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Review

# Mode I Characterisation in Polymer-Based Sandwich Structures: A Review of Test Methods

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## Abstract

Polymer-based sandwich structures are widely used for their lightweight and tailorable properties, but interfacial failure phenomena often govern their performance. Among these, Mode I skin/core debonding is a critical mechanism that limits structural reliability. This review provides a unified and critical assessment of experimental methodologies for Mode I fracture characterisation, focusing on the ASTM D8637/D8637M standard and alternative setups, including Double Cantilever Beam (DCB), Single Cantilever Beam (SCB), and Climbing Drum Peel (CDP) tests. Alongside, the influence of geometrical factors, processing conditions, and intrinsic polymer properties on Mode I characterisation is detailed. Conventional DCB setups are shown to introduce mixed-mode effects due to asymmetric loading. In contrast, the modified DCB-UBM setup achieves near-pure Mode I conditions at the expense of increased complexity. Comparative analysis indicates that SCB with roller base outperforms the standardised flexible-rod setup, particularly for specimens with non-linear responses. The geometric constraints imposed by ASTM D8637/D8637M are also revisited, demonstrating that reduced-dimension specimens can yield comparable fracture toughness, thereby enabling greater design flexibility. Additionally, while the standard prescribes Modified Beam Theory (MBT) and Area Method (AM) for initiation and propagation, both methods provide comparable propagation toughness under linear conditions. For non-linear systems, alternative data reductions based on CDP concepts, with the SCB-roller base setup, are effective. Mode I characterisation is strongly influenced by polymer properties, as well as processing-induced polymer and interfacial behaviour, requiring interpretation within a structure–property–processing framework. Based on this assessment, key challenges and potential improvements are identified, guiding the development of more accurate and reliable testing methodologies for polymer sandwich structures.

**Keywords:** polymer sandwich structure; Mode I characterisation; single cantilever beam; climbing drum peel; double cantilever beam; skin/core debonding; interfacial failure

## 1. Introduction

Advances in polymer processing technologies, encompassing both thermoplastic and thermoset systems, together with improvements in manufacturing efficiency, are driving the widespread adoption of polymer-based sandwich composites across diverse engineering applications. In such systems, the intrinsic behaviour of the polymer matrix, including viscoelasticity, ductility, and temperature-dependent response, plays a critical role in governing structural performance and failure. Consequently, a thorough understanding of the failure mechanisms governing polymer-based sandwich structures is essential to ensure safe and reliable service.

Polymer-based sandwich structures, consisting of fibre-reinforced skins bonded or welded to lightweight cores, exhibit complex failure mechanisms [1–4]. While thermoset-based systems generally display relatively brittle behaviour, thermoplastic matrices can exhibit significant plastic deformation and rate-dependent response, leading to distinct fracture characteristics. The most significant failure modes, according to Zenkert et al. [5] are: skin failure, skin wrinkling, core shear

failure, localised core crushing, global buckling and skin/core interface debonding. Among different damage modes, debonding at the skin/core interface is a crucial failure mechanism in polymer-based sandwich panels [6–8]. Experimental and numerical studies indicate that interfacial failure is the dominant failure mechanism, as insufficient adhesion between the skin and core compromises the structural integrity and load-transfer capability of the entire panel [7,9–14]. Unlike skin or core failures, this mode is strongly influenced by the manufacturing process, leading to insufficient skin/core wetting, particularly at welded or co-consolidated interfaces, where incomplete fusion, voids, or thermal gradients may be present [7,15,16]. The sensitivity of polymers to temperature, strain rate, and time-dependent viscoelastic effects further contributes to interfacial degradation during service. Other factors that contribute to the failure mode include service temperature and in-service loading over a period of time, due to overloading and impact-initiated debonds [17–20]. Debonding has been linked to various in-service failures, including structural issues in rudders and malfunctions of other aerospace control surfaces [21,22]. Its importance lies in the fact that it often remains barely visible while drastically reducing load transfer efficiency, promoting premature face wrinkling or core collapse. Hence, careful attention must be given to interface design, welding or bonding quality, and damage tolerance assessment with a high level of reliability to ensure safe and dependable performance of sandwich structures across their full operational load envelope.

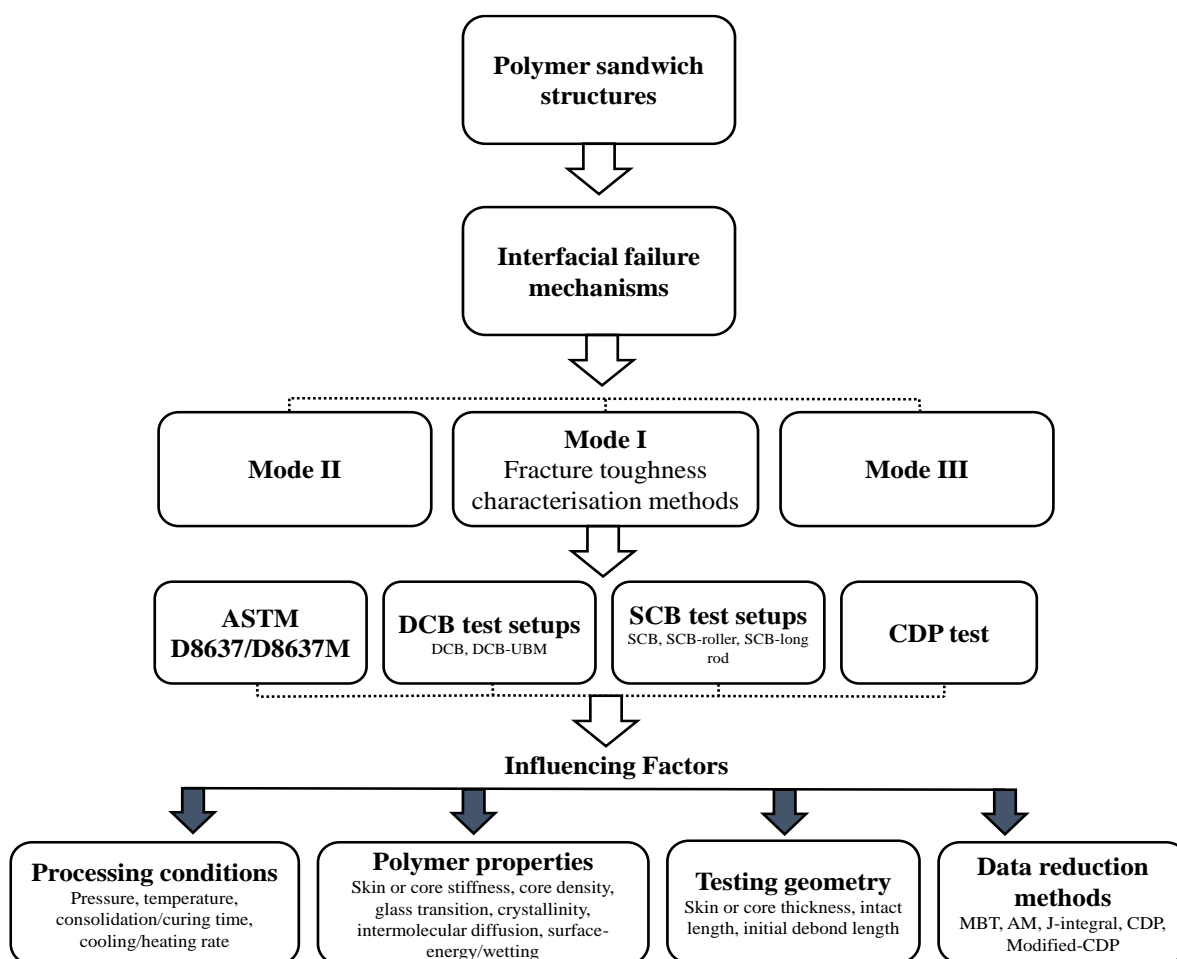
Skin/core debonding occurs when the skin separates from the core in a sandwich structure, which can compromise the structural integrity of the component. Therefore, the strength of a skin/core interface can be quantified by measuring the energy required to separate the skin from the core, commonly referred to as the interfacial fracture toughness or critical strain energy release rate (SERR) [23–26]. Understanding damage tolerance is essential in the design and analysis of sandwich structures, as it involves identifying and predicting crack initiation and propagation. Although standardised fracture toughness testing methods are well established for composite laminates, sandwich composites have historically received much less attention, with formal test protocols for failure modes emerging only in recent years. Skin/core interfacial debonding in sandwich structures can occur in various modes, including debonding under Mode I (opening), Mode II (shear) and mixed-mode (combination of Mode I and Mode II) conditions, each necessitating specific characterisation approaches.

For skin/core interfaces, fracture toughness must be characterised, in principle, over a range of mixed-mode conditions (Mode I + Mode II), as cracks in service are generally subjected to combined opening (Mode I) and shear (Mode II) loading rather than a single pure mode. Nevertheless, most numerical and experimental studies focus on dominant Mode I rather than Mode II or mixed-mode loading conditions [23–32]. This is because Mode I is the most critical and governing fracture mode for skin/core debonding. Ratcliffe et al. [26] and many other researchers [33–35] also claimed that the most critical failure mode at the skin/core crack tip is Mode I. Moreover, in several material systems, the Mode I fracture toughness of skin/core interfaces is typically much lower than the corresponding Mode II, which further promotes Mode I-controlled crack initiation [27,29]. Accurate characterisation of Mode I interfacial fracture toughness is therefore essential for predicting failure, improving design, and ensuring structural safety. Several experimental methodologies have been developed [24], among which ASTM D8637/D8637M [36] has recently been used for evaluating Mode I skin/core debonding resistance. The standard provides guidelines for specimen geometry and data reduction based on beam-theory assumptions, aiming to ensure dominant Mode I conditions during testing of sandwich systems under linear loading.

Alternative and modified testing approaches, including adaptations of the double cantilever beam (DCB) [37–41], single cantilever beam (SCB) [25,26,40,42–45] and peel-test (PT) methods [24,30] were widely used for measuring Mode I in polymer-based sandwich panels. These techniques aim to better replicate dominant Mode I conditions and improve the reliability of fracture toughness measurements. Wiedmann et al. [24] presented a comprehensive review of various Mode I characterisation techniques in thermoplastic sandwich panels, analysing methods such as DCB, SCB, and peel tests for evaluating dominant Mode I conditions at crack tips. However, a systematic and

critical comparison of these approaches with the current standard, ASTM D8637/D8637M [36], is still lacking. In particular, recent advancements in test configurations, such as DCB-UBM and SCB adapted for non-linear loading, as well as emerging sizing methodologies in sandwich structures for Mode I testing, have not yet been collectively assessed within a unified framework. Moreover, the coupled influence of data reduction and geometrical-material parameters on fracture behaviour and measurement reliability remains insufficiently understood.

