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Quantification of the Uplift Resistance of Adhesive Applied Low Slope Roof Configurations Subjected to a Tensile Loading Test Protocol

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Abstract

Adhesive Applied Roofing Systems (AARS) is a new generation of Built-Up Roofs, gaining popularity in North American low slope application. AARS uses no fasteners and all components (e.g. steel deck, vapour barrier, insulation board, cover board, and membrane) are integrated by application of adhesives. Even though the AARS have been in use, existing standards address only mechanically attached or fully bonded roof assemblies. To quantify the wind-uplift performance of the AARS, an industries-university-government collaborative research project, “*Development of Wind Uplift Standard for Adhesive Applied Low Slope Roofing System*”, has been initiated. The project has three major tasks: experimental investigation, formulation of a numerical model and development of wind design guide and standards. Task 1 developed test protocols to quantify the uplift and peel resistance of small scale AARS specimens respectively subjected to tensile and shear loading. Using the standardized tensile test parameters, this paper identifies the effect of material combinations and variation in the adhesive applications on the uplift resistance of the AARS subjected to tensile loading. This parametric study not only verified the applicability of the developed tensile test method for variations in the configurations, but it also identified the weakest link in the AARS. Data from this small scale testing can facilitate industries to optimize the material combinations such that it can be correlated with the systems wind uplift resistance.

Keywords: Adhesive, Tensile Force, Uplift Resistance, Roofing, Failure Plane

Introduction

Roofing systems are essential for the protection of building inhabitants from environmental conditions such as temperature fluctuations, moisture, and ultraviolet radiation. They are also designed to hold both dead and live structural loads. Conventionally, Canada uses built-up roof (BUR) for low slope applications. BUR systems use layers of roofing felts integrated with bituminous materials or hot asphalt (Baker, 1964). However, alternatives to the use of BUR systems are being developed. One alternative, and the focus of this study, is the Adhesive Applied Roofing System (AARS). AARS utilizes adhesives in place of hot asphalt for the bonding of roofing components, which eliminates the concern for toxic fumes as well as fires. Since there are no fasteners used in AARS pathways for heat transfer and water vapour infiltration through the holes created by the fasteners are also minimized.

Recent roofing failure investigations after major hurricanes by the Roofing Industry Committee on Weather Issues (RICOWI 2009 and 2010) indicated that shear and tensile forces are the fundamental forces caused by wind which lead to roofing failure. Existing North American wind uplift standards (CSA A123.21, FM 4474 and UL 580) mainly focus on mechanically attached and fully bonded roof assemblies. European standards (ETAG 2006 and NBI160 (1996)) also do not address the wind uplift evaluations of the AARS. In collaboration with industries, a university and government departments, a new project, *“Development of Wind Uplift Standard for Adhesive Applied Low Slope Roofing System”*, was initiated (Baskaran et al. 2010). The project has three major tasks: experimental investigation, formulation of a numerical model and development of wind design guide and standards. As part of the Task 1, a small scale

test method to quantify the uplift resistance of AARS specimens under tensile loading was developed. Currently, the developed test method is in the standardization process through the American Society of Testing and Materials (ASTM 2010). By investigating over 400 specimens systematically, three key parameters for the test method, namely uplift rate, test specimen size, and attachment conditions were optimized. Details of the test method development and data associated for optimizing the above parameters are reported by Current (2009) and documented in a parallel publication (Baskaran et al. 2010). These parameters can be summarized as follows:

- Uplift rate of 6.35 mm/min: To establish the uplift rate, experiments were carried out at an applied uplift rate of: 1.27 mm/min, 2.54 mm/min, 6.35 mm/min, and 12.7 mm/min. This test matrix resulted in a total of 128 (samples x specimens x uplift rate = $4 \times 8 \times 4$) uplift test data for the determination of an appropriate uplift rate.
- Specimen size of 300 x 450 mm: Two specimen sizes were tested, 300 x 450 mm and 300 x 900 mm, by constructing a total of 64 samples.
- Attachment condition: The experimental protocol proposes that every flute of the steel deck requires attachment to the specimen mounting platform. However, a greater amount of deflection may occur in the actual field compared to lab tested attachment conditions. It is useful to investigate the attachment condition of one that allows for more deflection, and then determine if changing this condition introduces any significant changes in the uplift response and in the development of the test protocol.

