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Baskaran, B. A.; Wu, J.; Tanaka, H.

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A Test Protocol to Quantify the Peel Resistance of Adhesive Applied Low Slope Roofing Specimens Subjected to Shear Loading

Dr. A. Baskaran*, P.Eng

National Research Council, 1200 Montreal Road, Ottawa, Canada, K1A 0R6

J. Wu, MASc, and Dr. H. Tanaka P.Eng

Department of Civil Engineering, University of Ottawa, Ottawa, Canada, K1N 6N5

Abstract

Adhesive Applied Roofing Systems (AARS), a new generation of Built-Up Roofs, are regaining popular in North American low slope application. AARS use no fasteners and all components (e.g. steel deck, vapour barrier (if any), insulation board, cover board, base sheet and cap sheet) are integrated by application of cold adhesives. As there are no metal fasteners, AARS can offer an advantage of reduction in moisture migration and thermal bridges of the roof assemblies. Moisture in the roof envelope can lead generally to material deterioration, structural integrity problems, and the growth of mould. Even though, the AARS have been in use, existing uplift standards do not certify them for wind-uplift performances. A new project, "*Development of Wind Uplift Standard for Adhesive Applied Low Slope Roofing System*", has been initiated in collaboration with industries, university and government departments. The project has three major tasks: experimental investigation, formulation of a numerical model and development of wind design guide and standards. This paper documents a segment of the findings from this project. Under the Task 1, investigations were completed by constructing over 600 specimens and examining the peel resistance of bonded roofing components through mechanical separation of bonded layers by applying shear forces. These specimens were constructed using cold adhesives. Based on this scrutiny, three key parameters, namely: peel position, peel angle, and specimen size were optimized. This paper presents the findings and development of a standardized test method to determine the peel resistance of AARS specimens.

Keywords: AARS, Cold Adhesive, Shear Force, Peeling Failure, Roofing, Failure Plane

Introduction

The roofing system is an integral part of a building envelope. It protects the building occupants from harsh outdoor environmental conditions such as wind, precipitation, ultraviolet light, and temperature. It also maintains the structural integrity of the building by preventing diffusions of water vapour into the building envelope, and it resists dead and live loads. The most traditional commercial roofing system is the built-up roof (BUR). This system consists of successive layers of roofing felts that have been laminated together with bitumen or asphalt. BUR roofs are installed using a hot-mopped technique which involves spreading hot asphalt over the roof as the primary waterproofing component, i.e., the membrane is constructed in-situ. Unfortunately, fumes emitted during this process can cause health concerns for workers and anyone else who may come into contact with the fumes. It is also labour intensive processes which can ultimately increases the cost of roof installation (Baskaran and Smith, 2005) compared to mechanically attached roofing systems.

Adhesive Applied Roofing Systems (AARS), a new generation of Built-Up Roofs, are regaining popular in North American low slope application. AARS use either cold (non-foaming) adhesives or foaming (urethane) adhesives to secure all roofing components. This paper documents only a segment of findings from a major collaborative research and development project with Natural Sciences and Engineering Council (NSERC) that is aimed to develop standards for AARS. Project partners are Department of Civil Engineering University of Ottawa, National Research Council – Institute for Research in Construction (NRC-IRC), Roofing Industries (Bakor Inc., IKO Industries Ltd, Soprema Inc., and Tremco Inc.) and

Roofing Contractor Association of British Columbia (RCABC). AARS project has the following tasks:

- Task 1: Pullout Testing
- Task 2: Peel Testing
- Task 3: Wind Uplift Testing
- Task 4: Numerical Modeling
- Task 5: Development of Design Guidelines

Under the Task 1, 2, and 3, variety of experimental configurations were investigated and data were archived by Current et al. 2007; Murty, et al. 2008a, b; Wu, et al 2008). Based on this investigation, standardized test methods for peel resistance, pullout resistance and wind uplift resistance were developed. These test procedures were respectively reported in Wu 2008, Current (2009) and Murty, B (2009). Peeling failure is the single most common premature failure of AARS and it leads to the loss of the watertight integrity of the AARS membrane (RICOWI 2006, 2007, 2010). Peel failure occurs due to shear force induced on the membrane at an angle as shown in Figure 1.

Little is known about the resistance of AARS against shear forces that are derived from the wind uplift and there are currently no standards that can be used to evaluate the peel resistance of AARS. Existing standards must be reviewed to find similarities that can be applied to the development of a peel test for AARS. The idea is that the similarities in variables and conditions found can be transferred to the new standard being developed. For the present study, standards from the following organizations were reviewed:

- American Society for Testing Materials (e.g. ASTM D 1876-01, 2001)
- International Standards Organization (e.g. ISO 8510-2:2006)

- European Standards (e.g. EN 12316-2:2000)

Findings of this review were reported elsewhere (Wu 2008). In summary, the review identified that three key parameters need further scrutinize, namely: peel position, peel angle, and specimen size. To find optimize conditions for these three parameters, the present experimental approach examines the peel resistance of bonded roofing components through mechanical separation of bonded layers by applying shear forces. This paper presents the findings and development of a standardized test method to determine the peel resistance of AARS systems.

