PROOFED BONDING – A NOVEL METHOD FOR VERIFYING ADHESION IN ADHESIVELY BONDED COMPOSITE REPAIRS

L. Heilmann[1], P. Wierach and M. Wiedemann

Institute of Composite Structures and Adaptive Systems, German Aerospace Center,
Lilienthalplatz 7, D-38108 Brunswick, Germany
www.dlr.de
[1]Lennert.Heilmann@dlr.de

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Abstract
The certification of adhesively bonded structural repairs on civil aircraft requires the proof of limit load capacity for each single bonded joint [1-3]. This is due to the fact that a failure of such a repair bond could lead to catastrophic loss of the airplane. To date, however, no feasible method is available that proper bond quality can be substantiated with. In this paper we present a novel method for process control that can potentially resolve this issue.

1. Introduction

Adhesively bonded repairs on aircraft components made of fibre-reinforced plastics are particularly susceptible to bonding defects. On the one hand, the components are exposed to numerous environmental influences and adhesion-inhibiting media during operation, and on the other hand, the repair process often has to be carried out manually and under adverse conditions. An inadequate adhesive bond, however, cannot always be detected with non-destructive inspection techniques. Therefore, boltless bonded repairs restoring limit load capacity in primary airframe structures can not yet be carried out in compliance with the regulations of the civil aviation authorities EASA and FAA in an economical manner [1-3].

Suggested solutions to overcome this issue include the assessment of the surface properties of the substrate prior to bonding to assure bondability [4], the use of extended non-destructive testing methods to evaluate the bonded joint [5] and the performance of mechanical tests on control specimens to validate the bond strength [6-9]. Nevertheless, no method is currently available that can give evidence that a proper bond has been formed throughout the joint.

In this paper a novel full-field adhesion test is presented that can mechanically verify the strength of repair bonds. By implementing this new method in the repair process, the issue of the unknown bond capacity of the damaged structure may be eliminated.

2. Mechanical validation of repair bonds

In this section, details of the novel method are introduced after a brief review of the state of the art of mechanical bondline control specimens.

2.1. State of the art methods and their limitations

A variety of mechanical test methods suitable for on-part testing are described in literature [6-11]. These methods are based on small test coupons that are bonded onto the part and that are subsequently tested. The coupons can either be applied and tested before the application of the repair patch or the application can take place in parallel to the patch, with the test being performed after the patch installation. These methods assume that the results of the coupon tests are representative for the quality of the entire repair bond.

Despite the various coupon geometries and different stress states generated in the bondline, the cited methods have two inherent drawbacks in common. Firstly, they rely on spot checks. Thus, depending on the number and size of specimens applied, only a relatively small portion of the total bond area is tested. Secondly, they are only applicable for indirect testing. This means that the actual load bearing bondline beneath the repair patch is not tested, but rather a bond adjacent to the patch. If instead the coupons are applied and tested prior to the patch installation as described in [7], then subsequent repeated surface preparation and pre-treatment is necessary which results in a new, untested surface. Therefore, a prerequisite for the ability of indirect methods to reliably detect inadequate bonds is that defects in the bondline are globally present, i.e. that the entire patch installation site and adjacent surface areas exhibit homogeneous bonding properties.

In comparison to metal bonding, where durability and corrosion may be an issue, the primary concern in composite bonding is that the formation of the adhesive bond may be impaired due to improper substrate treatment, contaminants or the influence of pre-bond moisture. In consequence of the manual surface pre-treatment and the ability of fibre-reinforced plastics to absorb media, homogeneous properties throughout the bonded joint can not generally be assumed. Therefore, indirect test methods with coupon spot-checks may not provide sufficient process reliability. Based on these conclusions, the novel method for verifying adhesion in adhesively bonded composite repairs has been developed.