This paper focuses on the application of the developed test method. For industrial partners of this project (please refer to the acknowledgements section), a comparative study of the effect of component changes is one of the practical applications of the developed test method. This paper presents results from such parametric study. From this parametric study, one can determine the ways and means to improve the uplift resistance of AARS by selecting optimum component combinations and isolating the weakest link from the selection. The results presented in this paper also validate the applicability of the developed test method for variations in the AARS specimens and thus offers confidence in moving forward to standardize this test method as a common platform for AARS uplift resistance evaluations.

Experimental Setup

Specimen preparation: For the present study, experimental specimens were prepared by the participating industrial partners so that the variability of the roof applicators can be accounted. Thus, the methodology presented here can be sufficiently reproduced by others. However, the paper does not claim that the exact results would be achieved by using the same physical components and constructing specimens with different applicators. Each specimen was constructed with a steel or concrete deck, vapour barrier, insulation, cover board, base sheet and cap sheet, which were bonded together using cold adhesives. Only a summary of the experimental set up is presented below, whereas all details were documented elsewhere (Current et al. 2007; Murty et al. 2008a, b; Current 2009; Baskaran et al. 2010). Figure.1 shows the steps involved in preparing an AARS specimen for testing under tensile loading.

Test preparation and setup: The 4502 series Instron frame is a piece of standard laboratory tensile testing equipment which was modified to perform uplift resistance testing of roofing components bonded using cold adhesives. Components of the Instron frame include a crosshead, loading cell, and plate-flanged housing. The rest of the apparatus includes a stress plate, stress plate mounting platform, specimen mounting platform, and attachment strips.

A typical setup for the uplift resistance test method is shown in Figure 2. The specimen mounting platform is a flat, immobile base that the test specimens sit on while undergoing testing. It is a minimum of 75 mm thick, 350 mm wide, and 600 mm long, with four pairs of holes 6.5 mm in diameter drilled along the perimeter with a center to center distance of 125 mm along the 600 mm dimension. The attachment strips are 350 x 25 x 12.5 mm steel strips. They are slid through the flutes of the test specimen and have 6.5 mm diameter holds, which are superimposed over the holes on the platform to secure specimens for uplift testing. The stress plate is a moveable steel plate placed over top of the test specimen and attached with #10 Robertson wood screws. A pin is used to attach this tension plate and specimen to the moveable crosshead of the machine. With the apparatus set up and the specimen constructed, testing is ready to be carried out. The specimen is centered on the specimen mounting platform and fixated with the attachment strips. The crosshead is jogged down so that the stress plate sits overtop of the specimen. A pin is removed and the crosshead brought back up so that the stress plate can be fastened. The crosshead is then reattached by replacing the pin. After manually removing the slack, the test can be run

until failure is achieved. The test is run at the specified variables of a 6.35 mm/min deflection rate, a 300 x 450 mm test area, and the attachment of all flutes by following fixed end conditions.

Results and Discussion

The following terminology was used in the data interpretation of the uplift test results of this study (Figure 3).

Peak Load: The maximum force the specimen is able to resist before failure occurs on the specimen. The peak load is like a barometer of uplift performance. The higher the peak load, usually the better the performance.

Deflection at Peak Load: A measurement of the specimen displacement at the time of peak load occurrence.

Failure Planes: The occurrence of the first failure is typically known as *failure 1*. *Failure 2* is the second failure observed on a specimen. When a specimen is unable to resist any further application of load, *specimen failure* has occurred. The plane in which this first failure is observed is defined as the *failure plane*.

Elastic Energy: For the sake of this investigation, *elasticity* was defined as the portion of the curve between one-third and two-thirds of the peak load. One-third and two-thirds of the peak load were systematically chosen because over the course of the first few millimeters of deflection, slack was removed from the specimen. In the final 1/3 of the test (from 2/3 to the peak load), the slope evolved from linear to non-linear. Based on these observations, the portion of the curve between these two bounds was numerically

integrated. The numerical integration that was chosen is explained by the following equation:

$$\int_{1/3 PL}^{2/3 PL} F(x) = \Delta x [(f(x_1) + f(x_2))/2 + (f(x_2) + f(x_3))/2 + \dots + (f(x_{n-1}) + f(x_n))/2] \dots\dots\dots(1)$$

where,

- $\int_{1/3 PL}^{2/3 PL} F(x)$ is the area under the curve from 1/3 to 2/3 of the peak load.
- $f(x_n)$ is a data point measurement indexed by starting at the load measurement at 1/3 of the peak load.
- Δx is the rectangle thickness. Since all numerical integration was performed on specimens tested at 6.35 mm/min and the data was sampled 10 times/second, this corresponds to a constant rectangle thickness of approximately 0.0106 mm.