Components Used for Specimen Preparation

Typical roofing components include the deck, vapour barrier (in some assemblies), insulation, cover board, and of the roof membrane. This study uses the insulation and the cover board components exclusively because they are the more vulnerable to peeling under wind-induced shear forces. Four different sample sets were used throughout these experiments, each provided by four industry sponsors of the study. For the purposes of this study, “specimen” refers to the roofing sample that is being tested. Each specimen is made up of insulation and a cover board or insulation and a membrane (Figure 2)

Insulation

An appropriate size of thermal insulation consisting of a central polyisocyanurate foam layer covered by facing materials was cut from 48” x 48” x 2” (1219 mm x 1219 mm x 51 mm) of commercial thermal insulation products. Two insulation types with facers, paper facer (PF) and acrylic inorganic coated facer (IF), were used. The PF is an organic paper facer with trace amounts of fibreglass fibres and the IF is a fibreglass mat facer surfaced with an inorganic coating.

Cover board

A cover board is placed on top of the insulation to protect the insulation from construction and maintenance traffic, mechanical impact, and overheating during torching. It should be chemically compatible with the components that are above and below. Two such boards were investigated by the present study.

Asphalt core cover board (ACB): A flat, rigid, 1/8" (3mm) thick sheet that has a high-melting-point asphalt core and mineral fillers of non-woven glass fibre mats.

Fibre-board cover board (FB): A 1/2" (12.5 mm) thick sheet made of wood fibres and recycled paper. It is highly moisture resistant and promotes membrane adhesion. However, under humid conditions it has the propensity to absorb water which may quickly degrade it into an unstable mixture of cellulose fibres.

Cold Adhesives

Cold adhesives should be formulated such that they are compatible with all materials, and have the desired rate of cure. They can be applied at ambient temperatures are generally above 4°C (40°F) without need for primary heating. In this study, non-foaming adhesives are used by applying full adhesion between the components of all specimens. Foaming (urethane) adhesives are also available in the market and they can be applied in ribbon format.

Specimen Preparation

Figure 2 also shows the specimen preparation for peel test evaluation. There were two types of specimens prepared in this series of experiments: edge position (E-P) specimens and corner position (C-P) specimens. E-P specimens include an overhang along one edge devoid of adhesives. In C-P specimens, there is a single

corner between the insulation and cover board unbound by adhesive. E-P and C-P specimen preparation are explained as follows:

E-P specimen preparation: In the preparation of an E-P specimen, the cover boards are cut into pieces that are 0.5" (13 mm) longer than the insulation in order to have an overhang devoid of adhesives. This overlay is used for gripping during the peel testing. For example, a 6" x 6" (152 mm x 152 mm) specimen would have a cover board size of 6" x 6.5" (152 mm x 165 mm) and an insulation size of 6" x 6" (152 mm x 152 mm). Once the pieces of cover board and insulation are cut, they are bonded together by applying cold adhesives in a full coverage format. Full adhesion is when a full layer of adhesive of uniform thickness is used between each layer of the construction materials. Figure 2 depicts the layout of a typical E-P specimen.

C-P specimen preparation: In the preparation of a C-P specimen, the cover board and insulation are cut to the same size. A line is drawn across one corner of the insulation to form an isosceles triangle. Cold adhesive is then applied uniformly over the whole surface excluding the triangle corner. The cover board is bonded to the insulation, leaving the adhesive free corner unbound for the insertion of the grip during peel testing.

Experimental Apparatus

The components of the experimental apparatus used in this study are as follows (Figure 3):

- Instron 5566
- Specimen mount (fixer)
- Grippers
- Angle Controller

Instron 5566

Used for performing various mechanical tests such as tensile, compressive, shear, torsion, and bending tests on a wide variety of materials. The determination of the mechanical characteristics of a specimen is used for purposes such as material characterization, selection, quality assurance, and failure analysis. The frame is controlled by a computer through the use of a Bluehill software pack which allows for defining testing input parameters and publishing of customizable reports which can illustrate an overview of the experimental results and generate graphs.

Specimen Mount

A mount having size 16" x 14" x 4" (406 mm x 356 mm x 104 mm) (l x w x d) holds the specimen stable during peel testing. It is made with either aluminum or steel plates and is mounted on a supporting table. Steel plates on three sides hold the specimen in position. For specimens less than the 4" (104 mm) in thickness, plywood fillets are inserted beneath the specimen to provide the required height. A row of small screws secures the specimen in place.

Grips

The grips connect the specimen to the Instron machine. There are two types of grips, the E-P grip and the C-P grip.

E-P grip: This grip is used for edge position specimens. There are two pieces of parallel steel plates that clamp to firmly grip the 0.5" (18 mm) cover board overhang. In order to accommodate for the different sizes of specimens, the length of the grip plates range from 8" (203 mm) to 12" (305 mm). The grip is then connected to the Instron machine by threading a 1/8" (3 mm) or 1/16" (1.5

mm) diameter steel wire through the centerline of the specimen assembly. The diameter size used depends on the amount of shear force to be applied.