2.2. The principle of the novel test method

The novel test method seeks to eliminate the issue of the unknown substrate bondability by full mechanical validation of the load-bearing interface. In order to do so, a thin fabric is bonded onto the pre-treated patch installation area by means of the repair adhesive. In contrast to peel ply, the applied fabric exhibits a porous structure, which allows high loads to be transferred into the bondline by positive locking (Fig. 1). During the subsequent peeling of the embedded fabric from the component, the adhesive joint is successively loaded until fracture. Any defects present in the bond should be indicated by the mode of fracture or as a deviation from the required peeling force.

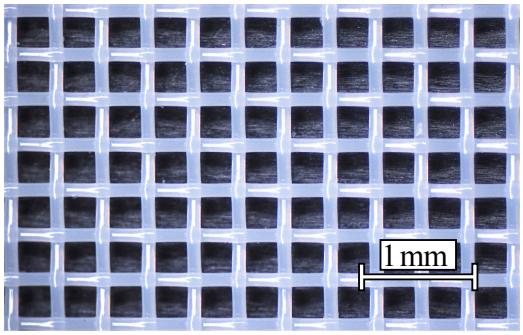


Figure 1. Microscopic image of a plain-weave filter fabric made of polyethylene terephthalate (PET).

In case of a proper bond, the cohesion of the bulk adhesive is quantified and strong adhesion to the component is verified in the entire repair area. During the test, the adhesive layer is fractured, which

results in a clean and chemically activated surface. This way, the test reproducibly generates a thin and well-attached layer of cured adhesive on the actual repair surface of the component, which exhibits a defined bondability (Fig. 2).

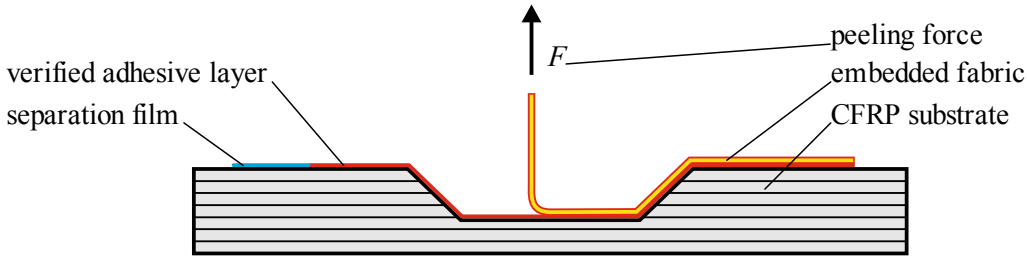


Figure 2. Schematic of the adhesion test in progress (cross-sectional view).

Following the combined detection and activation step, the repair patch is immediately applied onto this fresh substrate under specified environmental conditions and without further surface treatment to exclude potential contamination and other bonding errors (Fig. 3). Indirect mechanical test coupons applied onto surplus verified adhesive coating adjacent to the repair patch may now be representative for the entire repair bond, since the new substrate surface exhibits homogeneous bonding properties.

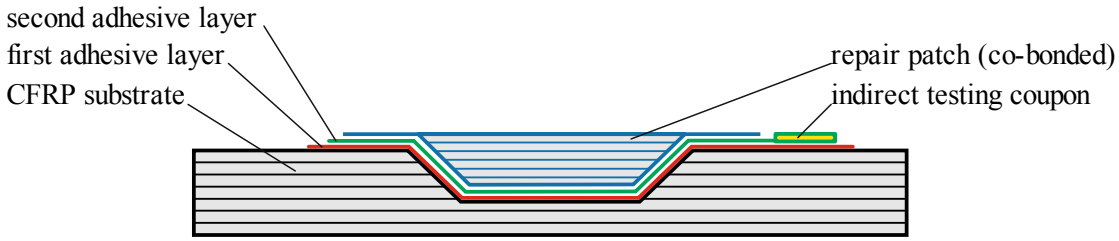


Figure 3. Schematic of an installed repair patch with an indirect test coupon on validated substrate.