To address these gaps, this review provides, for the first time, a unified and critical assessment of experimental methods for Mode I characterisation in polymer-based sandwich structures, with a specific focus on the limitations of ASTM D8637/D8637M [36]. Unlike previous studies, this work systematically integrates and compares conventional and emerging test configurations, while explicitly evaluating the influence of data reduction methods, key geometrical-material parameters and processing conditions (such as curing or polymeric chain interdiffusion) relationships on fracture toughness measurements. Furthermore, it highlights the limitations of current standardised approaches under non-linear and realistic service conditions. The pictorial representation of the organisational framework of the review is shown in Figure 1. Based on this comprehensive analysis, the review identifies critical challenges and proposes targeted recommendations for improving testing methodologies. Thereby, contributing to the advancement of more accurate, reliable, and application-relevant standards for Mode I characterisation of sandwich structures.

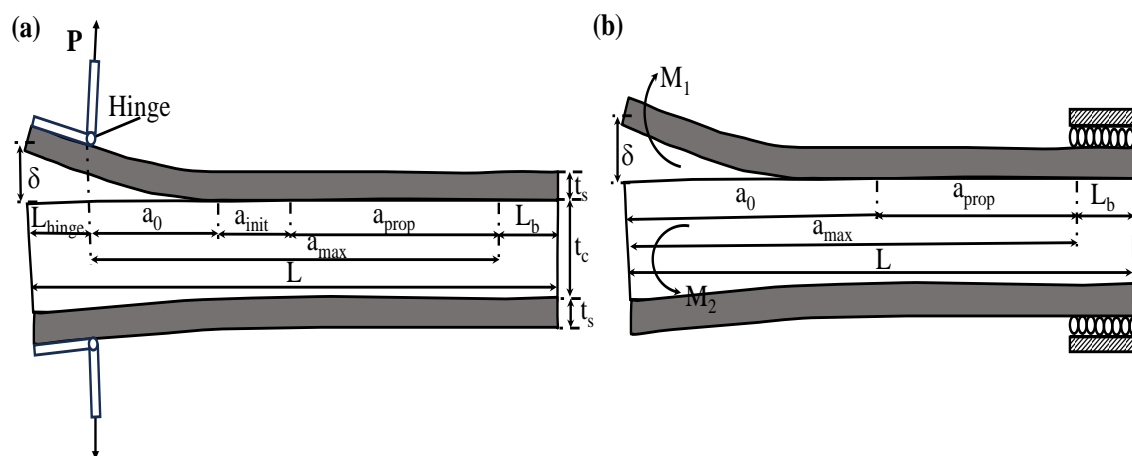


**Figure 1.** Schematic block diagram illustrating the organisation of the present review.

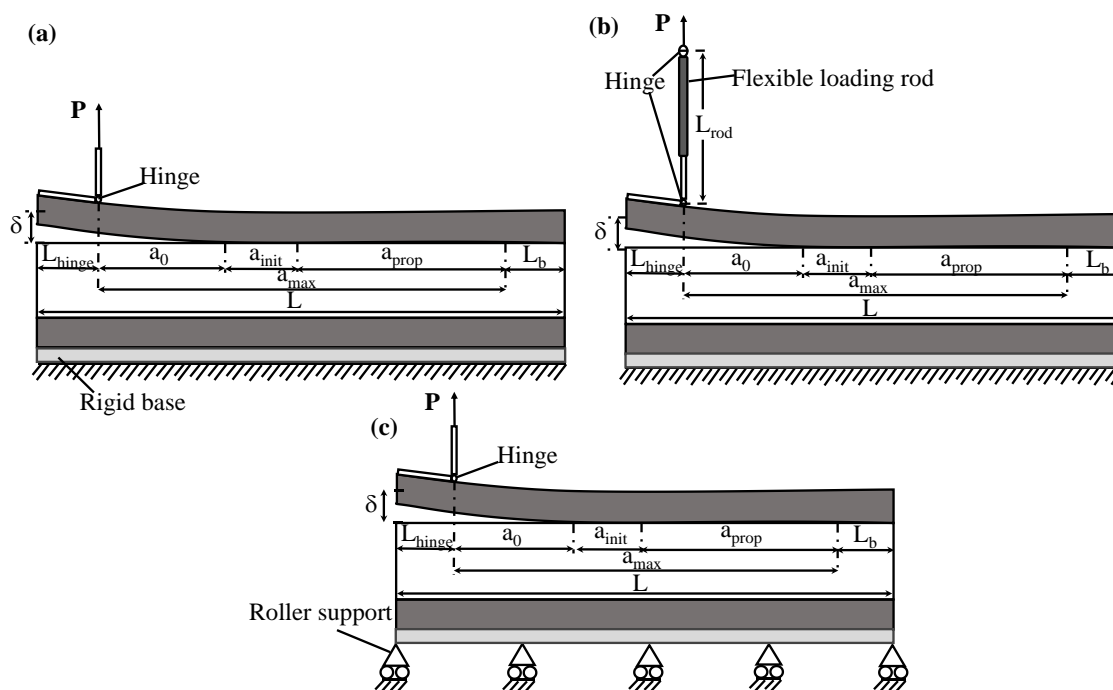
## 2. Mode I Skin/Core Interfacial Debonding Methods

Without claiming completeness in obtaining dominant Mode I in sandwich panels, the most commonly utilised non-standardised and standardised test methods are classified into two: the

cantilever beam methods (shown in Figure 2 and Figure 3), such as double cantilever beam (DCB) and single cantilever beam (SCB), and the peeling test, including the climbing drum peel test, as depicted in Figure 6. A comparative summary of testing configurations, data reduction methods, and governing parameters is presented in Table 1. A more detailed overview of different methods for characterising Mode I interfacial fracture toughness, data reduction schemes and governing parameters is provided in the following subsections.



**Figure 2.** Schematics of different double cantilever beam (DCB) methods: (a) DCB and (b) DCB with uneven bending moment.



**Figure 3.** Prominent single cantilever beam test (SCB) methods: (a) single cantilever beam with rigid base, (b) SCB with long, flexible loading rod and (c) SCB with a rigid roller base (Picture courtesy [43]).

**Table 1.** Summary of experimental methods and parameters for Mode I fracture characterisation in polymer-based sandwich structures.

Category	Method / Parameter	Key Features	Advantages	Impact on characterisation	Applicability
Testing Configuration	DCB	Symmetric beam loading	Simple concept, widely used	Mixed-mode effects due to rotation and eccentric loading	Not suitable for pure Mode I in sandwich
	DCB-UBM	Uneven bending moments	Reduces Mode II contribution	Complex setup and data reduction	Research-level applications
	SCB (rigid base)	Single arm loading with fixed base	Simple setup, low Mode II vs DCB	Load angle variation → mixed-mode	Limited Mode I dominance
	SCB (long, flexible, rotatable rod)	Controlled boundary conditions	Achieves dominant Mode I	Requires careful setup design	ASTM D8637
	SCB (roller base)	Single arm loading with movable base	Achieves dominant Mode I	Requires careful setup design	Suitable for linear/non-linear loading, Basics of ASTM D8637
	CDP	Peel-based loading	Suitable for thin/compliant skins	$G_{Icp}$ changes with drum diameters	Parametric optimization purposes
Data Reduction Methods	MBT	Compliance-based (LEFM)	Suitable for initiation and propagation of toughness	Sensitive to crack length, conservative	Linear elastic systems
	AM	Energy-based (dU/dA)	Simple, robust for propagation	Requires unloading, not instantaneous	Linear elastic systems

	J-integral / VCCT	Numerical methods	Handles non-linear behaviour	Requires modelling	Advanced analysis
	CDP/Modified-CDP expression	Peel mechanics	Suitable for non-linear behaviour	Less standardised	Compliant skins, use with SCB-roller base and CDP setups
Geometrical/Material Parameters	Skin thickness/modulus	Controls bending stiffness	Thickness increase promotes higher stiffness	Low values affect fracture toughness	Critical design parameter
	Core density/modulus	Affects stiffness mismatch	Influences crack propagation	Affects toughness values	Critical design parameter
	Initial debond length	Crack starter	Controls energy release	Large sizes required in ASTM	Design constraint
	Intact length	Load transfer region	Ensures Mode I dominance	Leads to large specimens	Design limitation

### 2.1. Double Cantilever Beam Methods

Mode I debonding is an interfacial failure mode in sandwich structures, in which the skin peels away from the core surface under tensile or opening-load conditions acting perpendicular to the skin/core interface. Under bending, tensile normal stresses develop in the loaded skin and produce peel stresses at the skin/core interface, leading to local crack opening and progressive interfacial separation. However, the chances for attaining a dominant Mode I condition at the crack tips are challenging. Test methods designed to apply predominantly Mode I loading to the skin/core interface may still generate a secondary Mode II component when used for sandwich structures. According to Hutchinson and Suo [46–48], this behaviour is attributed to the elastic mismatch between the core and skins, as well as to asymmetries in specimen geometries and in the applied loading conditions. As a result, the interfacial crack experiences mixed-mode loading, which is commonly described in terms of a mode-mixity phase angle or a mixed-mode ratio.

The DCB method for sandwich panels is derived from the ASTM D 5528 standard for monolithic polymer composite materials. The DCB configuration was modified for sandwich structures by Prasad and Carlsson [49] as shown in Figure 2a. Unlike the standard DCB specimen used for monolithic polymer composites, in sandwich structures, the pre-crack is not located at the mid-plane of the specimen thickness, but is instead positioned along the interface between the core and the upper skin, as shown in Figure 2a, b. Although significant attempts have been made to modify the DCB method for application to sandwich structures [23,29,37,50–53], important difficulties persist. In

particular, crack growth during the test causes a progressive rotation of the specimen around the bottom load application point [51,54] and bending moments are induced in the core due to the eccentric application of the load [26,45].

Hence, the DCB test method applied to sandwich structures involves a non-negligible Mode II component at the crack tip due to the asymmetric loading and material property mismatch [33,47,55]. It is widely accepted that a bi-material interface, such as the skin/core polymer interface in sandwich structures, results in coupling between normal and shear deformations [46,47,56,57]. Burlayenko et al. [29] examined the debonding behaviour of sandwich structures comprising glass fibre-reinforced epoxy skins and PVC foam cores using DCB and SCB configurations. Their experimental results, supported by finite element analysis, revealed significantly higher fracture toughness for the DCB method, which was attributed to pronounced Mode II fractions developed by the asymmetric loading. Moreover, they showed that shear stresses at the crack tip can induce crack kinking into the core. This result confirms earlier reports in which crack kinking in DCB specimens was associated with positive shear stresses (*i.e.*, crack kinking into the core) at the crack tip, which arises from asymmetric loading conditions and elastic mismatch between the skin and core materials [33,49,58]. Based on these findings and their evaluation against the criteria for dominant Mode I sandwich testing procedures, the DCB configuration is deemed inappropriate for Mode I-dominated determination of the fracture toughness of the skin/core interface in polymer-based sandwich structures.