This is essentially numerical integration using the mid-point rule. Although the methodology was not perfect, it provided an adequate and robust estimate of how loading would build based on a fixed uplift rate under the consistent boundary conditions applied. With reference to this investigation, elastic energy calculations were used for determining the uplift resistance.

Effect of Material Combination on the Uplift Resistance

Insulation and Cover board

Figure 4 outlines the experimental conditions used to determine the best and worst combinations of insulation and cover board materials that are commonly used in AARS

in Canada. There were two sets of samples prepared. In set #1, adhesives were applied on the components at predefined locations and those specimens were labeled as partially adhered (PA) specimens. In set #2, components were adhered with a full coat of adhesives, in other words, adhesives were applied to the entire surface area of each component that came in contact with other components. For each set, two samples were prepared. Partial adhesion was used in the construction of samples 1 and 2, while full adhesion was used in the case of samples 3 and 4. Components were supplied and specimens were constructed by the industrial clients.

For each sample, 6 specimens were constructed. Note that the specimens are replications of the same configuration and they are 300 x 450 mm in size. All specimens included a 22 gauge steel deck and two layers of bituminous membrane. Two insulation facers, acrylic facer (AF) and paper facer (PF), and two cover boards, asphalt core board (ACB) and fiberboard (FB), were tested together in various combinations: PF/ACB, PF/FB, AF/ACB, and AF/FB. This test matrix resulted in a total of 96 (samples x specimens x materials = 4 x 6 x 4) uplift test data for the determination of the best and worst insulation and cover board combinations for use in the field applications of AARS.

All specimens were subjected to a uplift rate of 6.35 mm/min and a fixed end condition. The uplift rate is the amount at which deflections are imposed on the stress plate mounting platform of the specimen, and the fixed end condition is defined as an all four flute attachment to the specimen mounting platform. Figure 5 shows the time history plot of load versus time relationship of the PF/ACB and PF/FB specimens from sample

4. The x-axis shows the time, whereas the load in kN is shown in the y-axis. Note that the values presented are not averages but raw data obtained directly from experimentation. The PF/ACB combination reaches a peak load of 4.27 kN, while the PF/FB combination only reaches a peak load of 3.34 kN. These results show that the PF/ACB specimen demonstrated superior uplift resistance to the PF/FB specimen. A hypothesis that the material combination of PF/ACB is better than that of PF/FB can be made.

In order to verify this finding, the raw data was analyzed further to find the peak load of each material combination for all sample sets. Figure 6 depicts the peak load from each material combination from the partially adhered samples 1 and 2 and fully adhered samples 3 and 4. The material combination is found in the x-axis and the peak load in kN is found in the y-axis. Note that the peak load presented is an average from the specimens of that particular sample. For example, in the case of PF/ACB, sample 1 and sample 2 had peak loads of 2.24 and 2.30, respectively. The dashed lines represent the combined averages of samples 1 and 2 of each material combination. For example, in the PF/ACB condition, 2.24 kN is averaged with 2.30 kN to generate a mean of 2.27 kN. Through observation of the mean peak load of each combination condition, the general trend of peak loads for partially adhered specimens is as follows: PF/ACB > AF/ACB > AF/FB > PF/FB.

The fully adhered specimens from samples 3 and 4 exhibit the same trend of peak loads as those found in the partially adhered specimens. Namely, the PF/ACB combination can reach a higher peak load than the PF/FB combination before its first failure. A comparison shows that the peak loads reached by the fully adhered

specimens are higher than those reached by the partially adhered specimens irrespective of the material combination. It is inferred from these observations that the best material combination is PF/ACB under full adhesion and the worst material combination is PF/ FB under partial adhesion. The previous supposition made from the raw data therefore proves to be global, giving more integrity to the conclusion.

