interface, with the result that it is initially carried by the lowest intact reinforcement. Load sharing does not occur to the same extent as in the tension test. Therefore, the membrane system must be tested because its performance cannot be predicted by testing only the individual plies.

The elongation measured by the joint-bridge test is mainly the result of tensile elongation of the reinforcement(s) and shearing of the bitumen. Theoretically, the elongation at the point of final failure (df) for the membrane system should be higher than that for the cap sheet tested alone because of the much greater amount of bitumen below the cap sheet reinforcement. This result holds for product A (see Table 2A) at all test temperatures, but not for product B (see Table 2B). At cold temperatures, the membrane system for product B has lower df values than the cap sheet when tested individually. These differences are also clearly evident in the tension test results (Tables 1A and 1B). This relative decrease in the deformation of the product B membrane system occurs because, upon failure of the base sheet, there is a rapid transfer of load that initiates failure of the cap sheet. The reinforcement in the product B cap sheet is presaturated in blown asphalt during the manufacturing process. The blown asphalt becomes brittle at low temperatures.

COMPARISON OF THE TENSION AND JOINT-BRIDGE TEST METHODS

The authors have certain reservations about both the tension and the joint-bridge tests with regards to accuracy, interpretation and use. Consider the following data.

Tension Test

In order to reduce slippage of the sample within the jaw plates, especially at cold temperatures, considerable clamping pressure is required. This pressure in turn causes stress concentrations to occur at the jaw face. As a result, many of the test samples failed at the jaw face and might not have reached their full load potential.

During the tension test, shearing of the bitumen within the jaws contributes to the measured elongation. Therefore, a true strain value cannot be obtained by the standard practice of dividing jaw displacement by the initial distance between the jaws. This is especially true at warm temperatures when the shear deformation is more significant. The validity of the so-called "strain" is also affected by the necking of the specimen.

Joint-Bridge Test

At room temperature, 21 °C, many of the system samples separated from the plywood. In the worst cases, entire samples peeled off. Pre-treatment of the plywood with asphalt-based primer did not resolve this problem. For future tests, the use of longer specimens may correct this problem.

The joint-bridge test is also subject to variation in both the method and quality of attachment. In this test, both the base sheet and cap sheet are torched into place. Too little torching results in a poor bond while excess heat can result in a thinner layer of bitumen.

In general, the joint-bridge test models the in-plane performance that can occur on a roof i.e., it represents one aspect of in-service performance. The tension test does not, for a fully-adhered system, model any in-service condition. However, the tension test has considerable merit in quality control during manufacturing. Furthermore, the tension test is easier, cheaper and less time consuming to run.

Additional work needs to be done using the joint-bridge test to assess the effect of repeated loading, especially low-cycle fatigue and cyclic preconditioning.

THE IMPORTANCE OF THE BASE SHEET AND ITS REINFORCEMENT

Physical testing with the joint-bridge test has shown that the nature of the base sheet has a significant effect on the response of the membrane system. Therefore, altering the base sheet will affect the load-deflection characteristics of the membrane system. For example, the use of a high-strength, low-elongation base sheet (a base sheet reinforced with a strong, stiff glass mat) may result in the base sheet largely dominating the performance of the membrane system. This situation occurs because, upon failure of the base sheet, there is a relatively fast transfer of the load from the base sheet to the cap sheet. This may cause immediate failure of the reinforcement in the cap sheet. Note that the immediate failure of the cap sheet may not occur if the rate of substrate separation is very slow or if the reinforcement in the cap sheet is very ductile or strong.

Even the type of bitumen used in a base sheet can greatly alter the performance of a membrane system. For example, a base sheet composed of oxidized asphalt will contribute a minimal amount of elongation to the membrane system under the joint-bridge-type conditions at cold temperatures.

These two examples show that to assess accurately the behavioral characteristics of a membrane, it is necessary to test the membrane system and not just the individual plies. Furthermore, because of its initial dominance, the base sheet is particularly important to in-plane performance.