C-P grip: This grip is used for corner position specimens. There is a pair of steel claws that clamp onto the non-adhered corner of the specimen. The bottom claw is sharpened so that it can be easily inserted into the unbound corner space between the cover board and the insulation.

The grip is tightened onto the cover board by screws. When the thickness of the cover board is more than ½" (18 mm) thick, springs are installed into the grip to balance out the thickness and achieve maximum grip force. When the thickness is thinner than ½" (18 mm), no springs are required.

Angle Controller

This device controls the initial angle of the shearing force. The Instron machine includes two self-aligning jaws. The bottom jaw is removed and replaced by a shaft that holds the angle controller. It has a pulley to keep the steel wire moving freely during the peel test with minimum friction. Part of the angle controller is a holder. It consists of an inner solid steel bar that is 8" (203 mm) long and 3/8" (10 mm) in diameter. The outer steel tube is 8" (203 mm) long and 7/8" (22 mm) in diameter. The length of the steel holder can be adjusted by sliding the inner steel bar along the outer tube. It is scaled by ¼" (6 mm) increments for fine-tuning the peel angle. The initial angle for shear force application is determined by the roller height and is adjusted by sliding the inner steel bar into the holder. During the experiment, the steel wire of the grip goes through the pulley of the angle controller and connects to the Instron machine's upper jaw.

Experimental Procedure

Specimen Mounting

E-Position: As shown in the Figure 4, the specimen mounting for peel resistance evaluation. The centerline of the mount and the supporting table are aligned with the center point of the shaft. Wooden fillets are then placed under the specimen to align the top of the specimen with the grip. The specimen is finally fixed at the central position of the mount.

C-Position: The mount is rotated 45° so that one corner is aligned with the shaft center point. The specimen is then fixed on that corner of the mount so that the unbound corner is aligned with the centerline of the shaft. The unbound corner of the cover board is clamped by the grip and connected to the upper jaw of the Instron machine with a steel wire. This allows for the specimen to be stretched at a constant rate of 1.0 in/min (25.4 mm/min) at a pre-defined angle.

Angle Control

To set up the angle controller, the horizontal distance between the midpoint of the grip and the inside edge of the free roller is measured using a ruler and a carpenter's level. The height of the roller is calculated based on the formula $\tan(\theta) = H/L$, where θ is the pre-defined peel test angle. The height of the roller (H) is adjusted by sliding the inside steel bar of the angle controller. The actual peel angle is confirmed using the angle locator.

Peel test protocol

For this study the extension rate was defined as 1 in/min (25.4 mm/min). The software was set to keep track of key data such as maximum and minimum readings of peak load, the mean value of the whole sample set, and standard deviation. After the software is set up, the specimen is fixed in the mount and

the test angle is set up as described above. The Instron machine is calibrated by balancing the load channel after the specimen is properly set up in the system. Varying peel forces are generated by the Instron machine at the constant peel rate until specimen failure occurs at which point the failure mode is evaluated and recorded manually as a photograph.

Results and Discussion

Only selected data is presented in this paper, whereas data from other samples are reported elsewhere (Current 2007, Murty et al 2008 a, b). The following terminology was used in the data interpretation of the peel test results of this study.

Peel Resistance: The shearing force required to completely separate two bonded components. The principle behind the test method was to pull one adhered component away from another adhered component until it breaks off or separates into two discrete components.

Peak Resistance: The maximum force the specimen is able to resist before failure occurs on the specimen. Each component of AARS assembly should have a peak resistance higher than the wind-induced inflection and subsequent shear force in order to have satisfactory performance.

Peel Resistance Ratio: Peak resistance of a specimen or average peak resistance of a sample divided by the peak resistance of a control specimen or average peak resistance of a control sample.

Peel Position Specification

Figure 5 outlines the experimental conditions used to determine an appropriate peel position in evaluating the resistance of AARS specimens against shear loading. The

peel position is the location at which the peeling force is applied. Since the peel stresses were applied near a horizontal angle to the specimen, they are intended to simulate horizontal shear wind uplift forces. Four sets of samples were prepared. All specimens were supplied and constructed by industrial sponsor (please refer to the acknowledgements section). Each sample was made up of six sets (2 insulation types, 2 cover board types, and 2 peel positions) that included a minimum of 7 specimens each. Note that the specimens are replications of the same configuration and they are 6" x 6" (152 mm x 152 mm) in size. All tests were run at a 15° peel angle; however, the effect of the peel angle will be discussed under Figure 10. Two insulation facers, inorganic facer (IF) and paper facer (PF) and two cover boards, asphalt core board (ACB) and fiberboard (FB), were used in various combinations: PF/ACB, PF/FB, AF/ACB, and AF/FB. Two peel positions were being tested: edge position (E-P) and corner position (C-P). In E-P testing, specimens are peeled along an edge that is devoid of adhesive (Figure 4). Likewise, in C-P testing, specimens are peeled at a corner that is devoid of adhesive (Figure 4). All cover board and insulation facer combinations were tested in the E-P condition. In other words, PF/ACB, PF/FB, AF/ACB, and AF/FB combinations were used. However, specimens being tested in the C-P condition used only the ACB cover board with PF or AF insulation facer. In other words, only the PF/ACB and AF/ACB combinations were used based on the data from the E-P investigation. This test matrix results in a total of 168 (sample x set x specimen = 4 x 6 x 7) peel test data for the determination of an appropriate peel position in evaluating the resistance of AARS specimens subjected to peeling forces.

