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Investigation of Peel Resistance of Adhesives Materials: A Review

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Abstract

Different adhesives are used for joining the different types of materials. The different types of peel tests available for investigating the adhesive strength are 90°, 135°, 180° and T-peel test. This paper reviews the different peel tests available as well influence of other factors for determining of peel resistance between two materials. The investigation of adhesive strength helps to select a proper adhesive material for joining of two different materials. The paper briefs the effect of peel angle, different types of peel tests such as 90° and T-peel test, temperature, moisture, thickness, the rate of change of peeling rate on peel strength.

Keywords: adhesive bonding, de-lamination, interface adhesion, peeling test

1. Introduction

Adhesive bonding is used on a large scale in different industries. With the invention of new adhesive materials, it can be a challenge to figure out a way to join two different materials while retaining their individual properties. Peeling force is an important property to characterize adhesion of materials. This force is defined as the force required to remove the adhesive film from a substrate. The peel strength is the measure of the average force to part two bonded materials like tape, labels, textile or plastic films. The strength is calculated during a peel test at a constant speed rate divided by the average force (the peel force) required during the test the unit width of the bonded samples. Depending on materials, norms, products, the tests can be done with different angles 90° and 180° are commonly used. The adhesive bonding is used where extremely small parts need to be bonded securely within a unit. The use of adhesive bonding is important in manufacturing products which are rugged, light-weight and transparent. In such case, the manufacturer should know about the adhesive strength of the adhesive. Different types of peel tests can be used to determine the adhesive strength between two bonded materials.

The applications of peeling and its role in adhesion are widespread in both engineering and biology. A specific problem that has captivated a diverse group of scientists, particularly technicians, in the area of peeling and adhesion for the last decade is the enhancement of the adhesive properties of materials through studying analogous behavior in nature. The investigations focused on naturally occurring reversible adhesion in biological systems can be applied to the development of engineered reversible adhesive systems, which have a wide range of engineering applications including biomedical devices, microelectronic storage and packaging, and surgical robotics.

At the core of the problem, how a natural reversible adhesion process works in both micro and macro scale mechanics should be known. The failure of adhesive joints is commonly said to be either adhesive failure or cohesive failure. The combination of these two is also possible. An adhesive joint failure occurs between the interface of adhesives and adherent. The cohesive failure is a failure that occurs in the largest part of the adhesive layer and usually desired mode of failure. If the adhesives and adherents have the different thermal-mechanical properties, it is observed to fail without additional load. The surface of the structure also affects the location failure, either smooth surface or a rough surface [1].

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The mechanics of the peel test can be examined through experiments, finite element simulations, and theoretical approach with the aim of developing, governing relations to describe the role of fracture in the peel test for elastic adhesive tapes. An inverse formulation was developed to extract a cohesive zone law from a set of experimental peel tests using a theoretical framework based on non-linear beam theory.

2. Literature

In the most of the literature, the peel test is preferred to determine the adhesive properties by performing theoretical calculation and experiment tests. The adhesion properties are evaluated with help of peel resistances which implicates the peel strength. The forces acting per unit width of the laminates measures the required energy for the peeling of the laminates. The peel test is also used to assess the knowledge about the effects of parameters like peel angle, a number of ingrained adhesion effects in between the laminates, thickness of the laminates, and the rate of the test. The temperature also plays a major role while performing the analysis.

Following table shows authors and their respective work is done with materials used during the peel test.