THE RELEVANCE OF PERFORMANCE TARGETS

Currently the CGSB standard 37-GP-56M specifies criteria for maximum strength and the corresponding elongation based on tension tests of the individual plies. One may question the adequacy of such a target for the acceptance of a fully-adhered membrane system. To reflect in-service performance more adequately, additional targets or criteria need to be developed. An improvement would be to subject the membrane system to the joint-bridge test over a representative temperature range. The appropriate performance targets should be developed and specified. As a minimum, this standard might specify the gap width and the rate of loading under displacement control, the membrane should be able to bridge a gap without sustaining any irreversible damage, i.e., without exceeding its proportional limit. Using this approach, the joint-bridge test should be conducted in addition to the standard tension test.

CONSISTENCY AND REPEATABILITY OF RESULTS

As the tension test is a generally accepted standard, it may be assumed that the variability obtained is acceptable. A comparison of Tables 3A and 3B with Tables 4A and 4B shows that the values for the coefficients of variation for the joint-bridge test are at least as low as the values obtained for the tension test. This comparability is an indication that results obtained from the joint-bridge test are at least as consistent and repeatable as those obtained from a tension test.

Three additional points, evident from the results of both the tension and the joint-bridge tests, should be noted:

- Usually, but not invariably, the coefficients of variation for strength values are less than those for the related deformation co-ordinate.
- In general, the values for the coefficients of variation for the co-ordinates of P, the proportional limit, are comparable to those for F, the failure point.
- In general, the coefficients of variation obtained for tests on the membrane system are comparable to those obtained from tests on individual plies.

CONCLUSIONS

Following are conclusions drawn from the data.

- To assess the performance of the roofing membrane, the entire membrane system, not just the individual plies, must be tested.
- To track membrane behavior adequately, the entire load-deflection curve must be recorded and the co-ordinates of the focal behavioral points tabulated. Recording only the maximum load and the corresponding elongation is not adequate, as the initial response is important.
- To understand membrane performance fully, testing must be conducted at a variety of temperatures representative of the conditions that occur. This may also include high temperatures.
- The joint-bridge test and the standard tension test model different situations and measure different characteristics.
- The joint-bridge test can be used to assess at least one aspect of in-plane performance that can occur during the service life of the fully-adhered roofing membrane, i.e., volume change in the substrate and its effect on the roof membrane.
- Tension testing of the individual plies has merit as a quality control test for manufacturing.
- Testing of the individual plies will facilitate understanding of the performance of the behavior of the membrane system and the contribution of each ply.
- The results obtained from the joint-bridge test are as consistent and repeatable as the results obtained from the tension test.

RECOMMENDATIONS

The authors recommend that future standards for the testing of fully-adhered, modified bitumen membranes incorporate the following:

- To measure in-service performance more adequately, the membrane system should be subjected to a joint-bridge test at representative temperatures.
- The appropriate performance targets should be developed and specified.

They also recommend that additional work on the joint-bridge test be done to assess the affects of cyclic loading, in particular, the influence of diurnal and seasonal thermal variation.

ACKNOWLEDGMENTS

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[2] Burnett, E.F.P. and C. Howson, "Performance Testing of Fully-Adhered, Polymer-Modified, Bituminous Roofing Membranes," Proceedings of the ASTM Symposium on Roofing Research and Standards Development, Special Publication 959, pp. 100-109, New Orleans, December 1986.