Cantilever beam test methods, except the DCB with UBM, consist of applying a load  $P$  to debond a skin from the core of a sandwich specimen with length  $L$ , width  $b$ , and total thickness  $h$ . Before testing, a pre-crack of length  $a_0$  is introduced at the skin/core interface. The load  $P$  is applied through a piano hinge or connecting blocks, which may be adhesively or mechanically attached to the specimen. As the applied load  $P$  and the load-point displacement  $\delta$  increase, crack initiation occurs, followed by stable crack propagation along the interface.

The fracture toughness, expressed in terms of the SERR, can be evaluated using several data-reduction methods [59,60], including the modified beam theory (MBT) [61–64], the compliance calibration (CC) method [65,66], the compliance-based beam method (CBM) [59], and the elastic foundation analysis (EFA) method [37,67,68]. Kanninen [69] first developed the EFA approach for isotropic materials, and later extended it to orthotropic materials by Williams [70]. However, all these methods are valid only when the assumptions of linear elastic fracture mechanics (LEFM) are satisfied, particularly small deflections and linear elastic material behaviour [63,71].

Among these approaches, the MBT, originally proposed by Williams [70], is widely used due to its simplicity and reliability. For Mode I fracture of skin/core interfaces in DCB specimens, Shivakumar et al. [60] recommend MBT, which requires measurement of the specimen width  $b$ , applied load  $P$ , load point deflection  $\delta$ , and crack length ( $a$ ) during testing. The Mode I SERR is then evaluated using the MBT expression for  $G_I$ .

$$G_I = \frac{3P\delta}{2b(a+\Delta)} \text{ J/m}^2 \quad 1$$

where  $\Delta$  is the effective crack length correction factor that accounts for root rotation and shear deformation at the crack tip. Here,  $\Delta$  can be determined from the cube root of the compliance  $C^{1/3}$ , measured during testing, together with the corresponding crack length,  $a$ .

DCB with Uneven Bending Moments (DCB-UBM) is used for interfacial fracture testing under controlled mode mixity, primarily to measure Mode I dominant and mixed-mode (Mode I + Mode II) fracture toughness. The DCB-UBM specimen was first introduced by Sørensen et al. [38] for the determination of fracture toughness in monolithic composites. Later, Lundsgaard-Larsen et al. [41] extended it to sandwich structures to overcome the drawbacks of the existing DCB testing method for sandwich panels. The test configuration comprises the DCB specimen loaded with uneven bending moments. The fracture specimen principle of DCB-UBM in the sandwich panel is depicted in Figure 2b, in which the crack flanks or specimen edges are subjected to pure moments ( $M_1$  and  $M_2$ ). For instance, dominant Mode I loading is obtained by applying opening moments with  $M_1 > 0$  and  $M_2 < 0$ . To ensure a constant mode mixity during fracture propagation, the two applied moments

must be actively controlled such that the moment ratio ( $MR$ ) remains constant throughout the test. When equal moments of opposite sign are applied (e.g.,  $M_1/M_2 = -1$ ), the loading is dominated by crack opening in the normal direction, corresponding to Mode I fracture. Conversely, when moments of the same sign are applied, shear sliding along the crack interface prevails, leading to Mode II-dominated behaviour. Accordingly, the mode mixity can be prescribed by varying the ratio of the applied bending moments,  $MR = M_1/M_2$ . Since this ratio is kept constant throughout the test, the DCB-UBM configuration represents a steady-state fracture specimen. As a result, both fracture toughness and mode mixity, expressed as the phase angle  $\psi$ , remain constant during crack propagation, ensuring stable Mode I-dominated fracture conditions [72–74]. Hutchinson and Suo [46] defined the mode-mixity phase angle,  $\psi$ , as a parameter characterising the proportion of Mode II relative to Mode I loading at the crack tip. In this definition,  $\psi = 0^\circ$  corresponds to pure Mode I conditions, while  $\psi = 90^\circ$  denotes pure Mode II loading.

A DCB-UBM test rig, capable of applying pure bending moments, is utilised to maintain a predominantly Mode I loading condition at the crack tip and to minimise Mode II contributions [72]. Several methods exist to maintain a constant moment ratio,  $MR$ , and each method is specific to the construction of the test rig. Hence, bending moments can be applied to the crack flanks through wire-and-roller systems [38], steel band-roller fixtures [75], rigid linkage mechanisms [76], or directly via independent torsional actuators [39,72], all of which represent different mechanical implementations of the same DCB-UBM loading principle. Berggreen et al. [39] developed a DCB-UBM test configuration, in which pure bending moments are applied directly to the crack flanks using independent torsional actuators. This setup enables controlled crack propagation along the glass-fibre skin/PVC H45 foam core interface. A constant mode-mixity was maintained throughout the experiments, enabling fracture toughness to be evaluated over a range of phase angles. In all cases, crack growth was confined to the skin/core interface. Under Mode I-dominated loading, the measured fracture toughness showed good agreement with values reported in previous studies employing alternative test configurations.

A similar experimental configuration was utilised by Vishnu et al. [72] for fracture testing of aerospace-grade Nomex<sup>®</sup>- and Kevlar<sup>®</sup>-based honeycomb core of different grades of sandwich panels with carbon fibre-reinforced polymer skins. Mode I-dominated fracture toughness values measured along the longitudinal (L) and transverse (W) directions were compared across the different core densities (32, 64, and 96 kg/m<sup>3</sup>). The highest Mode I toughness (1511 J/m<sup>2</sup>) was obtained for the 96 kg/m<sup>3</sup> core in the transverse direction, while the lowest value (872 J/m<sup>2</sup>) was recorded for the 32 kg/m<sup>3</sup> core in the longitudinal direction.

The fracture characterisation is performed within the framework of Linear Elastic Fracture Mechanics (LEFM) [39,72]. When employing the DCB-UBM specimen for sandwich composites, it is critical to avoid competing failure mechanisms such as plastic yielding, damage dissipation, excessive deflections, and large rotations, as these violate LEFM assumptions and compromise the validity of the measured fracture toughness. In particular, sandwich specimens with very thin skins are susceptible to large bending deformations under applied moments, which can invalidate the test results. To mitigate these effects, stiff reinforcement layers, typically high-strength steel, are bonded to the skins. These reinforcements reduce beam stresses and deflections while enabling reliable end-tab attachment using screws. The steel doublers are designed to remain fully elastic before crack propagation. The fracture toughness of a DCB-UBM specimen is evaluated using the J-integral, which under LEFM equals the energy release rate ( $G$ ) [39,41]:

$$G = J$$

2

The DCB-UBM specimen is modelled as three beams: (i) the debonded (upper) beam consisting of the top skin with or without a top doubler, contributing  $J_1$ ; (ii) the substrate (lower) beam comprising the core, bottom skin, and optional bottom doubler, contributing  $J_2$ ; and (iii) the intact base region ahead of the pre-crack, contributing  $J_3$ . The total J-integral is the sum of contributions from these three regions:

$$J = J_1 + J_2 + J_3$$

3

Here, the index  $i = 1, 2, 3$  correspond to the debonded beam, substrate beam, and base beam, respectively. Each contribution  $J_i$  is calculated from the applied bending moments  $M_i$ , the elastic modulus  $E_i$ , the beam stiffness terms  $A_i$ ,  $B_i$ ,  $D_i$ , and a geometric factor that depends on the layer thicknesses and their positions relative to the neutral axis ( $y_{NA}$ ). The J-integral for each beam is given by:

$$J_i = \sum_{p=1}^{10} \frac{E_i M_i^2}{6 (A_i D_i - B_i^2)^2} [A_i^2 (y_{p-1}^3 - y_p^3) - 3 A_i B_i (y_{p-1}^2 - y_p^2) + 3 B_i^2 (y_{p-1} - y_p)] \quad 4$$

The extensional, coupling, and bending stiffnesses of each beam are determined from the material properties and geometry of each layer as  $A_i = \sum_k E_k h_k$ ,  $B_i = \sum_k E_k h_k (y_k - y_{NA})$ , and  $D_i = \sum_k \frac{E_k h_k^3}{12} + \sum_k E_k h_k (y_k - y_{NA})^2$ . Where  $E_k$  and  $h_k$  are the elastic modulus and the thickness of the layer  $k$ , and  $y_{NA}$  is the neutral axis of the corresponding beam.

Although the DCB with uneven bending moment (DCB-UBM) predominantly induces Mode I loading at the crack tip, the J-integral-based data-reduction scheme, while providing a rigorous framework for evaluating fracture toughness under pure moments, relies on linear elastic beam theory. Consequently, it is highly sensitive to material properties, geometric parameters, and the determination of the neutral axis [39]. Moreover, the DCB-UBM fixtures require specialised moment application and have limitations in terms of achievable mode mixity and practical loading arrangements, indicating that the experimental setup is complex and sensitive to alignment and boundary conditions [39,73]. Owing to these criticalities, the applicability of the DCB-UBM configuration becomes restricted.

## 2.2. Single Cantilever Beam Methods

In search of a facile and dominant Mode I configuration, many researchers have developed and studied different variants of a single cantilever beam (SCB) [77], as shown in Figure 3. These setups offer simpler fixturing, improved stability during crack growth, and easier instrumentation compared with DCB-UBM.

Varying peel angles by tilting the specimen at an angle,  $\theta$ , and loading it with a vertical force  $P$  was performed using the tilted sandwich debond (TSD) variant [78]. However, this configuration often introduces mixed-mode loading and instability in crack propagation, limiting its suitability for reliable Mode I characterisation. Based on extensive experimental and analytical studies by Adams [33] as well as Ratcliffe et al. [26], the SCB configurations have emerged as the most promising approach compared to the TSD and DCB methods for characterising Mode I fracture toughness. Burlayenko et al. [29] investigated the Mode I dominance of DCB and SCB (with rigid base) test methods for sandwich structures with varying material and geometrical parameters. Based on their findings, the SCB configuration proves to be significantly more effective in promoting Mode I-dominated fracture compared with the DCB test. Furthermore, in addition to the dominant Mode I character, the SCB method shows only a limited propensity for crack kinking into the core, a behaviour also reported by several other authors [33,50,74]. The SERR for this configuration can be calculated using data-reduction methods analogous to those employed in the DCB test [71,79].