3. Practical findings

In this section, we present our findings for the practical realisation of the novel method. All our tests were performed on precured carbon fibre reinforced plastics with an epoxy matrix. The surface activation of the laminates was realised by wet grinding with sand paper under de-ionised water. The adhesive used was a 120°C curing 1C-epoxy adhesive film with a cured ply thickness of 0,2 mm and a non-woven carrier material. Curing was performed under vacuum in a circulating air oven.

3.1. Screening of potential peeling materials

The main requirement for the material to be peeled is to generate high mechanical stress in the adhesion zone of the bond during peeling and to simultaneously produce a thin layer of adhesive with a surface that is well-bondable. In a screening procedure, a large variety of potential materials such as foils and fabrics made from glass fibres, carbon fibres, metals and thermoplastics was investigated. In these tests, small strips of the materials were bonded onto CFRP panels with polytetrafluoroethylene (PTFE) film under one end to form a tab. Subsequently, we manually peeled the strips by coiling them onto a tube and rated the peeling resistance and the generated surface (Fig. 4). However, with non-perforated materials high load transfer into the adhesive layer could not be realised. Moreover, without special surface treatment of the materials, adhesion failure occurred at the interface with the adhesive. This was also the case for medical-grade cleaned thermoplastic and metallic fabrics.

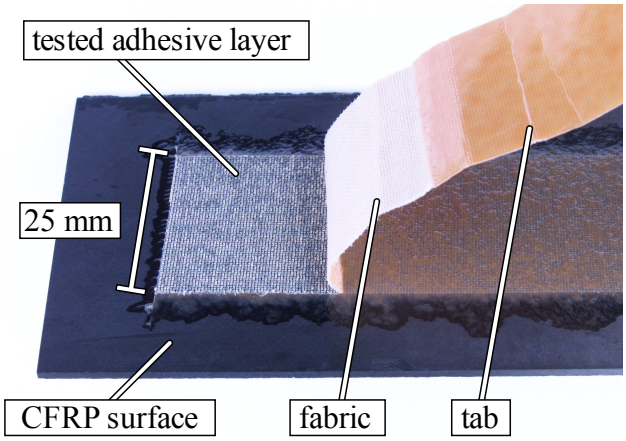


Figure 4. Specimen of the fabric screening tests.

Based on these findings, mechanical interlocking was chosen as a means of introducing the load into the bondline. This can generally be realised with porous materials such as open-meshed fabrics, perforated sheet material or expanded metal. Plain-weave monofilament filter fabrics made from stainless steel or thermoplastics (Fig. 1) appear to be especially suitable for this purpose, since they are produced in high precision and are available in a variety of variants in the required thickness range. Furthermore, these fabrics are readily available in specific cleanliness and surface states for medical and screen printing applications or for the food industry.

3.2. Fracture surface analysis

The equidistant mesh openings of filter fabrics enable a defined load transfer into the bondline. And due to the mechanical interlocking, the adhesive must be fractured in order to remove the embedded fabric from the substrate (Fig. 5). If the adhesive film is applied on top of the filter fabric during production of the bond, then the adhesive can be tested without the influence of the carrier, which is removed together with the fabric and excess adhesive, leaving behind a layer of pure epoxy resin.

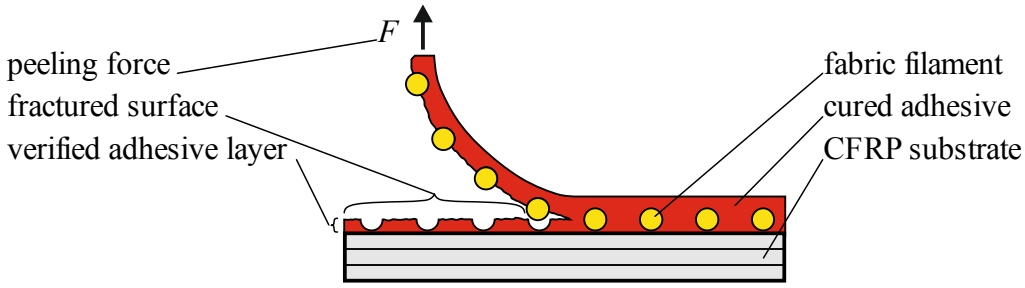


Figure 5. Schematic of the mesh removal process in detail (cross-sectional view).