Primary observations can be made from the raw data in a time history plot of two identical specimens peeled at two different positions (Figure 6). The x-axis depicts

the time in seconds and the y-axis represents the peel resistance in pound-force (lbf). Note that the values presented are not averages but raw data of two specimens obtained directly from experimentation. The peak peel resistance in the E-P condition was 235 lbf (1045 N) at around 80 seconds whereas the peak peel resistance in the C-P condition was 200 lbf (890 N) at around 65 seconds. Initially, the peel force of the C-P specimen increases faster than that of the E-P specimen. However, failure occurs sooner in the C-P specimen at an overall peel resistance lower than that of the E-P specimen.

The raw data was analyzed further to find the average peel resistances of multiple specimens in order to see if the previous findings are reproducible across specimens. Figure 7 illustrates the average peel resistance of PF/ACB specimen assemblies of the E-P and C-P conditions. The x-axis shows the sample number and the y-axis shows the peel resistance (lbf). Note that the data points presented are averages from the seven specimens. For three out of four samples, the peel resistance of E-P is higher than that of C-P. Of these samples, the peak peel resistance falls between about 200-230 lbf (890-1023 N) for E-P and 140-170 lbf (623-756 N) for C-P. These data form similar trend in peak peel resistance as the raw data previously presented for the two specimens in that E-P reaches a higher peak peel resistance than C-P. In the case of sample 2, the peel resistance was found higher with C-P than of E-P. While the C-P peel resistance at 147 lbf (654 N) fell in the range for all C-P samples, the E-P peel resistance was much lower than the normal E-P range at only 102 lbf (454N). The reason for this different mode of failure is not immediately clear, though the way the adhesive was applied to the test specimens might have been one of the factors.

In order to verify this finding, Figure 8 depicts the normalized peel resistance at the two different peel positions of another component combination, namely, data from the PF/ACB specimen samples. The x-axis shows the sample number and the y-axis shows the peel resistance ratios (E-P: C-P). In order to calculate the resistance ratio the E-P peel resistance was divided by the C-P peel resistance. For example, in sample 1, 232 lbf (1032 N) is divided by 162 lbf (721N) from Figure 7 which yields a peel resistance ratio of 1.4. This ratio indicates that the E-P condition is able to yield 140% of the peel resistance that the C-P condition produces. The E-P: C-P ratios range from 1.3 to 1.4 except for the 0.7 of sample 2. All samples show lower peel resistance at C-P than E-P with exceptions from sample 2 for reasons explained above. Normalized peel resistance at two different peel positions for PF/FB was also analyzed. The E-P: C-P ratios range from 1.2 to 1.8 except for the 0.6 of sample 2. The ratio range is larger in the AF/ACB case than the PF/ACB ratio was. However, the same general trend that E-P exhibits higher peel resistance than C-P is observed. Therefore, the PF/ACB specimens indicate that the E-P condition is the most ideal peel position for AARS specimens. Thus, the peel resistance is greater for the E-P specimens than the C-P specimens making E-P the testing condition of choice.

A possible explanation for this behavior is that the peeling stress intensity is larger for C-P than E-P at the beginning stages of the test when the same peel force is being applied. This can be explained by looking at a unit peel force analysis. If “a” is the specimen's width and “F” is the peel force acting on the specimen, then F/a is the peeling stress for that specimen. In the case of E-P specimens, the length subjected to the peeling stresses is always uniform. In other words, “a” is constant. In the case of C-P specimens, the length subjected to the peeling force is always changing.

The value of “a” starts out smaller at the corner, gradually increases as the diagonal length of the specimen is reached in the middle and then decreases again towards the back corner. The peel stress (F/a) of the E-P specimen is smaller than that of the C-P specimen at the early stage of the test because, at that point, the “a” value for the C-P specimen is smaller than the “a” value for the E-P specimen. This leads to the thought that the specimens peeled at C-P would fail more easily than those peeled at E-P because C-P initially generates higher peeling stress than E-P does. Peel stress for C-P is larger than that of E-P at the start of the test period which results in faster failure and lower peel resistance of C-P specimens than E-P specimens. Therefore, the E-P peel position proves to be the more appropriate peel position in evaluating the resistance of AARS specimens to peeling forces.

Peel Angle Specification

Outlined in Figure 9 is the breakdown of the experimental conditions used to determine an appropriate peel angle in evaluating the resistance of AARS specimens against shear loading. The peel angle is the angle at which the force is being applied. Samples 2 and 4 were used for this set of experiments. All samples were supported and constructed by the previously mentioned industrial clients. Each sample contained 6 sets of 7 specimens each. Note that the specimens are replications of the same configuration and they are 6” x 6” (152 mm x 152 mm) in size. All specimens were made of an asphalt core board with either AF or PF for insulation. To investigate the effects of different peel angles on peel resistance, 6 different peel angles were examined: 7.5°, 15°, 22.5°, 30°, 37.5°, and 45°. This test matrix results in a total of 84 (sample x set x specimen = 2 x 6 x 7) peel test data for

the determination of an appropriate peel angle in evaluating the resistance of AARS specimens subjected to shear forces.