As a further step toward confirming the formerly made conclusions, the elastic energy was calculated to determine the uplift resistance of each insulation and cover board combination. An average of the elastic energy displayed by each material combination is represented in Figure 7. The x-axis displays the material combination and the y-axis shows the elastic energy in joules. The elastic energy values presented are an average from the specimens of the particular configuration type. The data was grouped corresponding to the two sets, namely, fully adhered (FA) and partially adhered (PA). Consistent failure of specimens was observed in a very specific range of about 2.0 – 2.4 J of elastic work regardless of sample, material, and type of adhesion. There were two exceptions to this observation. First, the PF/ACB (FA) specimens were able to absorb double the amount of energy (~ 4J) before their failure. Second, all specimens of FB (PA) cover board combinations failed around only 1 J of elastic energy with PF/FB (PA) being the worst. These observations confirm the conclusion that the best material combination is PF/ACB (FA) and the worst material combination is PF/FB (PA). It should also be noted that the drastic drop in uplift resistance towards energy input from PF/ACB (FA) to PF/FB (PA) illustrates that it is the difference in the cover board which leads to premature failure, considering the insulation remains constant.

To validate this, failure plane analyses were carried out for all the tested specimens. There were three failure planes found: adhesive failure, insulation failure, and cover board failure (Figure 8).

Adhesive failures: This occurs when one roofing component layer is separated from an adjacent roofing component layer with the adhesive still fully bonded to one of the roofing component or when the adhesive is still partially bonded to the adjacent roofing component layers.

Insulation failures: There are two types of failure on the insulation component: facer rupture and facer delamination.

Facer Rupture: This occurs in the facer and partially into the insulating materials. The failure starts in the facer.

Facer Delamination: This occurs in the insulation immediately adjacent to the paper- or acrylic-based facer. Failure starts in the foam adjacent to the facer.

Cover board failures:

Separation: Separation failure of a cover board results in separation of cover board, with parts of the cover board material remaining in the adhesive layer. This failure mode normally happens in specimens with asphalt core cover board (ACB).

Splitting: The splitting failure is somewhat similar to the facer rupture failure, except that the failure occurs in the cover board. Splitting failures result in complete separation of the cover board into two discrete layers. This type of failure predominantly occurs in specimens with fiber cover board (FB) configuration.

Brittle: This type of failure happens in both FB and ACB. However, in the case of ACB, brittle failure mainly occurs during the experiment with corner peeling. The brittle failure process always took place within a very short duration.

Vapor Barrier Delamination:

Kraft paper is a laminated product of two sheets of kraft paper. When the delamination of one sheet from the other occurred during the tensile testing, it is termed as vapour barrier delamination. It should be noted that the kraft paper being pre-laminated, this failure is due to a manufactured adhesive failure between the sheets and is not unrelated to specimen construction. When peel and stick vapour barriers are used, this failure plane was not observed.

Of the PF/FB material combination, 22 out of 24 failures were due to the cover board (Figure 9a). In the case of the PF/ACB condition, insulation failure in the form of facer rupture (Figure 9b) and facer delamination occurred 18 out of 24 times indicating the insulation as the weak link. Despite these insulation difficulties, the PF/ACB (FA) condition is still the best material combination. Similar observations were also made when the AARS specimens were investigated under shear loading to simulate peeling failures (Wu 2008) and under dynamic loading to simulate wind uplift failure (Murty 2009).

Effect of Deck Material: Steel Versus Concrete

The next comparison test conducted was based on deck material. Figure 10 gives a breakdown of the experimental conditions used for characterizing the different uplift behaviour between specimens with concrete and steel decks. As before, partially

adhered and fully adhered sets of samples were used. For each sample, 6 specimens were constructed by the same industrial clients mentioned earlier. All specimens included 2" (50 mm) polyisocyanurate insulation, an asphalt core board, and two layers of bituminous membrane, and they were 300 x 450 mm in size with a fixed end condition (in the case of the steel decks). Each test was run at the ideal 6.35 mm/min uplift rate. Two deck types, 22 gauge steel and 25 mm thick concrete, were being compared. Note that the concrete deck data were being compared to steel decks constructed with the PF/ACB condition. This test matrix resulted in a total of 48 (samples x specimens x decks = 4 x 6 x 2) uplift test data for characterizing the deck material that induces the better uplift response in AARS specimens.