The surface that is generated upon removal of the filter fabric consists of two distinct types: the elevated squares in the openings of the fabric, and the surrounding filament imprints. By default, the squares exhibit cohesion fracture of the adhesive and are defined in size by the mesh aperture. The type of fracture occurring in the imprint area depends on the interaction between the adhesive and the fabric filaments. For untreated PET fabrics, adhesion failure seems to occur between the filaments and the adhesive (Fig. 6). However, it might also be surface-near cohesion failure in the PET. Therefore, the use of metallic mesh or treated fabrics may potentially be advantageous for the subsequent bonding process.

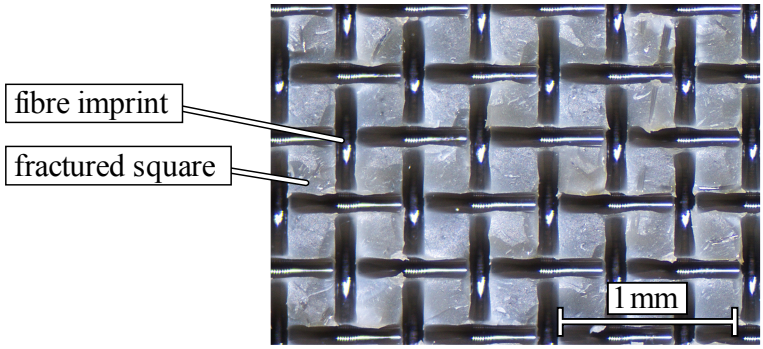


Figure 6. Microscopic image of a fractured adhesive layer after removal of a PET mesh (top view).

The width of the imprints is defined by the filament diameter and the relation between the geometric area of the squares and the projected imprint area is defined by the open area of the filter fabric. The thickness of the adhesive layer remaining on the substrate surface correlates to the fabric parameters and accounts for around two thirds of the fabric thickness, but has not yet been thoroughly studied.

4. Test definition and test results

In this section we define a test procedure and specimen geometry for quasi-static coupon testing of adhesive coatings with filter fabrics and report our findings and first test results.

4.1. Definition of the test method and coupon geometry

The new adhesion test is evaluated and characterised by means of coupon tests. As a basis, the floating roller peel test according to EN 2243-2 [12] has been selected. However, instead of two metallic sheets bonded together, the coupon consists of a single rigid CFRP substrate with filter fabric bonded onto one side. Independent of the positioning of the rollers, the bonded fabric is peeled off at an angle of 90 degrees relative to the substrate due to its low stiffness (Fig. 8).

Experiments have shown that specimens trimmed flush along the long edge may fail during the test, since the fabric can start ripping from the edges. Therefore, it is necessary to seal the long edges of the fabric and to cut the substrate slightly wider than the bonded fabric. For this purpose, weld-sealed fabric ribbons or ribbons with woven edges can be used. In the experiments presented, we sealed the edges of the specimens by means of a PTFE mask (Fig. 7).