The SCB test is a cantilever-type fracture configuration in which one free skin of a sandwich panel is debonded from the core while the opposite skin is constrained against a rigid base plate, as illustrated in Figure 3a. A load is applied to the free skin through a hinge or loading block, causing the crack at the skin/core interface to open primarily in Mode I. However, as the crack propagates during testing, the position of the load relative to the crack tip changes continuously. Consequently, the applied loading angle is not fixed but varies throughout the test. This variation generates shear stresses or horizontal load components within the core and gives rise to a Mode II contribution at the crack tip, which depends on the local crack-tip orientation [78–81]. Charalambides et al. [82] and

Cantwell [79] reported that apart from the pure Mode I, a dominant Mode II contribution locally occurs in an SCB on a fixed base subjected to a bending moment. As a result, specific measures are implemented to maintain a fixed position of the crack tip relative to the load displacement axis of the testing machine throughout the test. Consequently, a modification of the conventional SCB configuration is necessary to attain a dominant Mode I condition at the skin/core interface. To attain this, two modified SCB approaches have been proposed in literature: one utilises a movable base carrier (Figure 3b), while the other employs a long, flexible, and rotatable loading rod (Figure 3c).

In SCB with a movable base carrier setup, the sandwich specimen is attached to a rigid steel base plate mounted on a horizontally movable carriage, as shown Figure 3b. The vertical load is applied at the free end of the cantilever through a hinge or loading block. Any horizontal components of the load cause movement of the sliding carriage, effectively eliminating shear forces at the crack tip. This ensures that the crack experiences primarily dominant Mode I opening, reduces the risk of crack kinking, and improves the accuracy and repeatability of fracture toughness measurements. This setup was developed by Cantwell and Davies [83] and employed by Glaessgen et al. [80], where the horizontal movement of the base carrier ensures that the applied load acts purely in the vertical direction, as any horizontal load components would result in displacement of the carrier. The same SCB configuration was also employed by Irven et al. [27,84] to investigate Mode I-dominated skin/core debonding in sandwich structures with carbon-fibre-reinforced epoxy (DGEBA) skins modified with CSR and silica nanoparticles and epoxy foam cores. While the sliding base carriage effectively minimises Mode II loading from the test setup, their results revealed that a negligible local Mode II component still arises, leading to crack propagation into the core. This behaviour was attributed to the mismatch in material modulus between the skin and the core, which promotes local shear stresses at the crack tip.

To reduce the complexity associated with the SCB configuration using a moving carriage, McGarva et al. [81,85] introduced an SCB setup with a long, flexible, and rotatable loading rod. In this arrangement, the long, flexible, and rotatable loading rod connects a hinge mounted on the SCB specimen skin to the testing machine, allowing the load to remain nearly vertical throughout testing, thereby minimising horizontal components (Mode II) and maintaining predominantly Mode I loading at the crack tip. A schematic representation of the SCB with a long, flexible load rod is displayed in Figure 3c. In this configuration, the SCB specimen is fixed to a rigid base plate, and the rotatable rod allows the vertical load to remain aligned with the crack opening throughout testing, accommodating deflections without introducing horizontal forces. Wilk [71] examined the applicability of SCB with a long, flexible loading rod for the evaluation of Mode I-dominated debonding in carbon epoxy/aramid honeycomb sandwich panels under quasi-static and fatigue loading. Fracture toughness was evaluated using both MBT and the area method, showing that the rotatable-rod SCB provides reliable Mode I characterisation with a simple fixture. In comparison, the area method is more robust for propagation due to difficulties in visualising crack lengths in honeycomb cores. The debond propagated predominantly by cohesive fracture within the core, occurring very close to the core/skin interface, just beneath the adhesive bond line. No evidence of crack kinking into the core was observed during propagation; however, the resulting fracture surface exhibited a rough and irregular morphology, indicative of non-uniform crack advance within the core material. A similar crack deviation into the core, attributed to the mismatch in skin and core moduli, was also reported by EASA (European Union Aviation Safety Agency) [77]. This deviation was observed even when a long, rotatable loading rod SCB configuration was employed, which is intended to maintain a nearly vertical load path throughout testing. This introduces a negligible Mode II component at the crack tip, promoting crack deflection into the core rather than maintaining a pure interfacial Mode I failure. However, by providing a considerably simpler test apparatus, the use of a long rotatable rod minimises Mode II loading and suppresses shear development in the core [26]. This advantage has motivated Ratcliffe et al. [26,45] and Adam [33] to adopt and further develop this setup for interfacial bonding characterisation and for the standardisation of Mode I interfacial fracture toughness testing of sandwich structures.

Although the challenges associated with the test setups are largely minimised by using an SCB configuration with either a moving carrier or a long, flexible loading rod, experimental results can still be significantly affected by specimen geometry, material properties, and local heterogeneities at the skin/core interface, such as variations in adhesive thickness, fibre distribution, or core cell structure. The influence of various geometric parameters, such as specimen geometry, skin thickness, core thickness, and core density, on the fracture behaviour of sandwich structures has been extensively studied by various researchers [58,86]. Maleki and Toygar [58] reported that core density significantly influences the measured SERR in GFRP sandwich structures with PVC foam cores tested using the SCB method. Their results showed that sandwiches with higher-density cores exhibit increased SERR values, indicating improved resistance to skin/core debonding. Moreover, Viana and Carlsson [86] provide further support for this observation, as they also reported an increase in SERR with higher-density foam core sandwich structures, which inherently introduces a Mode II component. The increase in SERR with higher-density cores is attributed to the greater stiffness of the core, which reduces local deformation and ensures that more of the applied energy is directed toward opening the interface. Xue et al. [12] performed a parametric study to assess the influence of fracture toughness, characteristic length, skin thickness, and fracture-related parameters on the mechanical response of the sandwich structure. The study showed that higher fracture toughness increases fracture load, displacement, and interfacial strength, particularly at smaller characteristic lengths, while increasing the characteristic length reduces fracture load and interfacial stiffness, increases fracture displacement, and extends the damage zone. Thicker skins enhance bending and shear stiffness, resulting in higher interfacial strength and longer damage zones, whereas increasing core thickness slightly reduces interfacial strength with little effect on damage length. Similar findings of an increase in skin/core interfacial fracture toughness with the increase in skin thickness were reported by Amal et al. [43]. This trend was found to be similar across all the SCB configurations. Likely, Burlayenko et al. [29] found that the specimens must produce only negative phase angle values, which decrease with increasing skin thickness; this trend is consistent across the full range of pre-crack lengths and material combinations. Therefore, thicker skins reduce the magnitude of negative phase angle, helping maintain Mode I dominance across different crack lengths and material combinations. Adam [33] through both experimental and numerical studies, demonstrated that the use of a skin doubler to reduce skin deflection can alter the crack propagation path and affect the measured fracture toughness. Therefore, the use of skin doublers in SCB specimens with thin skins is not recommended. Denning et al. [87] demonstrated that failure mode strongly affects fracture toughness and resistance curves in sandwich structures. Core failure produces smooth, stable crack growth with low scatter, while pullout and adhesive failures show abrupt propagation and higher variability. Core type, cell size, and density influence the energy required for crack propagation, with higher-density cores requiring more energy. Also, changing the skin thickness can alter the failure mode of the material system, leading to significant differences in fracture toughness. Thicker skin specimens generally exhibit higher fracture toughness, as reflected in the resistance curves, although some systems show slightly rising or falling curves due to changes in failure mode and increased material nonlinearity. These findings emphasise the need to optimise core and skin properties in SCB specimens to achieve Mode I-dominated, reproducible measurements. Similar findings were also reported by several others [40,45,64,74]. Saseendran et al. [74] conducted a numerical parametric study to investigate local Mode mixity in sandwich structures, varying geometrical parameters (skin thickness and intact length) and material properties (skin-core modulus and Poisson's ratio). They found that skin modulus, Poisson's ratio, and thickness strongly influence the mixed-mode conditions, while the intact length significantly affects the phase angle ( $\psi$ ), particularly for longer cracks in shorter specimens. Similarly, Burlayenko et al. [29] used finite element analysis to examine SCB and DCB polymer specimens and reported that both specimen types are highly sensitive to changes in material properties, geometrical parameters (skin thickness, initial debond and intact length), and boundary conditions, affecting both Mode I and Mode II fracture responses. Amal et al. [44] studied the influence of different intact ( $L_b$ ) and initial debond ( $a_0$ ) lengths on SCB Mode I fracture

toughness. It was found that there exists a significant influence of the  $L_b$  and  $a_0$  on the Mode I fracture toughness of polypropylene (PP)-based thermoplastic sandwich panels.  $L_b$  and  $a_0$  dimensions lower than the proposed sizing constraints showed deviation from the dominant Mode I condition.

Apart from these geometrical influences, polymer-dependent properties of the sandwich systems significantly affect the Mode I fracture toughness. Various polymer-dependent factors affecting the Mode I characterization in sandwich structures were tabulated in Table 2. Processing temperature and pressure plays a critical role in determining the interfacial fracture behaviour of thermoplastic sandwich structures. As detailed in one-stage non-isothermal compression moulding process [43,44], an increase in press plate temperature from 30 °C to 50 °C was shown to enhance the measured Mode I fracture toughness by approximately 19% under dominant Mode I conditions in PP-based sandwich panels. This improvement is attributed to enhanced skin consolidation resulting from reduced cooling rates, which increases skin bending stiffness and modifies the global structural compliance in SCB configurations. Consequently, the energy release rate and the measured  $G_{ICP}$  are directly affected. Also, a better interdiffusion of molecular chain between the skin-core polymer resulted in cohesive fracture under Mode I loading. Ultrasonic welding parameters strongly influence interfacial fracture behaviour through their effect on polymer melting, flow, and interdiffusion at the interface of PP thermoplastic sandwich structures [88]. It was found that higher horn pressure (0.39 MPa) enhances interfacial contact and polymer chain mobility, resulting in cohesive failure within the core, indicating improved bonding. However, lower 0.29 MPa resulted in a higher value for Mode I fracture than 0.39 MPa associated with crack propagation through the skin. Similarly, with respect to welding speed, a lower speed of 4 mm/s promotes cohesive failure in the core and therefore provides a more reliable measure of skin/core interfacial toughness. In contrast, at 5 mm/s, although higher fracture toughness values (~51%) are observed, failure occurs within the skin due to delamination. Thus, the measured values reflect the fracture resistance of the PP skin rather than the true skin/core interfacial bond strength. Furthermore, Paolo et al. [89] observed that temperature variations across the steel mould during the manufacturing of PP sandwich panels through an in-situ physical foaming and skin/core bonding influenced the Mode I characterization. Gas diffusion into PP molten polymer across the mould walls occurred at higher rate due to the increased temperature. This leads variations in cell morphology alongside of the mould walls of the polymeric foam core with low dense, larger cells, while at the center has a high dense, smaller cells. As a consequence of the Mode I test, the crack propagated through the weaker skin/core interface having a low dense, larger cell foam core. This affected the Mode I fracture toughness of the in-situ foamed and skin/core bonded sandwich panels. As reported by Viana et al. [86], resin or adhesive penetration into partially open core cells forms a dense interphase layer that resists crack propagation under Mode I loading, promoting failure within the core rather than along the interface. Additionally, the bimaterial interface drives crack kinking into the compliant core. Although not explicitly stated, this behaviour is governed by wettability and surface energy, which control resin infiltration and interfacial bonding quality. Similarly, brittle polymer foam structure and skin/core interface affecting the Mode I fracture behaviors were reported by [27,83,84]. These findings highlight that processing-induced variations in polymer properties can significantly influence fracture characterisation, demonstrating that measured toughness values reflect not only interfacial adhesion but also changes in structural stiffness and energy distribution. Therefore, the fracture toughness values alone cannot rely to determine the performance of polymeric sandwich panels without considering mode of fracture.