Figure 11 illustrates the average peak load reached for steel and concrete decks. The data is grouped corresponding to the deck type, which is shown in the x-axis, while the related peak load is shown in the y-axis. Note that the peak loads are an average from the six specimens. The dotted lines represent the mean from all samples within a specific deck condition. For example, in the steel condition, 2.24, 2.30, 2.67, and 4.27 kN are added and divided by four to give a mean peak load of 2.87 kN for steel decks. The mean peak load of concrete decks is 2.58 kN. The average peak loads attained for specimens of both the steel and concrete deck conditions are very similar, making it difficult to come up with a sound conclusion based on this data interpretation alone. A different approach is taken as follows.

The specimen displacement at peak load for the two deck types is represented in Figure 12. The x-axis indicates the deck type and the y-axis shows the displacement at peak

load in millimeters. The data is grouped corresponding to the steel and concrete deck types. For each sample, the displacement at peak load is an average from the six specimens. As before, the dotted line represents the overall mean of displacements at peak loads from each deck type. The steel decks exhibited a mean displacement at peak load of 6.4 ± 0.5 mm, while the concrete decks demonstrated a mean value of only 4.5 ± 1.0 mm. Although the average peak loads attained for both the steel and concrete deck specimens were very similar, steel deck specimens were able to incur much greater displacement prior to failure. Steel can deform more than concrete, and this higher elasticity of the steel deck allows some of the work that is placed into the specimen to be manifested as deflections on the deck. Concrete decks are more rigid and do not allow the dissipation of energy in such a way. The conclusion, therefore, can be made that specimens constructed on steel deck performs better than concrete in AARS.

To confirm this, elastic energy comparisons were conducted for concrete decks versus steel decks with a fixed end condition (Figure 13). The x-axis shows the type of deck and the y-axis shows the elastic work in joules. Note that the elastic work is an average of the specimens, and the dotted line is a total mean of those averages. The data is grouped into steel deck and concrete deck. The mean elastic work done by the specimens on the steel deck is 2.51 J ($[1.78 + 1.79 + 2.28 + 4.21 \text{ J}] / 4$), while the mean elastic work for the concrete deck is 1.62 J. Despite the disproportionate inflation given by sample 4 of the steel deck condition, the specimens constructed on steel decks still outperform the concrete ones when you compare each sample to its corresponding sample of the other deck type. This supports the conclusions made from observations

of deflection at peak load, indicating that steel decks are superior to concrete decks due to their ability to dissipate the work put into the specimens during uplift tests.

The same three failure planes were found in the steel and concrete deck tests: adhesive failure, facer rupture, and facer delamination. During analysis, 12/24 failures of the steel deck specimens were facer ruptures (Figure 14a). In the case of the concrete deck specimens, facer delamination was the most common failure occurrence, appearing 12/24 times. Failures on facers tend to be the failures that attain the highest peak load before failure and thus are most desired by the designers. In the steel deck condition, 18/24 (75%) failures were insulation in nature in the form of either facer rupture or facer delamination. In the concrete deck condition, only 14/24 (58%) failures were of this same form. This is explained by the lack of ductility of the concrete deck, which places a larger stress concentration on the insulation facer and thus may cause failure to become more brittle than with a steel deck. More successive failures may occur with concrete decks as well, as adhesive or cohesive failure occurs in the cover board before the facer can delaminate. An adhesive failure in between the insulation and the cover board for concrete deck specimens is illustrated in Figure 14b. This failure occurred 10/24 times. Steel decks exhibit superior performance in terms of failure, deflection at peak load, and elastic energy and would therefore be a better form to use as an AARS specimen. As discussed in the experimental set up section, for the present study, experimental specimens were prepared by the participating industrial partners so that the variability of the roof applicators can be accounted. This includes preparation of the concrete deck specimens as well. Surface preparation is critical to have proper adhesion of components with the concrete deck. It would be interesting to

evaluate by using the same roofing components and adhesives on a concrete deck prepared in the field conditions using with different applicator.