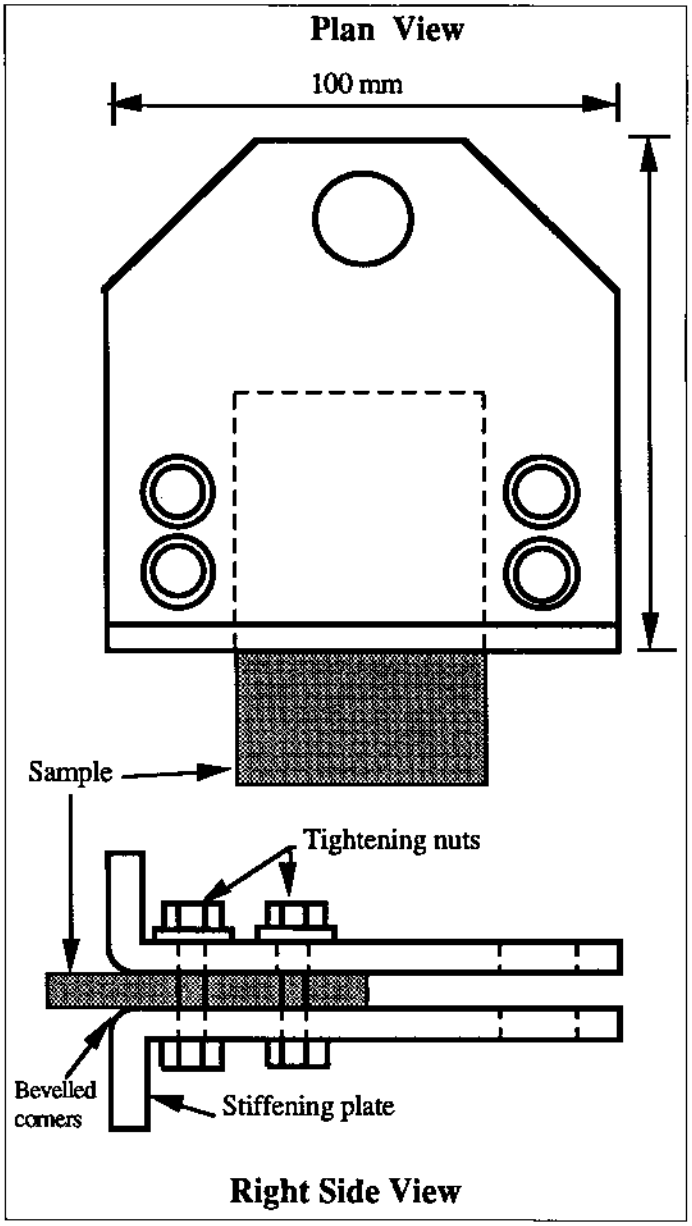

Figure 1 *Tension test jaw configuration.*

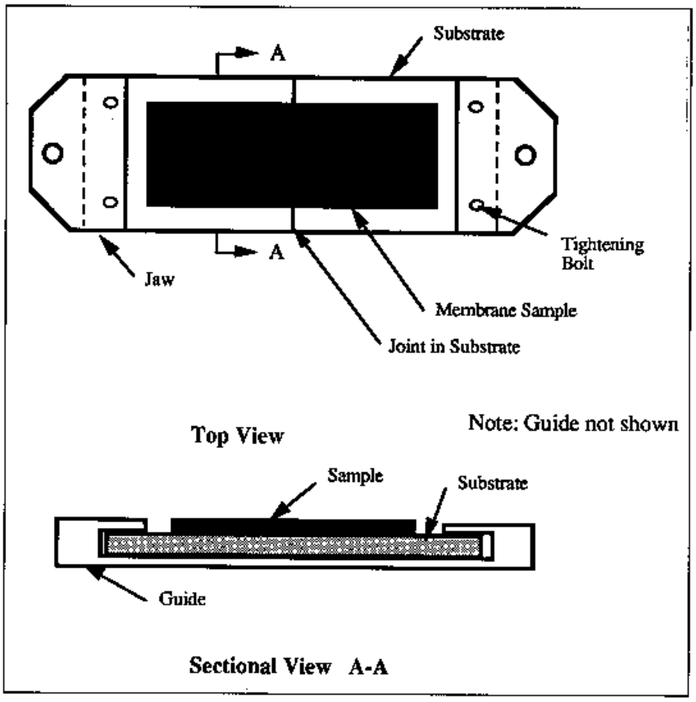

Figure 2 *Jaw configuration for joint-bridge test.*

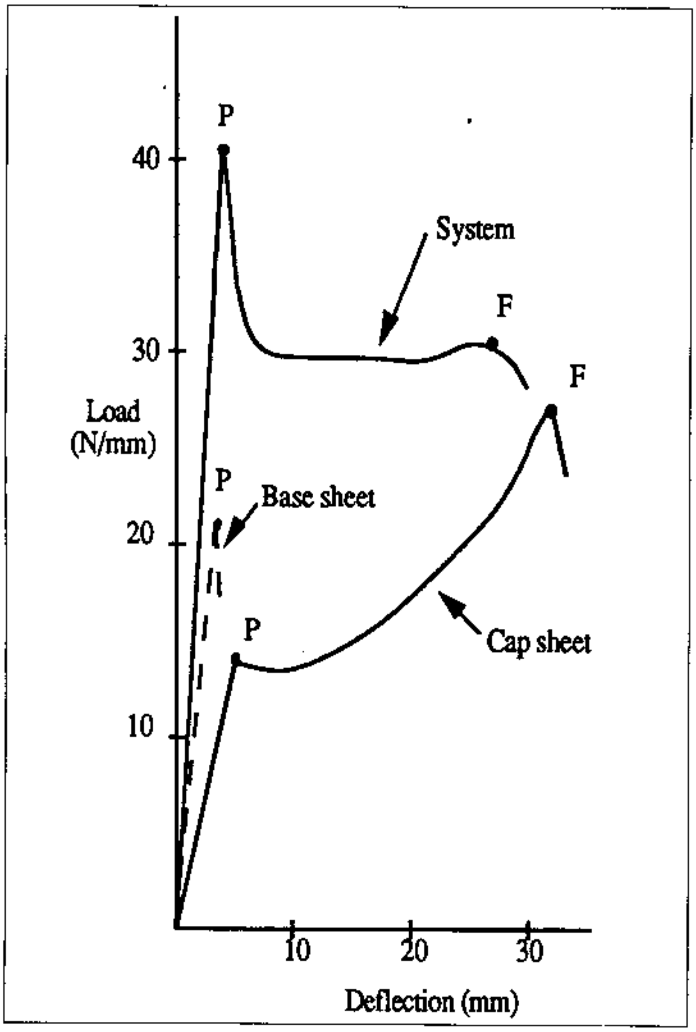

Figure 3A *Load-deformation, product A, tension test.*

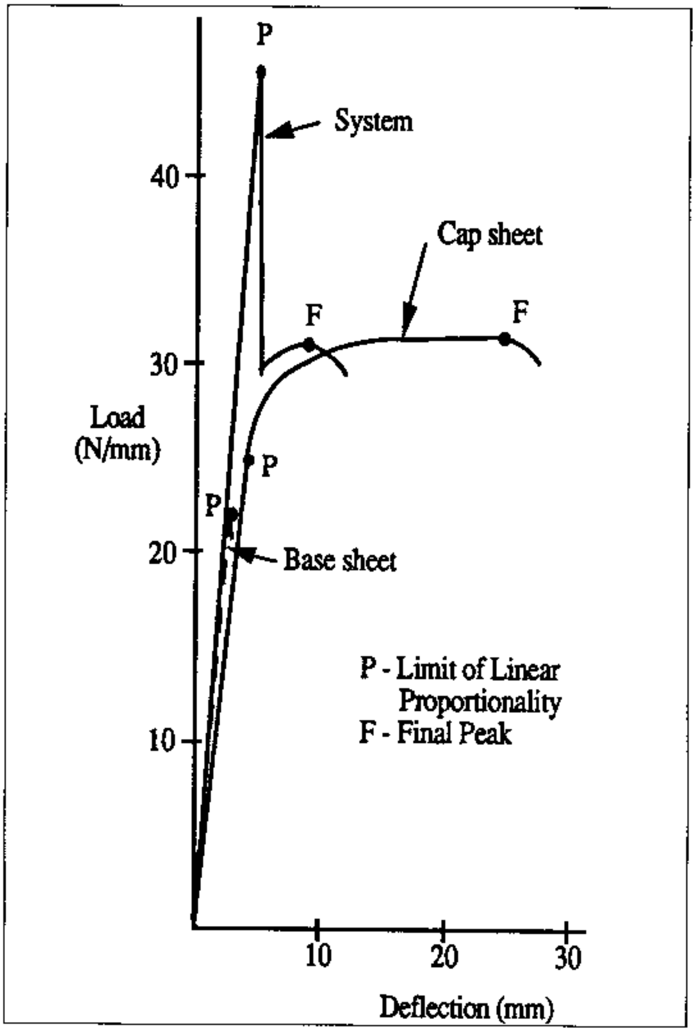

Figure 3B *Load-deformation, product B, tension test.*

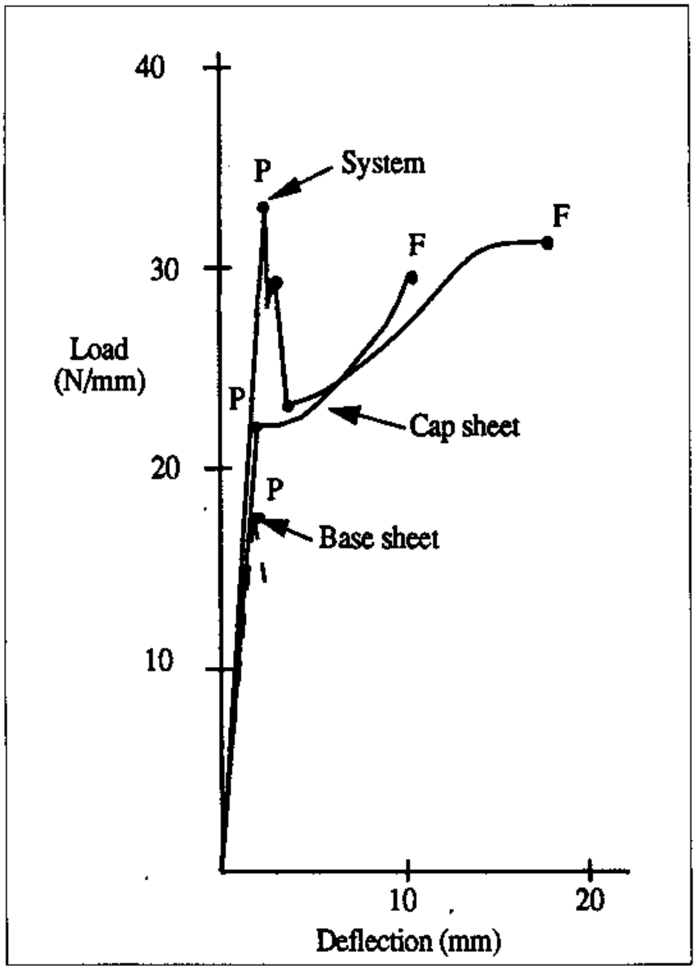

Figure 4A *Load-deformation, product A, joint-bridge test.*

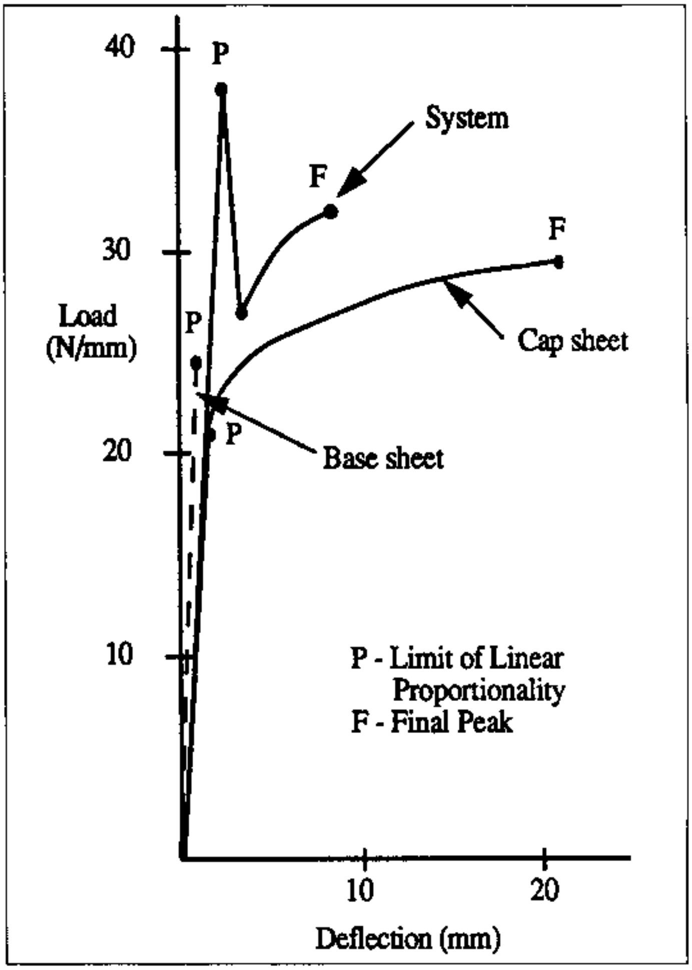