**Table 2.** Polymer-dependent factors influencing Mode I fracture toughness characterisation in sandwich structures.

Category	Method / Parameter	Influence on Fracture Behaviour	Impact on Characterisation (Mode I Tests)	Typical Effect on Measured Toughness
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Polymer properties	Crystallinity (thermoplastics)	Influences stiffness and crack resistance	Alters crack path and energy absorption	Higher crystallinity → higher toughness
	Intermolecular diffusion (fusion bonding)	Controls interfacial strength in thermoplastics	Dependent on temperature and pressure	Improved diffusion → higher toughness
	Surface energy / wettability	Affects bonding quality during processing	Influences repeatability of results	Poor wetting → lower toughness
	Cell structure (foam/honeycomb morphology)	Influences crack deviation into core	Affects failure mode interpretation	Irregular cells → scatter in results
Processing Parameters	Skin/core consolidation pressure	Controls interfacial adhesion, diffusion/penetration of polymer chains and void content	Influences bonding quality	Requires careful optimization for improved toughness
	Processing temperature	Governs melting, curing, and diffusion	Affects interfacial integrity	Optimal temperature → maximum toughness
	Cooling rate	Influences residual stresses, void formation and crystallinity	Affects crack propagation behaviour	Fast cooling → residual stress → affects measurements

Therefore, in line with the dominance of opening-mode debonding in sandwich structures, Ratcliffe et al. [26,45] defined the requirements for a standardised test method to evaluate the reproducible and consistent Mode I-dominant skin/core fracture toughness in the SCB method. Building on these findings, specific constraints regarding specimen geometry and testing procedures were proposed to improve repeatability and reliability of the SCB method. As a result of these collective efforts and the generally positive outcomes, a draft for an ASTM standard for the SCB method was developed and proposed to the ASTM D30 committee [33]. Subsequently, a large international round-robin testing programme was conducted by multiple research institutes and industrial laboratories worldwide [77]. These developments ultimately culminated in the publication of ASTM D8637/D8637M [36] in Nov 2025, a standard test method for Mode I dominant skin-to-core fracture toughness of sandwich constructions. This standard formalises the SCB configuration, specimen requirements, and data reduction procedures, and defines Mode I dominance as having at least 90% of the total SERR in Mode I.

ASTM D8637/D8637M [36] proposes MBT (Equation 1) as the data reduction method for determining crack initiation fracture toughness ( $G_{Ici}$ ), and the area method (AM) for computing crack propagation fracture toughness. The propagation fracture toughness ( $G_{Icp}$ ) measured utilising the AM is given as:

$$G_{Icp} = \frac{dU}{dA} \quad 5$$

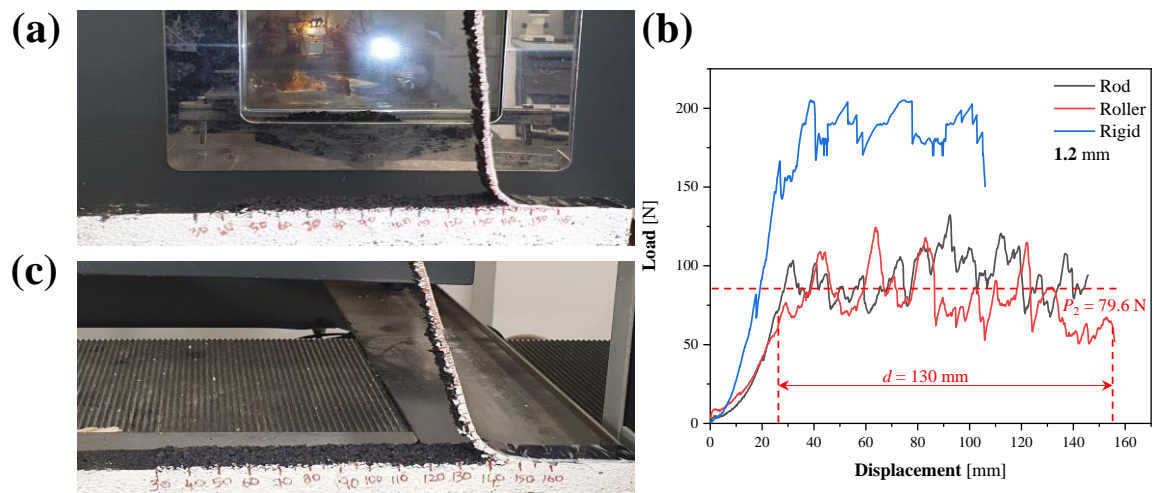
where,  $dA$ = incremental crack area (mm<sup>2</sup>),  $b$ = specimen width (mm),  $a_1$ = initial crack length (mm), and  $a_2$ = final crack length after increment (mm).

$$dA = b (a_2 - a_1) \quad 6$$

Several authors consider the average propagation fracture toughness ( $G_{Icp}$ ) as the value for fracture toughness in sandwich structures [26,43,44,88]. Wilk [71] conducted experiments that yielded similar results for the propagation toughness ( $G_{Icp}$ ) in SCB specimens, as evaluated using the two proposed data reduction methods (MBT and AM). However, accurate measurement of debond length during propagation remains challenging, particularly due to the honeycomb core structure, which affects visual tracking. Consequently, the AM is preferred as it relies only on initial and final crack length measurements. In contrast, the MBT approach is more sensitive to crack length measurement and may be influenced by run-arrest propagation behaviour, often yielding more conservative results. Drake et al. [90,91] investigated SCB testing for sandwich structures and compared different data reduction methods for opening-mode fracture toughness. The study showed that the AM is commonly used but requires periodic unloading, making it impractical for instantaneous evaluation. In contrast, the MBT showed deviations at large displacements due to nonlinear compliance effects and empirical crack-root rotation corrections. A numerical virtual crack-closure technique demonstrated good agreement with experimental results and provided an alternative J-integral-based approach for more accurate and instantaneous fracture toughness evaluation. Moreover, a similar propagation fracture toughness was reported with both MBT and AM.

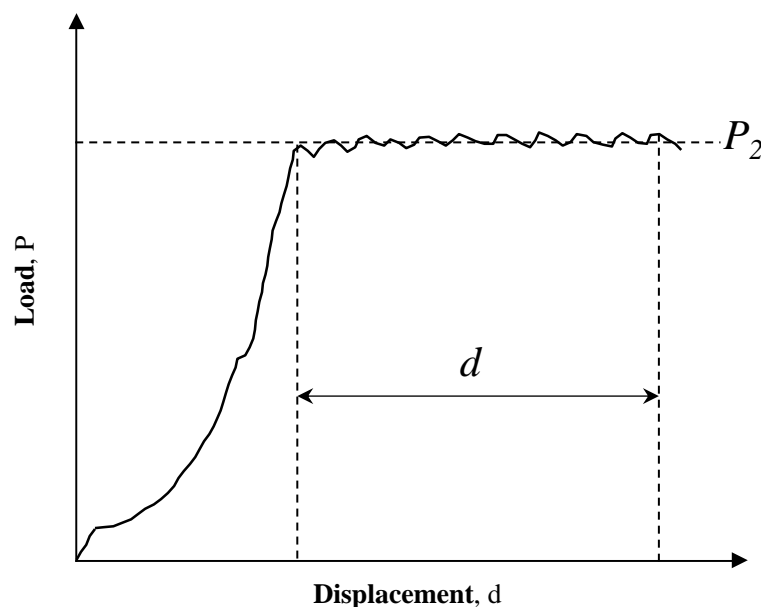
The two data reduction methods reported in the standard (Equations 1, 5) calculate the dominant Mode I fracture toughness in a sandwich structure utilising the linear elastic fracture mechanics. Therefore, their applicability is limited to specimens that demonstrate linear fracture responses, and no established methodology currently exists for specimens with compliant or highly deformable skins that exhibit non-linear loading behaviour. A comparative analysis among various SCB setups for determining the dominant Mode I in sandwich panels was performed by Amal et al. [43]. Both the SCB with the roller base and the long, rotatable loading rod configurations provide a dominant Mode I loading condition at the crack tips for stiffer and compliant skin specimens. Consequently, both configurations yield a similar average fracture toughness for stiffer skin specimens. The SCB with the rigid base setup showed a mixed-mode behaviour. Moreover, a near 90° peeling effect was observed for the SCB configuration with a roller base when testing compliant skin specimens exhibiting non-linear load-displacement behaviour, as shown in Figure 4a. As a result, a sawtooth load-displacement curve was observed as illustrated in Figure 4b. In contrast, the long, rotatable loading rod configuration induces a peeling angle lower than 90°, promoting crack kinking into the core rather than propagation along the skin/core interface, as depicted in Figure 4c. With the roller base configuration, crack propagation is confined to the skin/core interface, thereby ensuring predominantly Mode I conditions at the crack tip. This observation motivated the modification of the climbing drum peel (CDP) equation for a compliance-independent Mode I fracture toughness expression. The developed propagation Mode I fracture toughness equation ( $G_{Icp}$ ) for SCB specimens exhibiting non-linear behaviour in conjunction with the roller base setup is given as:

$$G_{Icp} = \frac{(P_2) d}{b D} \text{ J/m}^2 \quad 7$$



**Figure 4.** (a) Skin peeling under SCB with the roller base ( $90^\circ$ ), (b) load-displacement curve with compliant skin specimens (1.2 mm skin thickness) for different SCB setups and (c) SCB skin peeling with the long, rotatable loading rod ( $< 90^\circ$ ) (Picture courtesy [43]).

$P_2$  is accounted for by the average force required to completely peel off the skin from the core surface during crack propagation.  $d$  refers to the displacement of the load frame,  $b$  is the width of the specimen, and  $D$  signifies the total crack length or the length of the peeled skin. The parametric calculations for measuring the  $G_{Icp}$  were schematized in the load-displacement curve indicated in Figure 5. This compliance-independent data reduction method offers more reliable results for compliant skin specimens than those obtained using the MBT. In this approach, micro-cracks in the flexible skin material can affect test results.