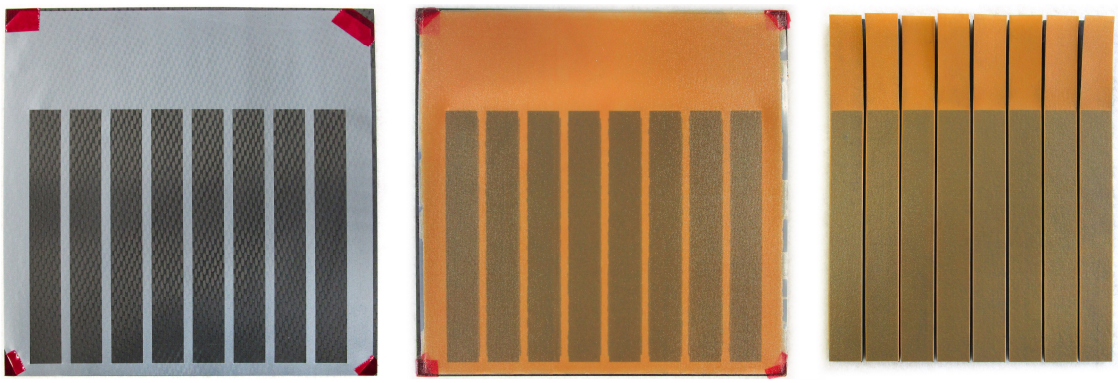


Figure 7. Images of the specimen production process: substrate with PTFE mask (left), bonded specimen panel (middle), ready to test specimens (right).

If the fabric is bonded to the substrate in 0° direction, the width of the foil-sealed edge should account for around 2-3 times the distance between two parallel fabric filaments. If the sealed edge is too narrow, ripping of the fabric is likely. On the other hand, if the sealed edge is too wide, then uneven elongation of the fabric occurs during peeling. In this case, the sealed fabric at the specimen edge exhibits less elongation than the peeled-out fabric in the middle of the specimen. Therefore, the absolute difference in length between the peeled fabric in the middle of the specimen and the peeled fabric at the edge increases in the course of the peeling. This leads to progressive rounding of the crack front, with the crack front lagging behind in the middle of the specimen (Fig. 8).

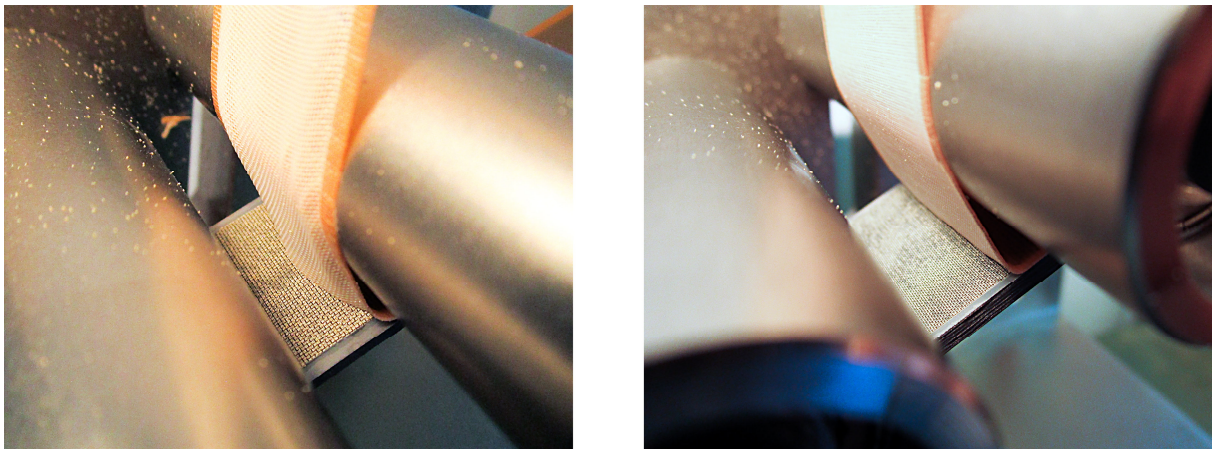


Figure 8. Peeling of a specimen with too wide sealed edge (left) and correct sealed edge width (right).

The rounding of the crack front also reflects in the colour of the fractured surface. Especially for fabrics with a large aperture, the squares fractured in 0° direction exhibit a dark surface, while the squares fractured at a higher angle exhibit a lighter surface. This effect can be observed in the fracture surface of the specimen shown in Fig. 9, which was intentionally produced with too wide edge sealing.