Figure 4B *Load-deformation, product B, joint-bridge.*

Conditioning	Test	Wp (N/mm)	dp (mm)	K1 (N/mm/mm)	Wf (N/mm)	df (mm)	Wp/Wf
21°C	Base sheet	11.3	3.6	3.3	N/A	N/A	N/A
	Cap sheet	10.5	4.2	2.5	24.4	40.1	0.43
	System	17.3	5.2	3.5	29.1	37.9	0.59
−5°C	Base sheet	21.0	3.5	5.9	N/A	N/A	N/A
	Cap sheet	13.8	5.2	2.8	27.4	33.2	0.50
	System	40.5	4.1	9.9	30.6	27.2	1.32
−18°C	Base sheet	24.7	3.9	6.4	N/A	N/A	N/A
	Cap sheet	21.4	4.9	4.4	30.3	31.7	0.71
	System	52.3	4.9	10.7	28.5	24.9	1.84

Table 1A *Behavioral characteristics—Tension test, product A, machine direction.*

Conditioning	Test	Wp (N/mm)	dp (mm)	K1 (N/mm/mm)	Wf (N/mm)	df (mm)	Wp/Wf
21°C	Base Sheet	15.0	3.3	4.5	N/A	N/A	N/A
	Cap sheet	10.7	3.1	3.6	28.8	68.3	0.37
	System	24.3	3.3	7.4	30.0	46.8	0.81
−5°C	Base sheet	27.4	3.9	7.0	N/A	N/A	N/A
	Cap sheet	22.1	2.3	9.8	31.4	25.0	0.70
	System	45.4	4.7	9.8	31.3	8.4	1.45
−18°C	Base sheet	31.0	4.1	7.5	N/A	N/A	N/A
	Cap sheet	14.6	0.9	15.7	31.3	20.9	0.47
	System	54.9	4.9	11.3	26.5	6.6	2.07

Table 1B *Behavioral characteristics—Tension test, product B, machine direction.*

Conditioning	Test	Wp (N/mm)	dp (mm)	K1 (N/mm/mm)	Wf (N/mm)	df (mm)	Wp/Wf
21°C	Base sheet	13.4	2.2	6.1	N/A	N/A	N/A
	Cap sheet	15.5	3.5	4.4	24.3	27.3	0.64
	System	19.0	2.9	6.7	21.8	39.9	0.87
−5°C	Base sheet	17.4	1.4	13.2	N/A	N/A	N/A
	Cap sheet	22.8	1.9	12.0	29.7	10.7	0.77
	System	33.4	2.2	15.7	31.5	17.9	1.06
−18°C	Base sheet	22.3	1.1	20.6	N/A	N/A	N/A
	Cap sheet	30.2	1.2	24.7	32.8	4.6	0.92
	System	37.7	1.5	23.8	32.3	5.9	1.17

Table 2A *Behavioral characteristics—Joint-bridge test, product A, machine direction.*