**Figure 5.** Illustrates the schematics of the load-displacement curve for compliant skin specimens.

Likewise, Amal et al. [43,88,89] utilised two data-reduction schemes to compute the Mode I fracture toughness of SCB specimens exhibiting non-linear fracture conditions. These investigations were performed on a full thermoplastic PP-based sandwich system. This was based on: one assuming a linear elastic fracture mechanics (LEFM) using MBT (using Equation 1), and another employing the climbing drum peel (CDP) expression (using Equation 7). The data reduced using the compliant-

independent CDP expression exhibit a higher fracture toughness than those reduced using the compliant-dependent MBT. In the MBT approach, the specimen compliance (C), which is directly related to structural stiffness, significantly influences the calculated Mode I fracture toughness. In particular, MBT tends to underestimate the skin/core debonding toughness for specimens with lower stiffness or non-linear loading, especially when a ductile interface is present. These approaches are effective for assessing Mode I fracture toughness and for comparing processing parameters and for optimisation purposes.

SCB dimensional constraints are proposed in ASTM D8637/D8637M [36] for the initial debond and intact lengths (shown in Equation 11), aimed at ensuring dominant Mode I bending conditions. The initial debond ( $a_0$ ) and intact specimen lengths ( $L_b$ ), as denoted in Figure 2, proposed by the standard to reduce the shear deformation are as follows:

$$a_0 \geq a_{0\min} = 2.7/\lambda \quad 8$$

$$L_b \geq L_{b\min} = 2.7/\lambda \quad 9$$

$\lambda$  is given as the ratio of the stiffness of the elastic foundation to the bending stiffness of the top skin and given as:

$$\lambda = \left[ \frac{3k}{t_s^3 E_{fs} b} \right]^{\frac{1}{4}} \quad 10$$

Here,  $b$  represents the width of the specimen, while  $t_s$  and  $E_{fs}$  denote the thickness and flexural modulus of the skin, respectively. Where  $k$  is the elastic foundation modulus and is related to the z-direction modulus of the core material. The optimal value for  $k$  is given as  $E_{cz}b/t_c$  by Li et. al [67] to minimise the shear and provide in the expressions proposed by Ratcliffe et al. [26].  $E_{cz}$  is Young's modulus of the core along the thickness direction, and  $t_c$  is the core thickness. Then the final expression for computing the values for  $a_0$  and  $L_b$  is derived by substituting Equation 10 with the above expression for  $k$  into Equations 8 and 9, resulting in the following:

$$a_0 \geq a_{0\min} = L_b \geq L_{b\min} = 2.7$$

$$\left[ \frac{t_c t_s^3 E_{fs}}{3 E_{cz}} \right]^{\frac{1}{4}} \quad 11$$

The  $a_0$  and  $L_b$  are kept above or equal to the minimum value according to Equation 11 to reduce the shear stress at the crack tips. However, the application of Equation 11 results in a significantly larger specimen dimensions for SCB configurations with higher skin stiffness or thickness. This requirement restricts the practical applicability of the standard, particularly for stiff sandwich systems, due to increased material and experimental limitations.

To solve this, Amal et al. [44] proposed two equations for  $a_0$  and  $L_b$ , where  $k$  expressed in terms of  $2E_{cz}b/t_c$  and  $2E_{cz}b/t_s$ , as suggested by Aviles et. al [37] and Quispitupa et al.[92], respectively. By substituting these values for  $k$  in the Equation 10, and subsequently into Equations 8 and 9, gives the expressions for  $a_0$  and  $L_b$  as:

$$a_0 \geq a_{0\min} = L_b \geq L_{b\min} = 2.7$$

$$\left[ \frac{t_c t_s^3 E_{fs}}{6 E_{cz}} \right]^{\frac{1}{4}} \quad 12$$

$$a_0 \geq a_{0\min} = L_b \geq L_{b\min} = 2.7$$

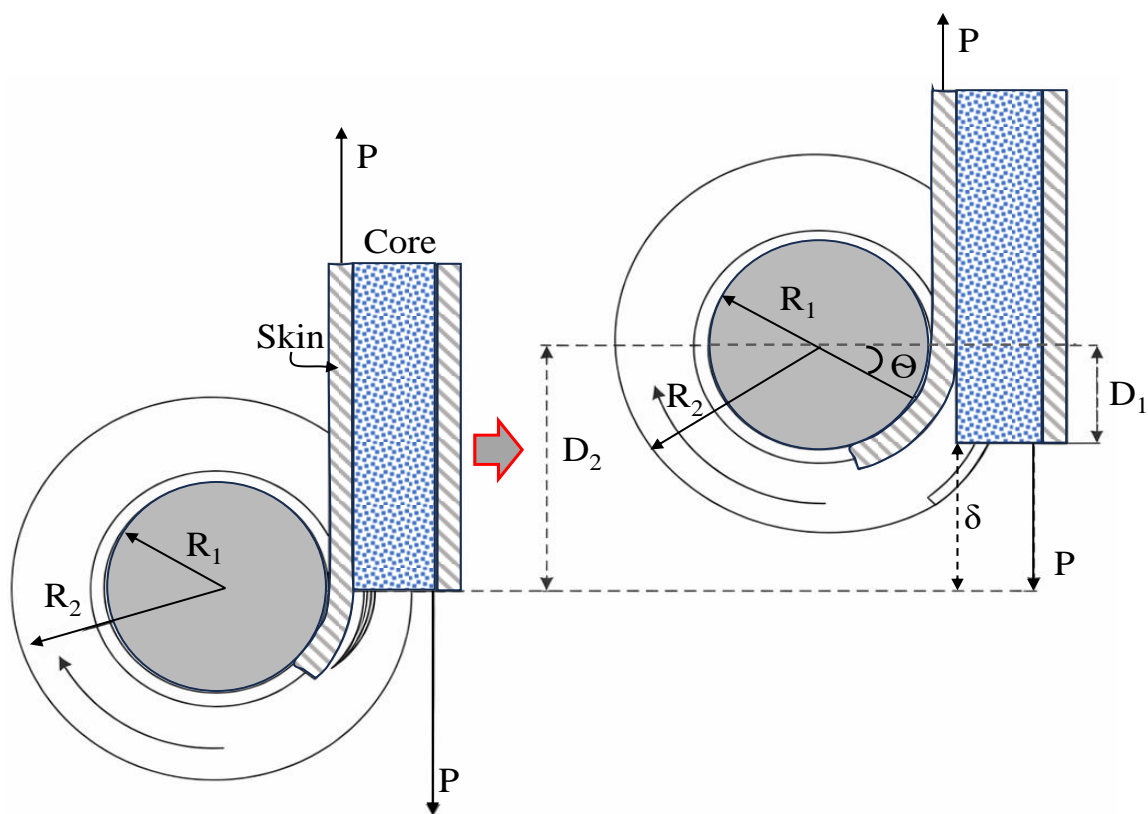
$$\left[ \frac{t_s^4 E_{fs}}{6 E_{cz}} \right]^{\frac{1}{4}} \quad 13$$

It was observed that the SCB sizing dimensions obtained by the equations 12 and 13, with lower dimensions, yielded average Mode I fracture toughness values comparable to those obtained using the dimensions recommended by ASTM D8637/D8637M [36] (Equation 11). Nonetheless, more stable crack propagation into the core and parallel to the skin/core interface was observed for specimens designed according to Equation 11. Comparatively, SCB based on Equations 12 and 13 showed deeper crack propagation into the core. Therefore, these Equations (12, 13) can be considered for measuring  $a_0$  and  $L_b$  in certain situations where the testing dimensions are limited. Otherwise, Equation 11 is considered the optimum sizing criterion for  $a_0$  and  $L_b$  to maintain a dominant Mode I condition at the crack tip. However, it was also found that deviations from the dimensioning criteria specified in Equations 11-13 leads to a variation from dominant Mode I behaviour.

### 2.3. Climbing Drum Peel Test

When the skin is compliant or flexible and shows non-linear load-displacement behaviour, conventional SCB or DCB-based fracture toughness methods become unreliable. This is because these methods rely on LEFM assumptions, which are violated when the polymer-skin undergoes large deformations, plasticity, or significant bending non-linearity. In such cases, the energy release rate (SERR,  $G_I$ ) cannot be accurately determined using standard beam theory or compliance-based approaches.

To overcome this limitation, a peeling test can be used as an alternative method for quantifying skin/core fracture toughness. Peeling tests for polymer-based sandwich structures were primarily derived from the determination of the peel strength of metal-metal bonds [93,94]. In addition to metal-metal bonds, many other material combinations require interfacial bonding evaluation. These include rigid-rigid systems such as welded thermoplastic composites, hybrid metal-composite structures, and adhesively bonded metals [95–99]; flexible-rigid systems such as coatings, thin polymer films, and printed circuit boards on rigid substrates [100–102]; and flexible systems such as multilayer foils and packaging materials [103–105].



**Figure 6.** Schematic illustration of the climbing drum peel (CDP) test, showing the initial configuration (left) and the configuration after peeling a skin length  $D_1$  (right) (Adapted from [62,106]).

In a peeling test, the skin or the top adherent is peeled away from the core or substrate at a controlled angle (typically  $90^\circ$  or  $180^\circ$ ) while measuring the peeling force. Unlike SCB, this method does not require linear elastic behaviour of the skin, making it suitable for flexible, ductile, or polymeric skins. The fracture toughness is then determined from the measured peel force using an energy balance approach rather than beam bending theory [107]. The work done by the peeling force is related directly to the interfacial fracture energy, accounting for both fracture and any plastic deformation in the skin [108]. This makes the peeling test more representative of real debonding mechanisms in compliant sandwich structures.

In the context of sandwich structures, the available literature on peel-based interfacial fracture testing is extremely limited. To date, the climbing drum peel test appears to be the only peel

configuration specifically applied to sandwich composites. Consequently, in this review, the climbing drum peel test is considered the sole relevant peel-based method for evaluating skin/core interfacial fracture toughness in sandwich structures. The climbing drum peel (CDP) test was originally standardised in the 1960s as ASTM D1781 [109]. It has since been widely used to characterise delamination resistance and skin/core interfacial bonding in sandwich structures, including thermoplastic sandwich systems. In this method, the upper skin of the sandwich panel is bonded to a rotating drum comprising two concentric sections with different radii, as shown in Figure 6. The skin is secured to the inner drum section of radius  $R_1$ , while tension straps are attached to the outer section of larger radius  $R_2$  ( $R_2 > R_1$ ). Both the straps and the sandwich specimen are clamped on opposite sides of a uniaxial testing machine. As the machine applies tensile load to the straps, a torque is transmitted to the drum, causing it to rotate along the surface of the sandwich specimen. This controlled rotation progressively peels the skin away from the core, enabling stable crack propagation under approximately constant load conditions. In its standard form, the climbing drum peel (CDP) test provides a measure of peel strength, expressed as force per unit width, and allows quantitative comparison of results only when the specimen and drum geometry remain unchanged. However, Nettles et al. [110,111] proposed a method to determine the Mode I fracture toughness from CDP tests, building on the work of Okada and Kortschot [112].