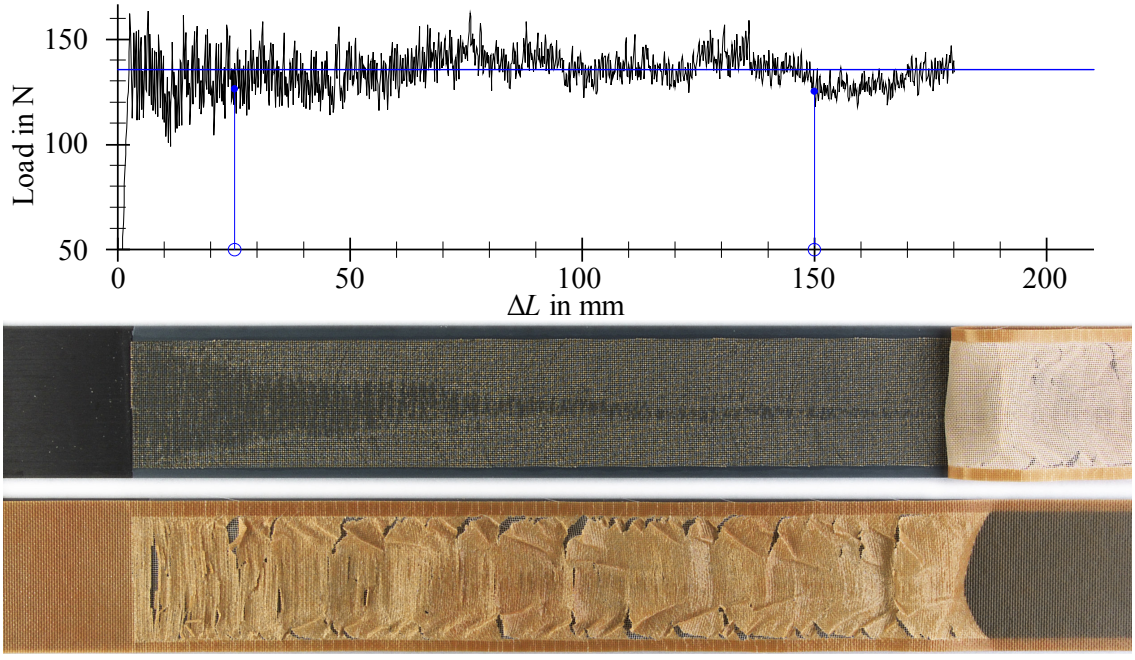


Figure 9. Tested coupon with too wide edge sealing (bottom) and associated peel diagram (top).

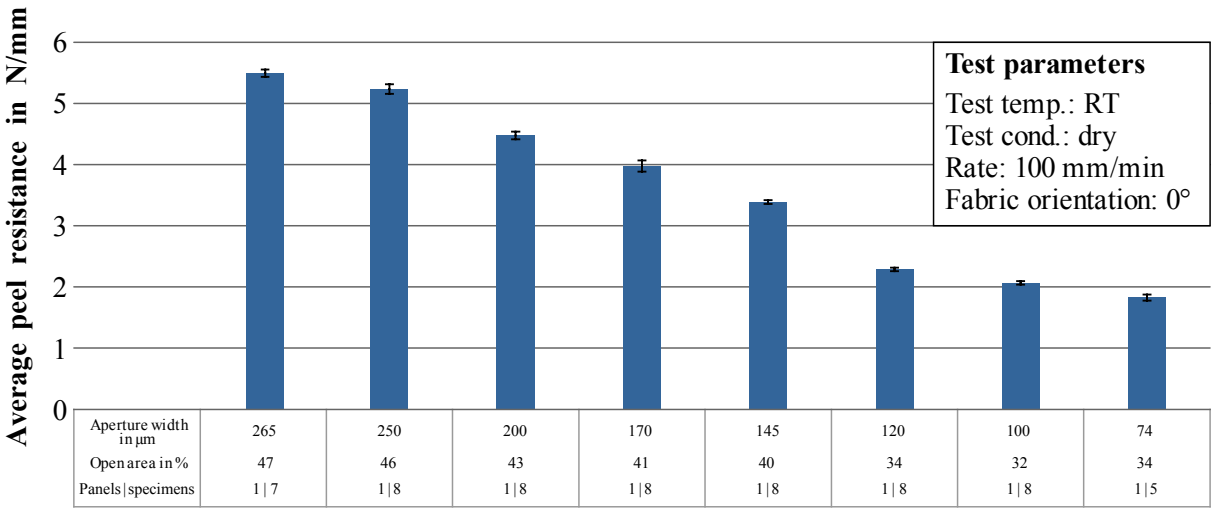
The fracture of adhesive squares in 0° direction leads to sudden crack propagation and results in high positive and negative peaks in the force diagram, accompanied by a crackling noise. The fracture of adhesive squares at a higher angle, i.e. starting from a corner of the squares, appears to be more continuous and leads to reduced peaks of the peeling force. Nevertheless, no distinctive difference in the mean peeling force could be observed for the two types of fracture (Fig. 9). Detailed experiments on the influence of the mesh orientation angle will be conducted.