The peel resistance of PF/ACB specimens at six different peel angles is presented in Figure 10. The x-axis shows the peel angle (θ) where the y-axis is showing the corresponding peel resistance. Note that each data point is an average of seven specimens from either sample 2 or 4. Both curves for each sample are displaying similar trends. In examining, each curve can be divided into three distinct segments:

- Segment 1 = 7.5° - 15°
- Segment 2 = 15° - 30°
- Segment 3 = 30° - 45°

Peel resistance is decreasing as the peel angle is increasing. This is mainly because the vertical tensile forces are introduced on the specimen and this vertical component increases as the peel angle increases. The most rapid slope change corresponds to segment 2 of each curve. This indicates a rapid change in peeling force related to the angles that lie in this range and is called the effective angle range. Peeling resistance is most sensitive to changes in peel angle over this effective angle range. Angles less than 15° or more than 30° would have smaller effects on the peel resistance. The range of angles between 15° and 30° is an important zone for the development of standardized peel test methods for the present study and for the future research in applying this during the development of a wind design guides of AARS. It is important, therefore, to develop a generalized curve that could be used to predict peel resistance performance under different peel angles.

To achieve this, the peel resistance ratios were used as a quantitative indicator to compare the test data. Figure 11 presents normalized peel resistance of PF/ACB specimens. The x-axis shows the peel angle (θ) and the y-axis represents the corresponding peel resistance ratio of samples 2 and 4. The peel resistance measured at a particular angle was selected as a reference to which peel resistance values from other configurations could be compared. The peel angle of 15° was selected as a reference point in this study. The peel resistance ratio for other angles could then be calculated by dividing the peel resistance at that angle by the peel resistance at 15° . For example, the peel resistance at the peel angle of 22.5° for sample 2 is 110 lbf (490 N) and for the peel angle 15° of sample 2, it is 165 lbf (734 N). Taking 110 divided by 165 gives a ratio of 0.67 which is the black diamond data point that is plotted at 22.5° in Figure 13. The ratios obtained from samples 2 and 4 were averaged to produce the representative curve for PF/ACB as shown in the Figure 11.

A generalized peel angle curve for peel resistance of AARS specimens is illustrated in Figure 12. It was made to develop a generalized understanding regarding the effect of peel angle on AARS peel resistance performance. The x-axis shows the peel angle (θ) and the y-axis represents the peel resistance ratio. The data points for the generalized curve were obtained by averaging the data points of the PF/ACB and AF/ACB curves. For example, at angle 7.5° the peel resistance ratio is 1.95 for the AF/ACB curve and 1.1 for the PF/ACB curve. The peel resistance ratio for the generalized curve is $[1.95 + 1.1]/2 = 1.51$. The PF/ACB curve was transferred from Figure 12 and the AF/ACB curve was attained in the same way as described earlier for the attainment of the PF/ACB curve. All curves intersect at the reference angle of 15° . There is a significant different between the AF and PF curves for angles less

than the reference angle, however, peel resistance does not differ much at angles greater than the reference angle. The generalized curve could be applied to calculate the peel resistance at various angles after obtaining the peel resistance at 15°. Based on the analysis above, the present study proposes 15° as the appropriate angle for the standard test method.

Specimen Size Specification

Figure 13 outlines the experimental conditions used to determine an appropriate specimen size in evaluating the resistance of AARS specimens against shear loading. Samples 2 and 4 were used for this set of experiments. All samples were supported and constructed by the previously mentioned industrial clients. Each sample contained 4 sets of 7 specimens each. Note that all specimens were of the PF/ACB configuration. The tests were run at a 15° test angle at the edge position. Four different sized specimens were used: 4" x 4" (102 mm x 102 mm), 6" x 6" (152 mm x 152 mm), 8" x 8" (203 mm x 203 mm), 10" x 10" (254 mm x 254 mm). Comparisons of these sizes are also shown in Figure 13. This matrix results in 14 specimens per size variable for the determination of the most ideal size for testing AARS peel resistance.

As illustrated in Figure 14 is a generalized sample size curve for the peel resistance of AARS specimens. Data for Figure 14 was analyzed similar to that of Figure 13. The x-axis shows the sample length in inches and the y-axis shows the peel resistance ratio. Note that the data points of the generalized curve are an average of the data points from the curves from samples 2 and 4. Using 6" x 6" (152mm x 152 mm) as a reference size, the peel resistance ratios of the specimen sizes were calculated in the same way as the peel resistance ratios for the peel angles as

described in the peel angle specification section. The slopes of the curves are steeper between 4" x 4" (102 mm x 102 mm) and 6" x 6" (152 mm x 152 mm) and less steep for the sample sizes larger than 6" x 6" (152 mm x 152 mm). This steeper slope segment is referred to as the effective size range because experimental observations suggest that the sample sizes within that segment have more influence over the peel resistance. Moreover, the importance of the generalized curve is that it can be used to estimate the peel resistance of a sample if there is a variation in the specimen size. For the present study to develop a standardized test method, 6" x 6" (152 mm x 152 mm) specimen size has shown to be the most ideal to use during peel testing because it lies in the effective reference size during the development of a generalized curve.