Table 1 Authors, material used and work done

Name of Author	Materials	Work Done
Ulrich Eitner, Li C. Rendler [2]	Ribbons.	Peel test on ribbons
S. Giannis, R.D. Adams, L.J. Clark, M.A. Taylor [3]	Aluminium, titanium.	Peel test on aircraft fuel tank sealants
Jinhyeok Jang, Minchang Sung, Sungjin Han, Woong-Ryeol Yu [4]	Steel, nylon	The delamination of steel-polymer composites
Idris K. Mohammeda, Anthony J. Kinlocha, Maria N. Charalambidesa [5]	polyethylene	Peeling Behavior of Soft Adhesives
Z. L. Peng, S.H. Chen, A. K. Soh [6]	Bio-mimetic nano-films	Peeling behavior of a bio-inspired nano-film
Stephan Marzi, Anders Biel, Olaf Hesebeck [7]	Steel	Peel test in a rotary impact device.
F. Nihal Tuzun, M. Safak Tunalıoglu [8]	Steel, Composites	Investigated the effect of five different fillers by using T-peel.
Michael Nase, Mirko Rennert, Konstantin Naumenko, Victor A. Eremeyev [9]	Self-adhesive polymers	Self-adhesive polymeric films.
G Hinopoulos and W R Broughton [10]	CR1 mild steel, 6Al-4V titanium, 5251 aluminium	FEA study carried out on a T-peel joint.
H. Hadavinia, L. Kawashita, A. J. Kinloch, D.R. Moore, J.G. Williams [11]	Hyperelastic thin films	Adhesive fracture energy.
Gregory Polyzois, Panagiotis Lagouvardos, SpirosZinelis, MaryFrangou [12]	Titanium (cpTi)	Investigation of bond strength
WeiZeng, Weixing Sun, Nicola Bowler, Simon Laflammea [13]	Aluminum, steel, concrete, and fiberglass	Peel resistance of adhesive joints with elastomer–carbon black.
Yasuhiro Tanimoto, Hiroyuki Saeki, Suguru Kimoto, Tsuyoshi Nishiwaki c, Norihiro Nishiyama [14]	GC Reline Soft, GC Reline Extra Soft	Investigation of adhesive properties
A. Nick, B. Nick, F. J. Wortmann [15]	Fibre-reinforced epoxy composite	Peel test between temperature -55℃ to 80℃
Sofia Teixeira de Freitas, Jos Sinke [16]	Fiber Metal Laminate (FML), Carbon Fiber Reinforced Polymer.	Peel test between temperature -55℃, room temperature (+22℃) and 100℃
G Hinopoulos and W R Broughton [10]	CR1 mild steel, 6Al-4V titanium, 5251 aluminum	Peel test for substrate thickness 1.5 to 5 mm
Zhilong Peng, Cong Wang, Lei Chen, Shaohua Chen [17]	Glass, viscoelastic polyvinylchloride	Peel test for film thickness 1.5 to 5 mm 0.13, 0.26, 0.39

2.1. Peel angle

Peel angle influences the peel force in the peeling test. The literature shows that as the peeling angle increases the peeling force decreases to some angles. Ulrich Eitner and Li C. Rendler [2] carried out a peel test for soldered or glued ribbons on solar cell metallizations. It was found that higher forces were required for decreasing peeling angles less than 90° and weakest forces required for 135°. The work also includes the adhesive fracture patterns. It was found that with the change of peeling angles from 90° to 180° helps to obtain adhesive or cohesive fracture patterns instead use of silicon cell fracture. The relation between peel force and adhesive fracture energy was proposed. The fig. 1 shows the relation between peel forces and adhesive fracture energies for 180° peeling angle. From results, it is observed that for the given force the adhesive fracture energy is maximum for the soft ribbon. S. Giannis, R.D. Adams, L.J. Clark, M.A. Taylor [3] carried out peel test on aircraft fuel tank sealants and observed results for different sealants are shown in fig. 2. The obtained results show that for the same thickness and the same sealant the peel resistance increases as the peel angle was increased from 135° to 180°. Also, Jinhyeok Jang, Minchang Sung, Sungjin Han, Woong-Ryeol Yu [4] carried out peel tests of steel polymer composite (nylon) at various angles and obtained results are shown in fig. 3.

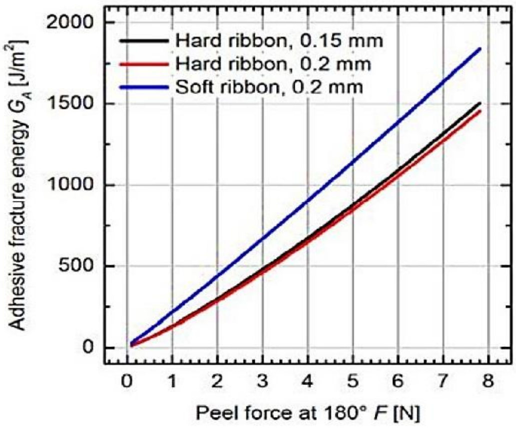


Fig. 1 The relation between peel forces and adhesive fracture energies for 180° peeling angle [2]