When peeling untreated thermoplastic fabrics, the sudden fracture of large squares generates small particles of cured adhesive (Fig. 8). These particles do not necessarily have to be removed since they exhibit an entirely fractured surface and are therefore expected to be safely embedded in the adhesive matrix in a consecutive bonding step. That being said, these particles have not been observed when peeling thin fabrics, fabrics with adhesion-promoting surface treatment or metal mesh.

4.2. First test results

The following test results were obtained with an electromechanical testing machine *Zwick 1464* and a load cell *Zwick/Roell Xforce HP* with a nominal force of 2,5 kN. A test fixture according to EN 2243-2 [12] was used and the rate of peeling was set to 100 mm/min. The tests were performed on dry specimens at room temperature.

In the test series presented, the influence of mesh parameters on the peel resistance was investigated. In order to do so, specimens with different PET filter fabrics were produced according to section 4.1 of this article. The fabrics were oriented in a 0° angle relative to the peeling direction.



Aperture width in µm	265	250	200	170	145	120	100	74
Open area in %	47	46	43	41	40	34	32	34
Panels | specimens	1 | 7	1 | 8	1 | 8	1 | 8	1 | 8	1 | 8	1 | 8	1 | 5

Figure 10. Comparison of the peel resistance of different PET fabrics peeled in 0° direction.

The test results presented in Fig. 10 show that with filter fabrics, a high load can be introduced into the bondline and that the peeling resistance is greatly dependent on the mesh parameters. The fabric with an aperture of 265 µm resulted in a peel resistance of 5,50 N/mm, while the fabric with an aperture of 74 µm resulted in 1,83 N/mm. In comparison, the peel resistance of conventional peel ply embedded in an epoxy matrix resin can be expected in the range of 0,05 to 1 N/mm [13]. However, the description of the relationship between the mesh parameters, the properties of the adhesive, the adhesive-to-fibre interaction and the peel resistance is subject to further investigation.

A particularly remarkable result of this test series is the uniformity of the recorded peel diagrams and a resultant variation coefficient of the average peel resistance of below 3 % for each set of coupons, indicating very low scatter.

5. Conclusions

Verification of the strength of repair bonds on substrates with potentially inhomogeneous bonding properties is inconclusive with indirect control specimens alone. In this paper a simple method is introduced that may be applied to fully verify the strength of adhesive bonds on such substrates. The presented research indicates that the practical implementation of this method may be possible by means of porous filter fabrics. First test results show that with these fabrics, a defined layer of proofed adhesive exhibiting a highly fractured surface can be generated on the substrate. Furthermore, a defined high load can be introduced in the bondline, generating peeling stress that may detect existing bonding defects regardless of their cause. For coupon testing, a suitable test method and specimen geometry is defined, which produces results with very low scattering.

Acknowledgments

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