Effect of Adhesive Application Method

In the field, to save cost on labour and material, there is the option to not fully adhere all of the flutes in a roofing system. The final test performed was designed to discover the effect of alternate adhesion patterns on the steel deck specimens between the deck and vapour barrier on the uplift performance of AARS. Outlined in Figure 15a are the experimental conditions used to determine the effect of alternate adhesive application methods between the deck and the vapour barrier on the uplift resistance of AARS specimens against tensile loading. Note that only the fully adhered specimens were used for this investigation. All specimens included a 22 gauge steel deck and two layers of bituminous membrane. They were subjected to a uplift rate of 6.35 mm/min, specimen size of 300 x 450 mm, and a fixed end condition. Two insulation facers, acrylic facer (AF) and paper facer (PF), and two cover boards, asphalt core board (ACB) and fiberboard (FB), were used together in various combinations: PF/ACB, PF/FB, AF/ACB, and AF/FB. Two adhesion patterns were being tested. In one case, Type A application method, the adhesive is applied on all of the flutes between the deck and vapour barrier. In the other case, Type B application method, the adhesive is placed only on the two outer flutes of the steel deck. Figure 15b illustrates these cases. The test matrix leads to a total of 96 (samples x specimens x materials x adhesion types = $2 \times 6 \times 4 \times 2$) uplift test data for characterizing the ideal vapour barrier-deck adhesion for uplift resistance of AARS.

Presented in Figure 16 are the peak loads from specimens of each material combination of the two application types. The x-axis shows the material combinations grouped into Type A and Type B application types. The peak load is represented in the y-axis. Note that the peak load displayed is an average from the six specimens. Type A exhibits a range of peak loads from 2.68-3.47 kN and Type B produces peak loads from 1.75-1.80 kN. The main observation is that Type A application has higher peak loads than Type B application, whereas the latter holds a more finite range irrespective of the material combination. By further analyzing the data, additional observations can be made.

Figure 17 presents the data in the ratio of peak load of Type B to peak load of Type A. The x-axis presents the material combination and the y-axis presents the ratios. To illustrate, from Figure 16, the Type B application value of PF/ACB is 1.80, and it was divided by the corresponding Type A application value of 3.47 to produce a ratio of 0.54. This value means that the Type B application reaches only 54% of the peak load that the Type A application for the PF/ACB material combination reaches. Overall, the ratio ranges from 0.5 to 0.7, indicating that the Type A application may be the more ideal adhesion type.

Type B application uses less adhesive. Less adhesion means less contact area, which would result in less work required to break the adhesive bonding or induce cohesive material failure. By removing the adhesive from the middle flute, the stress concentration is limited to the outer perimeter of the deck and therefore in the majority of instances, the Type A application displayed more elastic energy than the Type B

application. These observations combined with conclusions from the former peak load analysis indicate that the Type A adhesion is the most ideal of the two adhesion types.

Concluding Remarks

The parameters of the proposed test method were applied to different AARS configurations to determine the effects of specific variables on the overall uplift performance. Assessments were focused in three segments: cover board/insulation material combinations, steel/concrete deck combinations, and adhesion patterns.

Effect of Material Combinations

- Superior performance is exhibited by the paper facer insulation & asphaltic core board material combination and to a slightly lesser extent the acrylic facer insulation & asphaltic core board combination.
- Poor performance is exhibited by the paper facer insulation & fiber board and acrylic facer insulation & fiber board combinations.
- From calculating elastic work, there are three ranges at which failure occurs: performance of fully adhered paper facer insulation & asphaltic core board (excellent, > 4.0 J), performance of all other fully adhered material combinations and partially adhered combinations with asphaltic core board (good, $2.0 - 2.5$ J), and the performance of partially adhered fiber board (inadequate, $1.0 - 1.1$ J).
- Based on the previous two findings, the type of cover board used plays a significant role in the uplift resistance of AARS specimens.

Effect of Deck Material

- Specimens with steel decks attained much higher peak loads than concrete decks.
- Specimens with steel decks were able to exhibit much more deflection at peak load than those specimens with concrete decks and therefore experienced greater elastic energy performance as well.

Effect of Adhesive Application

- Uplift resistance was reduced comparing the Type B application to the Type A application, and the reduction ranged from 0.6 to 0.8.
- Failure planes shifted in the specimen closer to the location where adhesive was deliberately omitted.

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