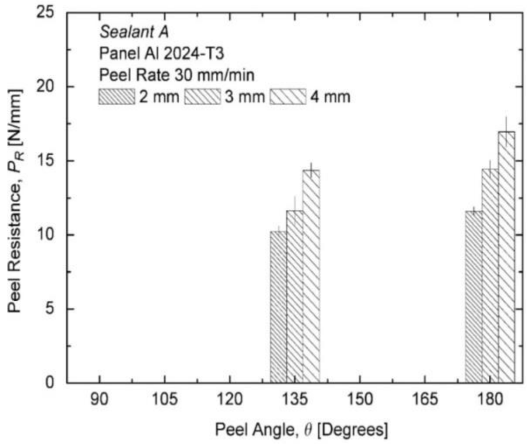
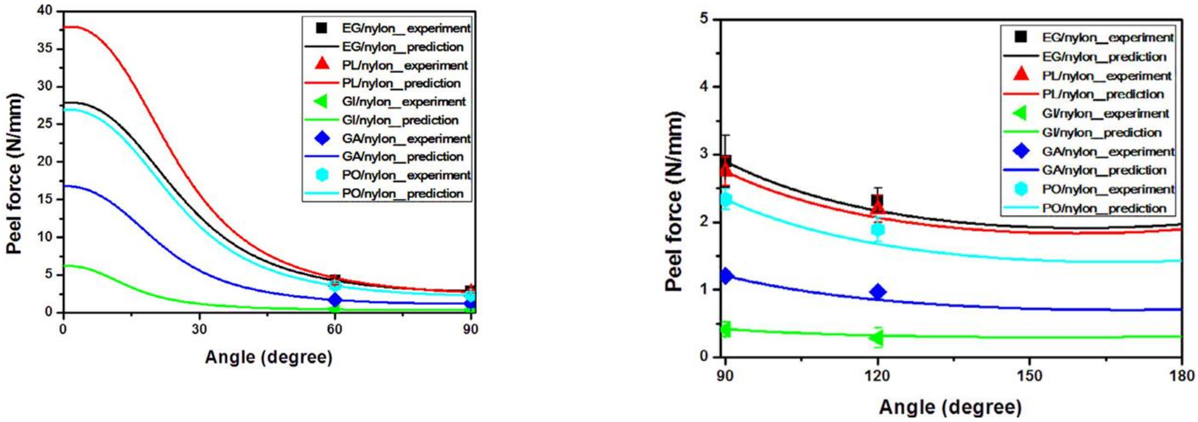


Fig. 2 The relation between peel resistance and the peel angle [3]



(a) 0–90 degrees (b) 90–180 degrees

Fig. 3 Comparison of experimental and predicted peel strengths for different peel angles [4]

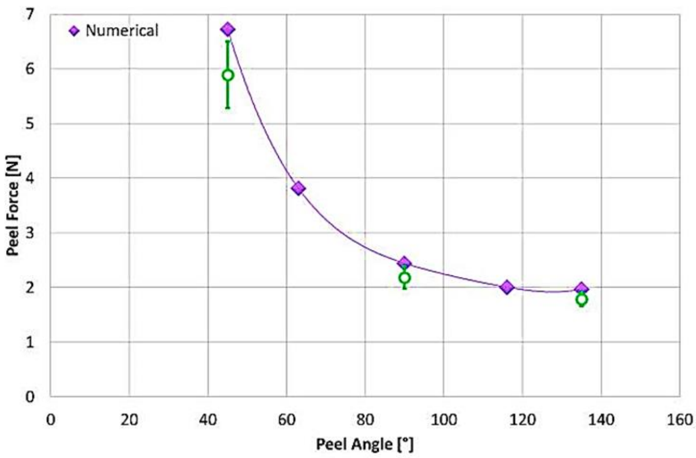


Fig. 4 Experimental (green marked) and numerical peel forces at different angles [5]

The results were obtained for different materials which shows that as the peel angle increases the peel force decreases. The materials used for peel tests were EG steel–nylon, PL steel–nylon, GI steel–nylon, GA steel–nylon, POSMAC steel–nylon from which combinations of EG steel-nylon shows lesser deviation in experimental and predicted results. Also, the peel test was carried out by Idris K. Mohammeda, Anthony J. Kinlocha, Maria N. Charalambidesa [5] for pharmaceutical drug patches which consist of a polyester backing membrane supporting an acrylic pressure-sensitive adhesive (with and without anti-fungal drug) adhered to a polyethylene substrate. The results obtained through experimentation are shown in fig. 4 with respect to peel angle.