In the CDP setup, the kinematic constraints cause the instantaneous crack length  $D_1$  to depend directly on the crosshead displacement  $\delta$  and the drum radii  $R_1$  and  $R_2$ , as expressed by:

$$D_1 = \frac{R_1 \delta}{R_2 - R_1} \quad 14$$

During the peeling process, two distinct load stages are observed as indicated in Figure 7. Initially, the skin is wrapped around the inner drum of the radius  $R_1$  using the pre-crack region, without any skin/core debonding, generating a load  $P_1$ . This is followed by the initiation and stable propagation of the skin/core debond under a nearly constant load  $P_2$ . The work done during the peeling process is indicated as a grey area in Figure 7, can be translated into the fracture toughness by relating the energy to the peeled surface area, the specimen width  $b$ , and the crack length  $D_1$ . The SERR ( $G_I$ ) in the CDP test can be calculated as:

$$G_I = \frac{(P_2 - P_1) \delta}{b D_1} \quad 15$$

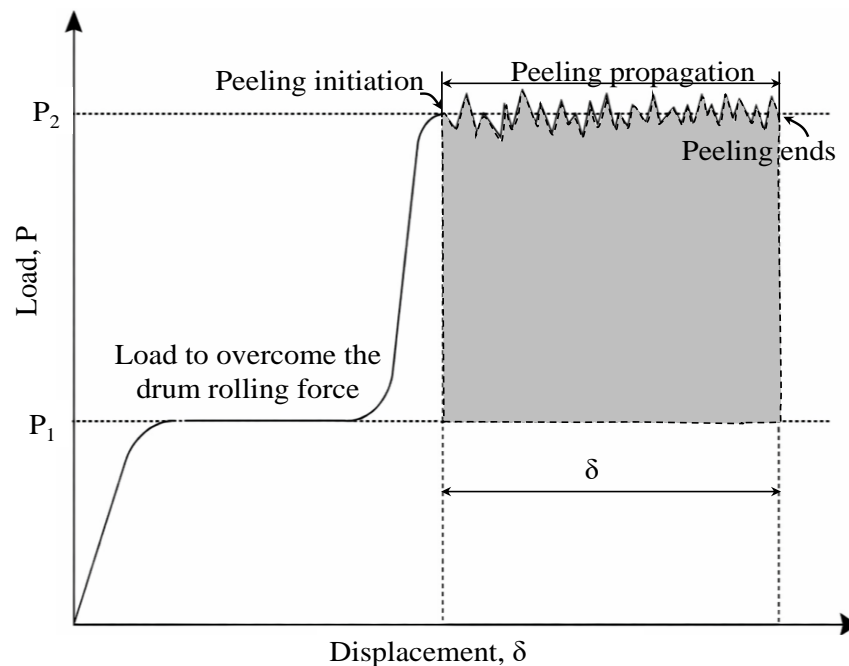


Figure 7. Sketch of the experimental load-displacement of the climbing drum peel test (Adapted from [62]).

Using this approach, the debonding of carbon fibre-reinforced epoxy skins from glass/phenolic honeycomb cores was experimentally evaluated. Comparisons with conventional DCB tests showed that both methods yielded similar  $G_I$  values. However, the CDP test offers a clear advantage in terms of ease of execution and practical handling. Moreover, Adams et al. [33] also performed a comparative analysis between the CDP test and the SCB with a rigid base method for honeycomb-based sandwich panels. They carried out Mode I fracture toughness measurements using different drum peel radii, 2 in. (as specified in ASTM D1781 [109]), 4 in., and 6 in., along with various skin thicknesses (3, 6, and 9 plies). Their findings showed that the SERR derived from the SCB test is sensitive to changes in skin thickness, whereas the CDP test generally produces SERR values that are less dependent on thickness. However, they also observed that modifying the roller diameter in the CDP test resulted in varying SERR values. This variation was attributed to potential conformity issues in roller peel tests, particularly because there is no predefined alignment between the bending arm and the roller. Furthermore, the CDP method assumes perfect contact between the bending arm and the drum during SERR calculation, a condition that may not always be achieved experimentally.

Restrictions on utilising the CDP test are primarily associated with the mechanical behaviour of the skin and the resulting failure mode of the sandwich structure. The skin cannot be excessively thick or stiff, as it must be able to conform to the curvature of the drum to ensure meaningful loading conditions. In addition, the test is most appropriate when interfacial debonding between the skin and the core is the dominant failure mechanism; if fracture instead occurs in the core or within the skin, the measured SERR no longer represents a true characterisation of the bondline fracture toughness. Finally, the skin must have adequate tensile strength to avoid premature tensile rupture during loading, which would invalidate the test outcome.

### 3. Conclusion

The present review critically examined a range of experimental methods for the accurate characterisation of dominant Mode I fracture behaviour in polymer-based sandwich structures, with particular emphasis on the applicability and limitations of ASTM D8637/D8637M. A comparative assessment of DCB, SCB, and CDP configurations highlighted their ability to achieve dominant Mode I conditions, as well as their experimental complexity and practical limitations. Furthermore, the influence of polymer-dependent response, processing effects, and fracture behaviour on the Mode I characteristic was detailed.

The analysis shows that conventional DCB configurations are inherently affected by mixed-mode conditions due to asymmetric loading and specimen rotation, making them unsuitable for accurate Mode I characterisation in sandwich structures. Although modified DCB-UBM configurations can effectively reduce these effects, their experimental and analytical complexity limits their broader applicability. In contrast, SCB configurations provide a more practical and adaptable approach; however, maintaining dominant Mode I conditions strongly depends on boundary conditions, with a rigid base inevitably introducing mixed-mode effects, proving ineligible to maintain Mode I conditions. On the other hand, SCB with roller-base support and long, flexible, and rotatable loading systems proves more effective in maintaining dominant Mode I conditions at the crack tips. Considering design simplicity, the approach with the long, flexible, and rotatable loading rod with SCB sizing requirements was adopted in ASTM D8637/D8637M for measuring dominant Mode I fracture toughness. The CDP test is suitable for sandwich structures with thin, compliant skins exhibiting non-linear behaviour, where LFM-based methods are limited. However, its accuracy is affected by drum roller diameter and contact uncertainties. Thus, while useful for parametric and comparative studies, further refinement is needed for reliable fracture toughness evaluation.

A key limitation of ASTM D8637/D8637M is its restriction to linear elastic fracture behaviour, making it unsuitable for sandwich structures with compliant skins that exhibit non-linear responses. In addition, the standard imposes stringent specimen sizing requirements, particularly for intact and initial debond lengths (Equation 11), which often result in impractically large specimens and

increased material and experimental constraints. Furthermore, the prescribed SCB configuration does not fully account for variations in boundary conditions that can significantly influence crack tip loading.

The study also highlights the critical influence of geometrical and material parameters on fracture behaviour. It is demonstrated that alternative reduced-dimension specimen sizing (Equations 12, 13) can yield fracture toughness values comparable to those prescribed in the standard, offering greater flexibility in specimen design while reducing experimental constraints. The boundary conditions strongly influence the loading conditions at the crack tip, particularly in bi-material systems with asymmetric elastic properties. The increasing skin thickness enhanced bending stiffness, promoted more linear elastic behaviour, and increased measured fracture toughness.

In terms of data reduction, although the standard prescribes MBT for initiation and AM for propagation fracture toughness, both methods were found to provide comparable propagation toughness under linear elastic conditions, indicating potential flexibility in their application. However, AM remains more experimentally robust, while MBT is more sensitive to crack-length measurement and propagation instability. For SCB exhibiting non-linear behaviour, conventional LFM-based approaches are insufficient, and alternative methods based on the climbing drum peel concept (Equation 7) with the roller-base supports provide a more suitable framework.

Irrespective of the testing configuration, data reduction method, and boundary conditions, the Mode I interfacial fracture behaviour in polymer-based sandwich structures is strongly governed by the interplay between processing conditions, polymer properties, and interface quality. Variations in manufacturing parameters significantly influence interfacial bonding, defect formation, and failure mechanisms, which in turn affect the measured fracture toughness. Importantly, the results demonstrate that fracture toughness alone cannot reliably assess interfacial performance without considering the underlying failure mode. Therefore, accurate Mode I characterisation requires a combined evaluation of polymer-dependent behaviour, processing effects, and fracture response.

Overall, this review identifies key limitations in existing standards and provides new insights into boundary-condition design, specimen-sizing flexibility, and data-reduction strategies. Future work should focus on developing unified testing methodologies capable of accurately capturing non-linear fracture behaviour, integrating experimental and numerical approaches, and refining standardised procedures to accommodate a wider range of material systems and realistic service conditions.

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## Abbreviations

The following abbreviations are used in this manuscript

SCB	Single Cantilever Beam
DCB-UBM	Double Cantilever Beam with Uneven Bending Moment
DCB	Double Cantilever Beam

CDP	Climbing Drum Peel
SERR	Strain Energy Release Rate
TSD	Tilted Sandwich Debond
LEFM	Linear Elastic Fracture Mechanics
MBT	Modified Beam Theory
AM	Area Method
$G_{Icp}$	Mode I Fracture Toughness Propagation