Identification of Weakest Link Investigation

The failure mode indicates the weakest link within the specimen. The weakest link of roofing systems varies depending on the components used. For the present study, the specimen had three components (cover board, insulation and adhesive) and failure can occur in any one of them or of its combination. In literature, terminology can vary in defining a failure. To maintain consistency, the present classification for failure modes are presented in the appendix.1. To offer recommendation for the participating industrial partners, failures were securitized as show in the flow chart. For example, rather than classifying it as an insulation failure, it has been further divided into three types, namely, facer delamination or facer tearing or facer rupture. Appendix also provides illustrations and photographs to differentiate the failure modes. This close examination can facilitate to improve product development.

Similar approach was followed for the cover board and adhesives and included in the appendix.

To investigate the relationship between failure mode; i.e., the weakest link, and the components, the raw experimental data were analyzed as follows: After a specimen was tested, the failure mode of the specimen was determined based on the percentage of the failure area to the total failure surface. To illustrate this process, Table 1 summarizes the various failure modes of tested samples comprised of paper facer insulation and asphalt core cover board, labelled as PF/ACB. Parallel samples were provided by four different industry partners, each of which is identified here by a 'Source' number such as I-1, II-1 etc. The resulting failure modes are summarized. Some specimens have only one failure mode, whereas others have combined failure modes. Therefore, the weakest link for each sample can be judged by comparing the failure modes.

At the end of the experiment, the failure occurrence value (FOV) for each sample was calculated. FOV is the number of failures that occurred in various modes in a sample set. In principle, the FOV of each sample set should be equal to the total number of specimens tested. This is further illustrated by taking the II-1 sample set as an example (Table 1). This set has 5 specimens. Hence, the total FOV is 5. Out of these 5 failures, 1 specimen failed in facer tearing (Facer/T), 3 specimens failed due to facer rupture (Facer/R) and 1 specimen had a mixed failure mode of adhesive failure (Adh) and facer rupture (Facer/R). Therefore, the FOV for this case is counted as:

- Facer tearing = 1
- Adhesive failure = 0.5

- Facer rupture = 3.5

Table 2 summarizes the FOV distribution of all failure modes of 24 sample sets from 4 different industry sources, designated as I, II, III, and IV. In total, 120 FOV (24 sample sets, 5 FOV per sample set) were considered for analysis out of 168 specimens tested. As seen in Table 2, the occurrence of failure modes is arranged according to the types of samples and sources.

The percentage frequency of FOV under each failure mode represents the probability of that particular failure mode being the weakest link in the samples examined. For example, of all samples examined, the likelihood of having an insulation tearing failure is less than 1%, or only 1 case observed out of 120. The occurrence of a cover board brittle failure is 37%. Of course, one can also calculate the likelihood of each failure mode occurring in samples from different sources or different configurations. This is explained hereafter.

Investigation of Insulation Failure Mode

In order to determine which insulation configuration (AF or PF) is more prone to failure under wind pressure, the failure modes of AF and PF were investigated. Table 3 summarizes the percentage of FOV for different insulation failure modes under different roofing configurations. Higher frequency is an indication of the weaker link of that material. From this table it is clear that the performance of each configuration varies. When PF insulation and AF insulation are considered, regardless of the cover board combination, AF failed more frequently than PF. The percentage of FOV for AF is $25.5/120=21\%$, whereas it is $19.5/120=16\%$ for PF. This result suggests that PF performs significantly better than AF under wind peeling

pressures. The observation is supported by previous peel resistance analyses, demonstrating that AF has lower peel resistance than PF. It may be argued that the PF insulations can be susceptible to moisture and its resistance can weaken due to moisture absorption.

Insulation failure can be classified into three modes: facer delamination, facer tearing, and facer rupture. This study also analyzes which of these failure modes is more likely to occur in the insulation component. The facer delamination, with a total of 38 FOV, is the most frequent failure mode when compared to the other two types; 1FOV for the facer tearing and 6 FOV for the facer rupture. The facer delamination failures mostly occurred at the top surface of the insulation foam. This fact was probably due to physical characteristics of the foam; weak tensile strength, low thermal conductivity, low heat capacity, low permeability, or material incompatibility. As indicated before, the PF insulations can be susceptible to moisture and its resistance can weaken due to moisture absorption. However, this interpretation needs further investigation.

In this study, the facer delamination failures which 25.5 FOV predominantly took place in specimens with AF configuration, suggesting that the AF configuration is more prone to the facer delamination failure than the PF configuration. Indeed, all AF specimens' insulation failures were in the facer delamination mode as seen in Table 3, suggesting possibility of the material incompatibility between AF and the insulation foam.