A numerical peeling model of nano-films with a finite length in adhesive contact with a rigid substrate is investigated by Z. L. Peng, S.H. Chen, A. K. Soh [6]. It was found that the given peeling angle, peeling-off force remains constant if the length of the nano-film is larger than an effective adhesive length. The literature summary for peel angle is shown in table 1. Specialization is to assign specific types of members and joints to every available generalized chain subject to certain design requirements to obtain the specialized chains. Design requirements are determined based on the concluded topological structure of the original designs.

2.2. T-peel test

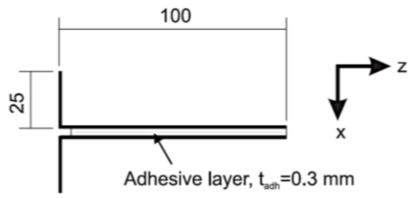


Fig. 5 Schematic diagram of T-peel test [7]

It is a peel test in which both materials are pulled simultaneously as shown in fig. 5. The one end of the joint is tightly held in the jaws and the other end is pulled in the vertical direction by holding in another jaw. By measuring the peel forces the peel resistance was determined for the adhesive. Such type of peel test is used when both adherents are flexible. Stephan Marzi, Anders Biel, and Olaf Hesebeck [7] also performed the T-Peel test on a rotary impact device where the material is not supported but clamped stiffly. The deformation of the specimen and its clamping is analyzed by three-dimensional digital image correlation system.

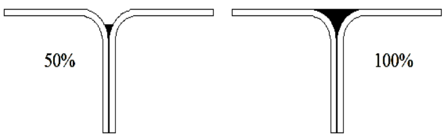


Fig. 6 Schematic of the adhesive fillet geometries for the T-peel joint [10]

Also, F. Nihal Tuzun, M. Safak Tunalıoglu [8] investigated the effect of five different fillers on the adhesion strength of the metal parts. Michael Nase, Mirko Rennert, Konstantin Naumenko, and Victor A. Eremeyev [9] used T type peel test for self-adhesive polymeric films. Whereas G Hinopoulos and W R Broughton [10] used a T type peel test to investigate the effect of adherend properties, geometric parameters, and environmental conditioning on joint performance. The finite element analysis was carried out for steel joints with the adhesive fillet occupying either half or all of the space between the steel substrates. The schematic diagram of the adhesive fillet geometries for the T-peel joint is shown in fig. 6.

It was observed that the joint with the 50% adhesive fillet deformed substantially more than the joint with the 100% fillet under the same tensile load. The Von Mises equivalent stress at the end of the overlap for the specimen with 100% fillet was reduced by 200% compared with the 50% fillet specimen [10]. Also, H. Hadavinia, L. Kawashita, A. J. Kinloch, D.R. Moore, and J.G. Williams [11] determined the adhesive fracture energy with the help of a peel test. The literature summary for the T-peel test is shown in Table 1.

2.3. 90° peel test

In 90° peel test, bottom substrate is made rigid and the upper substrate is exposed so as to obtain a smooth pull of peel arm as shown in the fig. 7. The bottom substrate is rigid by means of grips and the peel arm of the upper substrate is pulled in order to measure the peel force. This test is preferred when the upper adherend to be pulled is having less thickness than that of the adherend which at the bottom.

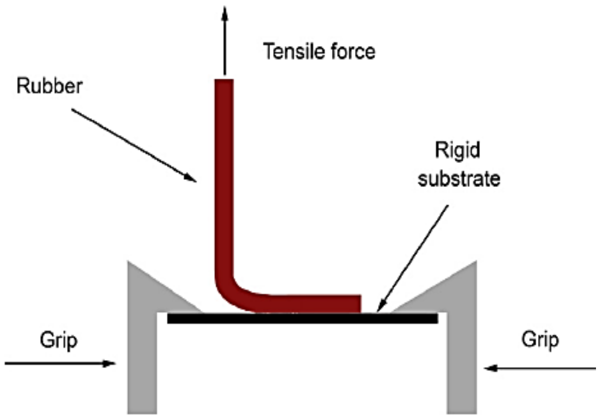


Fig. 7 Schematic representation of the experimental set up of 90 degree peel test [12]