Conditioning	Test	Wp (N/mm)	dp (mm)	K1 (N/mm/mm)	Wf (N/mm)	df (mm)	Wp/Wf
21°C	Base sheet	17.1	2.0	8.9	N/A	N/A	N/A
	Cap sheet	9.5	1.3	7.5	—	—	—
	System	23.7	2.3	10.7	27.7	42.8	0.86
−5°C	Base sheet	25.15	1.1	23.8	N/A	N/A	N/A
	Cap sheet	21.0	1.2	17.5	29.9	20.9	0.70
	System	38.3	2.7	14.4	32.2	8.5	1.19
−18°C	Base sheet	28.4	0.9	32.2	N/A	N/A	N/A
	Cap sheet	22.0	1.0	21.9	29.4	6.1	0.75
	System	41.8	1.1	39.7	29.2	4.7	1.43

Table 2B *Behavioral characteristics—Joint-bridge test, product B, machine direction.*

Conditioning	Test	Wp (%)	dp (%)	K1 (%)	Wf (%)	df (%)
21°C	Base sheet	11.80	5.89	3.01	N/A	N/A
	Cap sheet	9.30	12.49	7.57	5.07	4.43
	System	3.30	22.67	21.12	2.58	2.45
−5°C	Base sheet	4.66	5.23	2.54	N/A	N/A
	Cap sheet	15.47	19.68	25.82	8.65	6.11
	System	5.92	9.45	10.98	5.71	11.77
−18°C	Base sheet	9.96	4.29	7.70	N/A	N/A
	Cap sheet	12.38	10.88	11.10	6.11	5.89
	System	5.26	10.20	8.84	7.65	15.36

Table 3A *Coefficients of variation—Tension test, product A.*

Conditioning	Test	Wp (%)	dp (%)	K1 (%)	Wf (%)	df (%)
21° C	Base sheet	11.8	5.89	3.10	N/A	N/A
	Cap sheet	7.02	20.66	18.10	4.98	8.12
	System	4.10	11.13	9.93	6.97	12.55
−5°C	Base sheet	4.66	5.23	2.54	N/A	N/A
	Cap sheet	6.00	19.32	19.94	5.45	16.20
	System	4.57	9.98	8.19	8.57	10.18
−18°C	Base sheet	9.96	4.29	7.70	N/A	N/A
	Cap sheet	16.99	35.5	23.39	4.15	18.46
	System	7.15	8.34	2.15	5.50	4.35

Table 3B *Coefficients of variation—Tension test, product B.*

Conditioning	Test	Wp (%)	dp (%)	K1 (%)	Wf (%)	df (%)
21°C	Base sheet	5.00	14.00	12.00	N/A	N/A
	Cap sheet	9.77	17.64	9.21	5.77	34.27
	System	4.28	7.70	11.34	5.18	18.90
−5°C	Base sheet	3.00	4.00	5.00	N/A	N/A
	Cap sheet	6.35	11.78	8.46	7.47	28.71
	System	7.74	14.62	12.13	6.63	5.34
−18°C	Base sheet	7.00	9.00	6.00	N/A	N/A
	Cap sheet	5.11	14.16	13.74	3.34	20.08
	System	5.17	10.23	10.31	5.76	7.75

Table 4A *Coefficients of variation—Joint-bridge test, product A.*

Conditioning	Test	Wp (%)	dp (%)	K1 (%)	Wf (%)	df (%)
21°C	Base sheet	5.00	6.00	3.00	N/A	N/A
	Cap sheet	10.07	29.83	24.91	5.94	—
	System	6.62	9.90	12.01	5.82	11.83
−5°C	Base sheet	8.48	12.28	4.74	N/A	N/A
	Cap sheet	5.41	12.77	10.38	5.89	21.02
	System	9.41	11.32	6.17	8.56	5.66
−18°C	Base sheet	10.00	9.00	12.00	N/A	N/A
	Cap sheet	9.48	19.96	18.1	9.71	16.15
	System	8.78	4.86	9.96	4.08	3.20

Table 4B *Coefficients of variation—Joint-bridge test, product B.*