Investigation of Cover Board (CB) Failures

In order to investigate the failure mode within the CB component, the percentage of FOV for the ACB and FB are summarized in Table 4. It shows that FB is more likely to fail than ACB; the frequency of FB failure is 33% (40/120), whereas the frequency of ACB failure is 20% (23.5/120). Table 4 also shows the detailed frequency distribution, calculated as the FOV of all failure modes in the CB component. CB failures were found to be mostly brittle failures (refer appendix 1 for illustrations). Further analysis shows that the brittle failure mode is related to different material configuration. Normally, brittleness and splitting are caused by material stiffness, stress concentration, insulation movement, or thermal contraction. In this study, for the specimens with FB configuration, the brittle failure may be caused by material stiffness, since all FB specimens failed with brittle or splitting mode. However, for specimens with ACB configurations all brittle failures happened with the corner peeling condition.

Adhesive failures represent 10% of all samples. All adhesive failures occurred in combination with secondary failure modes. This may be due to bonding conditions as follows. During the fabrication of specimens, many factors, such as component flatness and adhesive thickness, can affect the specimens' bonding conditions, resulting in poor bonding at the edges. When the specimens are subjected to the peel force, an adhesive failure occurred first, because of a poorly bonded edge, followed by the secondary failure mode as the peeling proceeded.

Failure Mode Investigation Observations

Figure 15 provides a summary that combines these data. Figure indicates that over a half (53%) of the failures occurred in CB component and 37% in the insulation

component, leaving about 10% due to adhesives. These results suggest that the CB component is the weakest link, followed by the insulation, in AARS performance under wind uplift.

Overall, CB seems to have higher probability of failing under the current peel test conditions. But the above analysis also indicates that the industrial sources of assembly were another important factor to be considered. The high frequency of FB failure was the biggest contributing factor as to why CB was the weakest link in the samples examined. It is reasonable to consider that if ACB materials were used for the CB component with different insulation for AARS, most failures would have occurred in the insulation layer. This means that when the wind uplift acts on AARS, the present data indicate the weakest link is in the insulation layer if ACB is used as cover board. However, if FB is used for the cover board, the failure is likely to occur in the cover board layer. The above analyses also indicate that the weakest links where failures are most likely to happen are in the CB and insulation components. Figure 14 shows the detailed frequency distribution, calculated by percentage, of the failure modes of all samples. In summary, the delamination represents the weakest link for insulation component, and brittle failure represents the highest frequency for CB component under wind peel force. This observation has been found from data in failure mode observation as well. The combination of paper facer insulation with ACB forms the best combination, and yields the highest peel resistance. Discussion of these data with the industry sponsors confirmed that similar observations were noticed in the field when the tested components were used.

Conclusions

The present study provided both quantitative (peel resistance) and qualitative (failure mode) measurements of AARS performance under simulated shear loading. The following conclusions were drawn from the present laboratory study:

- Peel resistance ratio analysis:
 - Asphaltic core board performs better than fiber board under all peel tests conditions.
 - Paper faced insulation outperformed acrylic (inorganic) faced insulation when asphaltic core board was used.
 - Based on the materials tests, insulation had no significant influence on the peel resistance if the particular fibre-board was used.
- Failure mode analysis:
 - In general, the insulation layer represents the weakest link when asphaltic core board was used.
 - Based on the materials tested, failure is most likely to take place in the cover board layer if this particular fibre-board was used
- AARS performance under wind peel resistance ranking based on the failure mode and material performance
 - Rank by the frequency of various failure modes: separation > adhesive > delamination > brittle
 - Rank material performance (wind peel resistance from high to low): Asphaltic core board > paper facer insulation > acrylic facer insulation > fiber board.

The developed standard peel test protocol would facilitate more effect building design criteria which in turn would help to minimize the wind-induced peel failures in

AARS. During the review process of this paper, additional research efforts were completed in developing a correlation when AARS specimens were subjected to tensile, shear and wind uplift forces. Based on this investigation, a new hypothesis, “*Higher resistance in both peel and pullout tests will result in the same or higher wind uplift resistance*” was proposed and demonstrated (Li, 2010).

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Figure 1: Peeling Failure of a Roofing Membrane and Induced Forces

Component used for specimen preparations

E- Position Specimen

C- Position Specimen

Figure 2: Specimen Preparation for Peel Resistance Evaluation

Instron Machine

Specimen Mount (Fixer)

Edge Gripper

Angle Controller

Figure 3: Components used for the experimental apparatus

Edge position peel test with 6" x 6" specimen

Corner position peel test with 6" x 6" specimen

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Figure 15: Summary of Failure Mode Distributions

Table 1 Failure mode comparison of PF-ACB-15^o-E-P samples

Sample ID	I-1	II-1	III-1	IV-1
Specimen #	Failure Mode			
#1	Facer/D	Facer/R & Adh	CB/Se	Facer/D
#2	Facer/D	Facer/R	CB/Se	Facer/D & Adh
#3	Facer/D	Facer/R	CB/Se	Facer/D & Adh
#4	Facer/D	Facer/T	CB/Se	Facer/D
#5	Facer/D	Facer/R	CB/Se	Facer/D