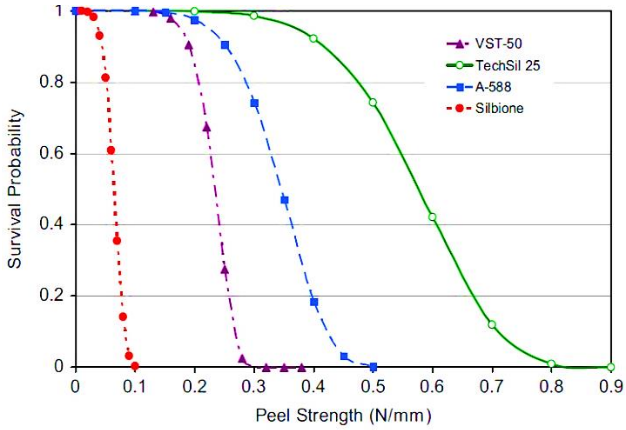


Fig. 8 Survival graph of the four PDMS bonded to acrylic substrate with primer [12]

Polyzois, Panagiotis Lagouvardos, SpirosZinelis, and MaryFrangou [12] investigated the bond strength of four silicone (PDMS) pro Gregory sthetic elastomers such as VST-50, A-588, TechSil 25 and Silbione used for the construction of official prostheses to cpTi and acrylic resin as control through a primer and bonding enhancer application. The peel bond test at 90° was conducted as per ISO 813:97 and the obtained results were analyzed and interpreted using ANOVA and Weibull regression analysis as shown in fig. 8. From the analysis, it is observed that only one of the materials TechSil 25 has a high probability of surviving a stress.

Also, H. Hadavinia, L. Kawashita, A. J. Kinloch, D.R. Moore, and J.G. Williams [11] determined the adhesive fracture energy using a single arm 90-degree peel test as shown in fig. 9.

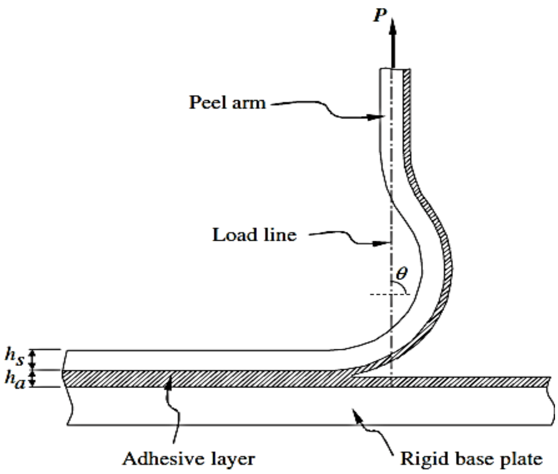


Fig. 9 The single-arm 90° peel test [11]

For the single-arm peel joints, aluminum-alloy sheets of 180 mm X 20 mm X 10 mm served as the rigid base plates. The dimensions of the peel arms were measured prior to joint preparation. The single-arm peel tests were carried out by maintaining the peel angle of 90°. All peel tests were carried out at the same temperature, humidity (21℃, 55% RH), and crack growth rate (5 mm/min). Also, WeiZeng, Weixing Sun, Nicola Bowler, and Simon Laflammea [13] carried out peel test for four different adhesives which were J-B Weld, 3M Scotch-Weld DP125Gy, Loctite PL Premium (3x) Construction Adhesive, and Henkel Hysol EA 9394 and evaluated the results based on adhesive costs. The characteristics of adhesive properties between a denture base and resilient denture liner were investigated by Yasuhiro Tanimoto, Hiroyuki Saeki, Suguru Kimoto, Tsuyoshi Nishiwaki c, and Norihiro Nishiyama [14] using 90° peel test. The literature summary for 90° peel test is shown in Table 1.

2.4. Temperature

The temperature parameter has a major impact on adhesive strength. With the change in temperature changes the properties of the adhesive. A. Nick, B. Nick, and F.-J. Wortmann [15] studied the effect of temperature on four different types of adhesives as shown in Table 2. The peel tests were performed by keeping the same relative humidity for all samples and temperature ranges between -55℃ to 80℃. The observed results are shown in fig. 10.