Table 2 Failure occurrence value (FOV) distribution

Sample ID	Failure Mode						
	Insulation			Cover Board			Adhesive
	Delamination	Tearing	Rupture	Separation	Splitting	Brittle	Adhesive
I-1 (PF/ACB-E)	5						
I-2 (PF/FB-E)						5	
I-3 (AF/ACB-E)	5						
I-4 (AF/FB-E)					1	4	
I-5 (PF/ACB-C)	3					2	
I-6 (AF/ACB-C)	4					1	
Total/Source I	17	0	0	0	1	12	0
II-1 (PF/ACB-E)		1	3.5				0.5
II-2 (PF/FB-E)					5		
II-3 (AF/ACB-E)	5						
II-4 (AF/FB-E)					5		
II-5 (PF/ACB-C)			2.5				2.5
II-6 (AF/ACB-C)	2.5						2.5
Total/Source II	7.5	1	6	0	10	0	5.5
III-1 (PF/ACB-E)				5			
III-2 (PF/FB-E)					1	4	
III-3 (AF/ACB-E)	3						2
III-4 (AF/FB-E)						5	
III-5 (PF/ACB-C)						5	
III-6 (AF/ACB-C)	1					4	
Total/Source III	4	0	0	5	1	18	2
IV-1 (PF/ACB-E)	4						1
IV-2 (PF/FB-E)					1	4	
IV-3 (AF/ACB-E)	2.5			0.5			2
IV-4 (AF/FB-E)						5	
IV-5 (PF/ACB-C)	0.5					4	0.5
IV-6 (AF/ACB-C)	2.5					2	0.5
Total/Source IV	9.5	0	0	0.5	1	15	4
Total/All Sources	38	1	6	6	13	45	12
Total Percentage	31%	1%	5%	5%	11%	37%	10%

Table 3 Failure occurrence value (FOV) distribution of insulation

Component		Insulation					
Type		Paper Facer (PF)			Acrylic Facer (AF)		
Failure Mode		Delamination	Tearing	Rupture	Delamination	Tearing	Rupture
Failure Occurrence Value (FOV)	Source I	8	0	0	9	0	0
	Source II	0	1	6	7.5	0	0
	Source III	0	0	0	4	0	0
	Source IV	4.5	0	0	5	0	0
	Total/Mode	12.5	1	6	25.5	0	0
	Total/Type	19.5			25.5		
	Total/Component	45					
Percentage of All Specimens		16%			21%		

Table 4 Failure occurrence value (FOV) distribution of cover board

Component		Cover Board					
Type		Asphalt Core Board (ACB)			Fiber Board (FB)		
Failure Mode		Separation	Splitting	Brittle	Separation	Splitting	Brittle
Failure Occurrence Value (FOV)	Source I	0	0	3	0	1	9
	Source II	0	0	0	0	10	0
	Source III	5	0	9	0	1	9
	Source IV	0.5	0	6	0	1	9
	Total/Mode	5.5	0	18	0	13	27
	Total/Type	23.5			40		
	Total/Component	63.5					
Percentage of All Specimens		20%			33%		

Table 5 Weakest link identification at various peel resistance

Sample ID	Component at Which Failure Occurs			
	Insulation		Cover Board	
	PF	AF	ACB	FB
I-1 (PF/ACB-E)	232		232	
I-2 (PF/FB-E)	117			117
I-3 (AF/ACB-E)		226	226	
I-4 (AF/FB-E)		121		121
I-5 (PF/ACB-C)	162		162	
I-6 (AF/ACB-C)		127	127	
Total/Source I	170	158	187	119
II-1 (PF/ACB-E)	102		102	
II-2 (PF/FB-E)	44			44
II-3 (AF/ACB-E)		85	85	
II-4 (AF/FB-E)		46		46
II-5 (PF/ACB-C)	147		147	
II-6 (AF/ACB-C)		147	147	
Total/Source II	98	93	120	45
III-1 (PF/ACB-E)	202		202	
III-2 (PF/FB-E)	80			80
III-3 (AF/ACB-E)		199	199	
III-4 (AF/FB-E)		91		91
III-5 (PF/ACB-C)	142		142	
III-6 (AF/ACB-C)		120	120	
Total/Source III	141	137	166	85
IV-1 (PF/ACB-E)	223		223	
IV-2 (PF/FB-E)	105			105
IV-3 (AF/ACB-E)		140	140	
IV-4 (AF/FB-E)		101		101
IV-5 (PF/ACB-C)	171		171	
IV-6 (AF/ACB-C)		112	112	
Total/Source IV	166	118	161	103
Mean/All Sources	144	126	159	88
SD	33	28	28	32

Figure A.5 One type of combined failure mode photograph

Figure A.4 Typical adhesive failure mode sketch and photograph

(a) Cover board separation

(b) Cover board splitting

(c) Cover board brittle

Figure A.3 Typical cover board failure mode sketch and photograph

(a) Facer Delamination

(b) Facer Tearing

(c) Facer Rapture

Figure A.2 Typical insulation failure mode sketch and photograph

Figure A.1 Failure mode classifications