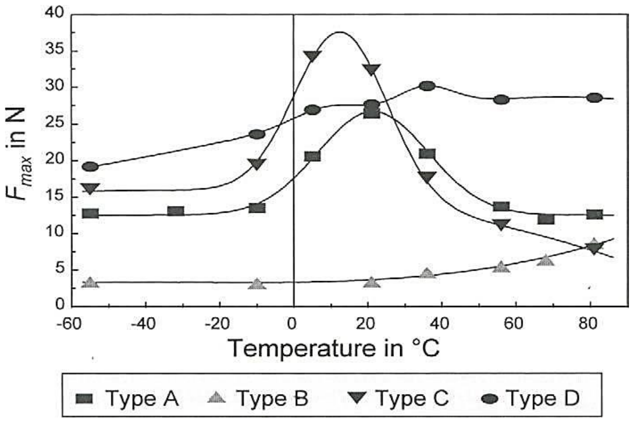


Fig. 10 Relation between maximum force and temperature [15]

Table 2 Different types of adhesives used for peel test

Type	Curing system	Specification
A	cold curing epoxy/polyamine-system	(Scotch-Weld DP 190)
B	hot curing 3-component epoxy-system	(Araldit LY 556, HY 917, DY 070)
C	Cold curing polyurethane/isocyanate-system	(Scotch-Weld 3532 B/A)
D	cold curing epoxy/polyamine-system, different in composition than type A	(Scotch-Weld 9323 B/A)

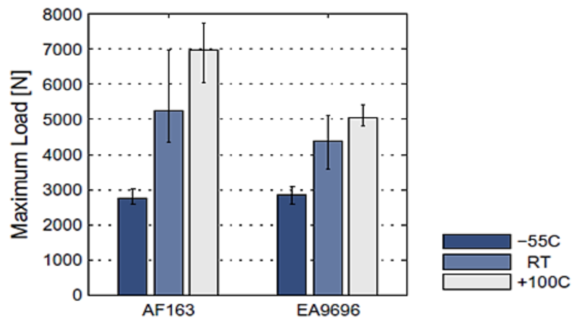


Fig. 11 The relation between Max load and temperature of adhesives AF163 and EA9696 [16]

The obtained peel test results show significant differences in peel strength of different adhesives. The uniform dependency of the peel strength of the temperature is observed. For the cold curing systems, the peel strength increases with increasing temperature up to the glass transition temperature of the adhesives. At the higher temperatures, the peel strength decreases. Hence, a maximum of peel strength is observed near room temperature for adhesive type A and C. The adhesive D shows a nearly linear increase in peel strength up to high temperatures at a relatively high level. The consequent type D can be used for applications over a broad temperature range. Whereas Sofia Teixeira de Freitas and Jos Sinke [16] studied the effect of temperature on two different adhesives. The tests were carried out at the three different temperatures -55℃, room temperature (+22℃), and 100℃ under quasi-static loading. The obtained results are shown in fig. 11 where it is observed that for both adhesives as the temperature was increased the peel load was also increasing as a consequence of enhancement in adhesive strength. The literature summary at different temperatures for the peel test is shown in Table 1.

Every feasible specialized chain is particularized into its corresponding mechanical device in a skeleton drawing. Therefore, the last step is to identify all non-existing designs from the atlas of designs as the new designs.

2.5. Moisture and thickness:

The moisture content in the adhesive as well as around the adhesive affects the adhesive strength. Also, the adhesive film thickness has a major impact on peel resistance. G Hinopoulos and W R Broughton [10] carried out the effect of environmental conditions on the performance of mild steel joints. This was investigated using a sequentially coupled mechanical-diffusion finite element model, which incorporated continuously varying adhesive material properties.

Table 3 Summary of parametric study [10]

Property	Moisture Content	Adherend Stiffness	Adhesive Fillet	Adherend Thickness
Joint stiffness	-	↑	↑	↑
Equivalent stress	↓	↓	↓	↓
Peel Stress	↓	↓	↓	↓
Axial stress	-	↓	↓	↓
Shear stress	-	-	↓	↓
Plastic strain	↑	↑	↓	↓

The results revealed that the distributions of stresses become more uniform along the adhesive layer when the adhesive contains an increased amount of moisture. The peel stresses at the edge of the adhesive fillet were observed to decrease with increasing moisture content. These changes were due to moisture plasticising the adhesive which results in lower adhesive stiffness. The Von Mises equivalent stress distribution along the center line of the adhesive layer is shown in fig. 12 and a summary of parametric study are shown in Table 3.

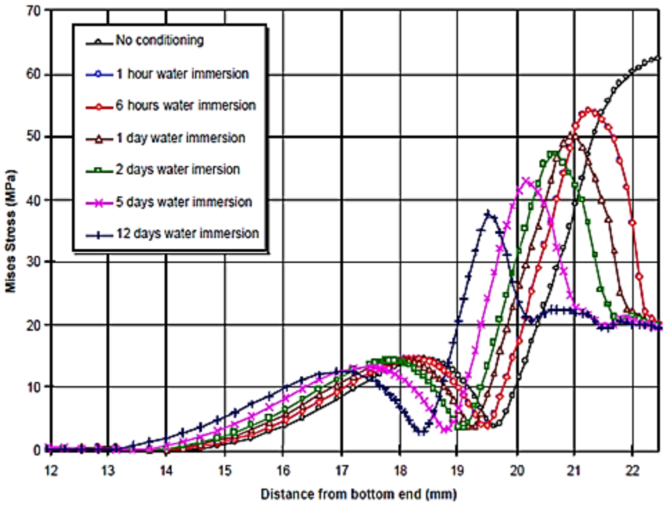


Fig. 12 Mises equivalent stress distribution along the center line of the adhesive layer [10]

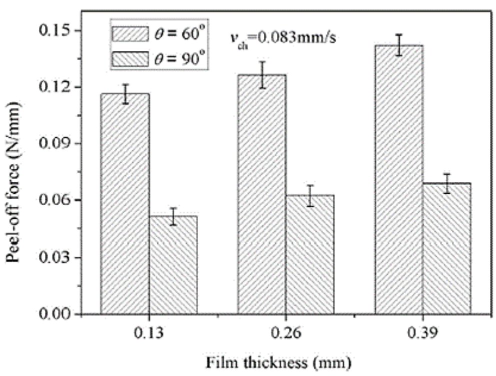


Fig. 13 The influence of film thickness on the peel-off force with a determined peeling rate (peeling: angles 60° and 90°) [17]

The study implies that the stress distributions are sensitive to adherend material properties, adherend thickness, and flange radius with the effect of changes in flange radius being less pronounced. Also, Zhilong Peng, Cong Wang, Lei Chen, and Shaohua Chen [17] carried out a peel test and investigated the effect of thickness on the peel-off force. The results obtained from the experimental test are shown in fig. 13 where it indicated that, as the adhesive film thickness was increased the peel-off force increased.

The tests were carried out for two different angles such as 60° and 90°, which shows that as the peel angle is increased from 60° to 90° peel-off force decreases. The summary of peel testing of materials with the different thickness of adherend and film is shown in Table 1.

2.6. Fracture Mechanism

During the peel test, the failure may be cohesive or adhesive. When the adhesive bond is stronger than the adherend used then cohesive failure occurs. Sometimes the combination of both cohesive and adhesive failure occurs at the interface. Cohesive failure leads to fracture of the adherend. Sofia Teixeira de Freitas and Jos Sinke [18] has carried out peel test on composite and aluminium adherend. During the peel test failure occurs at the interface and pictures of the fracture surfaces of two adhesives scanned by the electron microscope are shown below.

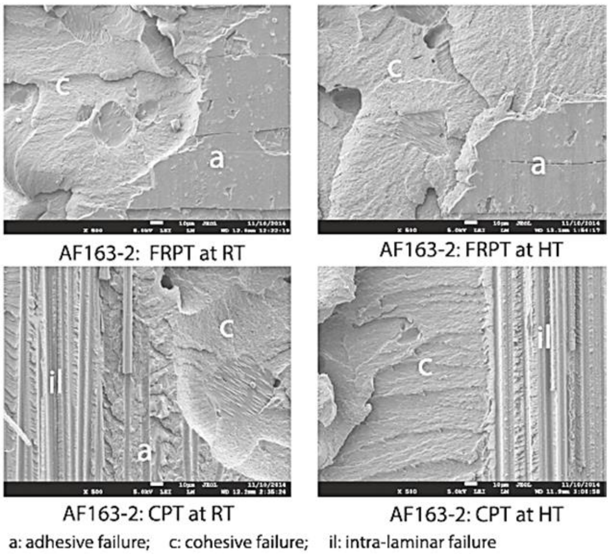


Fig. 14 Peel test carried at room temperature (RT) and high temperature (HT) [18]

Peel tests carried out were FRPT (Floating Roller Peel Test) and CPT (Composite Peel test) at room temperature (RT). AF 163-2 is the adhesive used during the test. The pictures above shows ‘a’ as an adhesive failure, ‘c’ as a cohesive failure and ‘il’ as an intra-laminar failure. Intra-laminar failure of the composite also indicates good adhesion, since the failure is cohesive within the composite adherend and not at the interface. Furthermore, this type of failure also indicates that the intra-laminar strength of the composite adherend is lower than the debonding strength of the adhesive. The above peel tests also concluded that in most cases of good adhesion. Increasing the temperature favors cohesive failure of the adhesive in detriment of intra-laminar failure of the composite. The fracture mechanism of a cohesive failure is independent of the peeling-off adherend (composite or Aluminium).

2.7. Effect of peeling rate on peeling strength

Figure 15 shows the relationship between the peeling rates and the peeling strength. In Figure 15, the unhardened test pieces with a peeling angle of 135° is plotted on the black line with dot marks, while the unhardened test pieces with a peeling angle of 80° is plotted in the red line with triangle marks and the hardened test pieces with a peeling angle of 135° is plotted in blue line with diamond marks.

Increasing peeling strength leads to increasing peeling rate. Peeling rates are positively correlated to adhesive energy, as the adhesive energy required is larger when the cracking velocity increases. Compared to the black curve and the red curve, it is found that increasing the peeling angle leads to decreasing peeling strength. Comparison of the black and blue curves indicated that hardened test pieces gave rise to higher peeling strength values due to greater elastic modulus values.

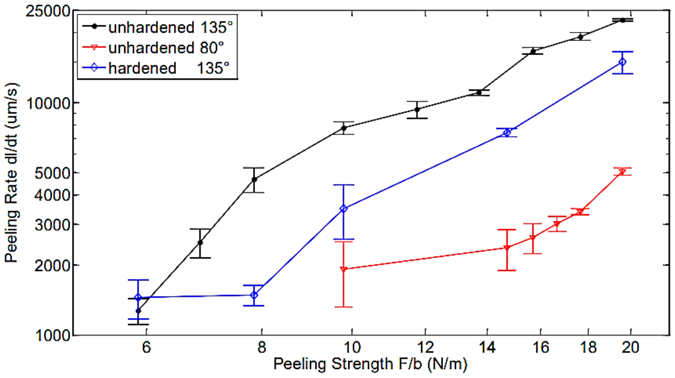


Fig. 15 Relationship between peeling rate and peeling strength. (Peeling angle: 135°or 80°) [19]

3. Discussions and Conclusions

The T-peel test can be performed for materials like mild steel, titanium, aluminum and composites for various types of adhesive material used for joining. The selected specimen should be flexible in order to obtain a uniform bending.

From the literature, it is found that the selection of peel test is based on types of adhesives, types of materials to be joints, and the flexibility of materials. The 90° peel test is used when the upper adherend is flexible and adherend at the bottom is rigid. Also, it can be used when both adherends are flexible. The adherend to be pulled upward must be flexible so that uniform vertical force can be applied to get an accurate reading. The 90° peel test can be used for the adhesives such as epoxy, Al_2O_3.

In case of 135° peel test, the same types of adhesives and materials can be used. For 180° peel tests, the material to be peeled must more flexible so that there is a uniform bending while pulling action is performed.

Peel test can be used successfully to assess the interface adhesion in aged and non-aged conditions and can be used as a fast, easy, and reliable test to study the long-term durability of composite-metal bonded joints. The peel resistance increases as the peel angle changes from 135^0 to 180^0 and this tendency seem to be independent of the adhesive layer thickness.

There is a degradation in chemical bonding because of moisture content in the adhesive. Adhesive bond becomes stronger as the adhesive layer thickness is increased. During the experimental determination of adhesion strength through a peel test, the deformation energy of the peeled foil, plus frictional losses may constitute a significant portion of the total peel energy. When the true adhesion strength is desired, the energy dissipated in bending of the foil has to be found, whether experimentally or analytically, and deducted from the total peel energy to get the net adhesion strength.

While carrying out peel test cracks are formed at the adhesive film and substrate interface. Such cracks are responsible for inducing the film by the formation of crack tip at the interface. When the film is thin then transverse shear is dominating for a crack at the interface. For thick film, the crack will induce the three films only if bending being entirely elastic [20].

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