## References

1. Latsuzbaya, T.; Middendorf, P.; Voelke, D.; Weber, C. Thermomechanical Analysis of Thermoplastic Mono-Material Sandwich Structures with Honeycomb Core. *Journal of Composites Science* **2024**, *8*, 18, doi:10.3390/jcs8010018.
2. Ong, M.; Silva, A. Effects of Low-Velocity-Impact on Facesheet-Core Debonding of Natural-Core Composite Sandwich Structures—A Review of Experimental Research. *Journal of Composites Science* **2024**, *8*, 23, doi:10.3390/jcs8010023.
3. Han, X.; Cai, H.; Sun, J.; Wei, Z.; Huang, Y.; Wang, A. Numerical Studies on Failure Mechanisms of All-Composite Sandwich Structure with Honeycomb Core under Compression and Impact Loading Conditions. *Polymers* **2022**, *14*, 4047, doi:10.3390/polym14194047.
4. Dhaliwal, G.S.; Newaz, G.M. Flexural Response of Degraded Polyurethane Foam Core Sandwich Beam with Initial Crack between Facesheet and Core. *Materials (Basel)* **2020**, *13*, 5399, doi:10.3390/ma13235399.
5. Zenkert, D. *An Introduction to Sandwich Construction*; Engineering Materials Advisory Services, 1995; ISBN 978-0-947817-77-0.
6. Weidmann, F.; Ziegmann, G.; Wieser, J. A Review of Mode I Dominant Interfacial Fracture Toughness Test Methods of Skin-Core Bonding for Thermoplastic Composite Sandwich Structures. *Journal of Thermoplastic Composite Materials* **2023**, *36*, 2643–2673, doi:10.1177/08927057221083493.
7. Funari, M.F.; Greco, F.; Lonetti, P. Sandwich Panels under Interfacial Debonding Mechanisms. *Composite Structures* **2018**, *203*, 310–320, doi:10.1016/j.compstruct.2018.06.113.
8. Ong, M.; Silva, A. Effects of Low-Velocity-Impact on Facesheet-Core Debonding of Natural-Core Composite Sandwich Structures—A Review of Experimental Research. *Journal of Composites Science* **2024**, *8*, 23, doi:10.3390/jcs8010023.
9. Xue, P.; Wei, X.; Li, Z.; Wang, Y.; Selivanov, M.F.; Xiong, J. Mechanics of Inner Core Debonding of Composite Sandwich Beam with CFRP Hexagonal Honeycomb. *International Journal of Solids and Structures* **2024**, *293*, 112760, doi:10.1016/j.ijsolstr.2024.112760.
10. Bahabadi, H.M.; Farrokhhabadi, A.; Rahimi, G.H. Investigation of Debonding Growth between Composite Skins and Corrugated Foam-Composite Core in Sandwich Panels under Bending Loading. *Engineering Fracture Mechanics* **2020**, *230*, 106987, doi:10.1016/j.engfracmech.2020.106987.
11. Farmand-Ashtiani, E.; Cugnoni, J.; Botsis, J. Monitoring and Characterization of the Interfacial Fracture in Sandwich Composites with Embedded Multiplexed Optical Sensors. *Composite Structures* **2013**, *96*, 476–483, doi:10.1016/j.compstruct.2012.08.059.
12. Xue, P.; Wei, X.; Li, Z.; Xiong, J. Face-Core Interfacial Debonding Characterization Model of an All-Composite Sandwich Beam with a Hexagonal Honeycomb Core. *Engineering Fracture Mechanics* **2022**, *269*, 108554, doi:10.1016/j.engfracmech.2022.108554.
13. Han, X.; Cai, H.; Sun, J.; Wei, Z.; Huang, Y.; Wang, A. Numerical Studies on Failure Mechanisms of All-Composite Sandwich Structure with Honeycomb Core under Compression and Impact Loading Conditions. *Polymers* **2022**, *14*, 4047, doi:10.3390/polym14194047.
14. Xue, P.; Wei, X.; Li, Z.; Wang, Y.; Selivanov, M.F.; Xiong, J. Mechanics of Inner Core Debonding of Composite Sandwich Beam with CFRP Hexagonal Honeycomb. *International Journal of Solids and Structures* **2024**, *293*, 112760, doi:10.1016/j.ijsolstr.2024.112760.

15. Martin, R.G.; Johansson, C.; Tavares, J.R.; Dubé, M. Manufacturing of Thermoplastic Composite Sandwich Panels Using Induction Welding under Vacuum. *Composites Part A: Applied Science and Manufacturing* **2024**, *182*, 108211, doi:10.1016/j.compositesa.2024.108211.
16. Martin, R.G.; Johansson, C.; Tavares, J.R.; Dubé, M. CF/PEEK Skins Assembly by Induction Welding for Thermoplastic Composite Sandwich Panels. *Composites Part B: Engineering* **2024**, *284*, 111676, doi:10.1016/j.compositesb.2024.111676.
17. Gomez, A.; Sanchez-Saez, S.; Barbero, E. Experimental Analysis of the Impact Behaviour of Sandwich Panels with Sustainable Cores. *Composites Part A: Applied Science and Manufacturing* **2023**, *166*, 107383, doi:10.1016/j.compositesa.2022.107383.
18. Karsandik, Y.; Sabuncuoglu, B.; Yildirim, B.; Silberschmidt, V.V. Impact Behavior of Sandwich Composites for Aviation Applications: A Review. *Composite Structures* **2023**, *314*, 116941, doi:10.1016/j.compstruct.2023.116941.
19. Al-Fasih, M.Y.; Kueh, A.B.H.; W. Ibrahim, M.H. Failure Behavior of Sandwich Honeycomb Composite Beam Containing Crack at the Skin. *PLoS One* **2020**, *15*, e0227895, doi:10.1371/journal.pone.0227895.
20. Wei, Y.; Chen, Y.; Hu, F.; Xue, X. Effect of Temperature and Thermal Cycles on the Mechanical Behavior of Sandwich Structure with Entangled Metallic Wire Mesh. *Thin-Walled Structures* **2023**, *187*, 110750, doi:10.1016/j.tws.2023.110750.
21. Government of Canada, T.S.B. of C. Aviation Investigation Report A05F0047 - Transportation Safety Board of Canada Available online: <https://www.tsb.gc.ca/eng/rapports-reports/aviation/2005/a05f0047/a05f0047.html> (accessed on 21 January 2026).
22. Glaessgen, E.H.; Reeder, J.R.; Sleight, D.W.; Wang, J.T.; Raju, I.S.; Harris, C.E. Debonding Failure of Sandwich-Composite Cryogenic Fuel Tank with Internal Core Pressure. *Journal of Spacecraft and Rockets* **2005**, *42*, 613–627, doi:10.2514/1.5567.
23. Bragagnolo, G.; Crocombe, A.D.; Ogin, S.L.; Mohagheghian, I.; Sordon, A.; Meeks, G.; Santoni, C. Investigation of Skin-Core Debonding in Sandwich Structures with Foam Cores. *Materials & Design* **2020**, *186*, 108312, doi:10.1016/j.matdes.2019.108312.
24. Weidmann, F.; Ziegmann, G.; Wieser, J. A Review of Mode I Dominant Interfacial Fracture Toughness Test Methods of Skin-Core Bonding for Thermoplastic Composite Sandwich Structures. *Journal of Thermoplastic Composite Materials* **2023**, *36*, 2643–2673, doi:10.1177/08927057221083493.
25. Wilk, J. Investigation of the Applicability of Single Cantilever Beam Test for the Evaluation of Fracture Toughness of Sandwich Composites. *Engineering Fracture Mechanics* **2023**, *281*, 109075, doi:10.1016/j.engfracmech.2023.109075.
26. Ratcliffe, J.G.; Reeder, J.R. Sizing a Single Cantilever Beam Specimen for Characterizing Facesheet–Core Debonding in Sandwich Structure. *Journal of Composite Materials* **2011**, *45*, 2669–2684, doi:10.1177/0021998311401116.
27. Irvén, G.; Whitehouse, A.; Carolan, D.; Fergusson, A.; Dear, J.P. Toughening of Face-Sheet Core Bonds in Sandwich Structures. *Engineering Fracture Mechanics* **2023**, *290*, 109498, doi:10.1016/j.engfracmech.2023.109498.
28. Saeid, A.A.; Donaldson, S.L. Experimental and Finite Element Evaluations of Debonding in Composite Sandwich Structure with Core Thickness Variations. *Advances in Mechanical Engineering* **2016**, *8*, 1687814016667418, doi:10.1177/1687814016667418.
29. Burlayenko, V.N.; Pietras, D.; Sadowski, T. Influence of Geometry, Elasticity Properties and Boundary Conditions on the Mode I Purity in Sandwich Composites. *Composite Structures* **2019**, *223*, 110942, doi:10.1016/j.compstruct.2019.110942.
30. Nettles, A.T.; Gregory, E.D.; Jackson, J.R. Using the Climbing Drum Peel (CDP) Test to Obtain a GIC Value for Core/Face Sheet Bonds. *Journal of Composite Materials* **2007**, *41*, 2863–2876, doi:10.1177/0021998307079974.
31. Drake, D.A.; Ratcliffe, J.G. Measurement of Opening Mode Facesheet/Core Interfacial Fracture Toughness of Sandwich Structure Using J-Integral.
32. Hosseini, M.R.; Taheri-Behrooz, F.; Salamat-talab, M. Mode I Interlaminar Fracture Toughness of Woven Glass/Epoxy Composites with Mat Layers at Delamination Interface. *Polymer Testing* **2019**, *78*, 105943, doi:10.1016/j.polymertesting.2019.105943.

33. Adams, D.; Nelson, J.; Bluth, Z.; Bluth, J.; Kuramoto, B.K.; Weaver, C.; Gill, A.; Davies, C. Development and Evaluation of Fracture Mechanics Test Methods for Sandwich Composites.; 2008.
34. Farmand-Ashtiani, E.; Cugnoni, J.; Botsis, J. Monitoring and Characterization of the Interfacial Fracture in Sandwich Composites with Embedded Multiplexed Optical Sensors. *Composite Structures* **2013**, *96*, 476–483, doi:10.1016/j.compstruct.2012.08.059.
35. Müller, M.; Herák, D. Dimensioning of the Bonded Lap Joint. *Research in Agricultural Engineering* **2010**, *56*, 59–68, doi:10.17221/35/2009-RAE.
36. Standard Test Method for Mode I Dominant Face Sheet-to-Core Fracture Toughness of Sandwich Constructions Available online: [https://store.astm.org/d8637\\_d8637m-25.html](https://store.astm.org/d8637_d8637m-25.html) (accessed on 3 February 2026).
37. Avilés, F.; Carlsson, L.A. Analysis of the Sandwich DCB Specimen for Debond Characterization. *Engineering Fracture Mechanics* **2008**, *75*, 153–168, doi:10.1016/j.engfracmech.2007.03.045.
38. Sørensen, B.F.; Jørgensen, K.; Jacobsen, T.K.; Østergaard, R.C. DCB-Specimen Loaded with Uneven Bending Moments. *Int J Fract* **2006**, *141*, 163–176, doi:10.1007/s10704-006-0071-x.
39. Berggreen, C.; Saseendran, V.; Carlsson, L.A. A Modified DCB-UBM Test Method for Interfacial Fracture Toughness Characterization of Sandwich Composites. *Engineering Fracture Mechanics* **2018**, *203*, 208–223, doi:10.1016/j.engfracmech.2018.06.036.
40. Schäuble, R.; Albertone, Y.; Saseendran, V.; Berggreen, C.; Hilgers, R. Fracture Characterization of Aerospace Grade Honeycomb Core Sandwich Using SCB and DCB-UBM Test Methods – A Comparison. In Proceedings of the 12th International Conference on Sandwich Structures ICSS-12: Proceedings; EPFL - CCLab Composite Construction Laboratory, 2018; pp. 229–231.
41. Lundsgaard-Larsen, C.; Sørensen, B.F.; Berggreen, C.; Østergaard, R.C. A Modified DCB Sandwich Specimen for Measuring Mixed-Mode Cohesive Laws. *Engineering Fracture Mechanics* **2008**, *75*, 2514–2530, doi:10.1016/j.engfracmech.2007.07.020.
42. Saseendran, V.; Carlsson, L.A.; Berggreen, C.; Seneviratne, W. Crack Length Correction and Root Rotation Angle in a Sandwich Single Cantilever Beam (SCB) Fracture Specimen. *International Journal of Lightweight Materials and Manufacture* **2020**, *3*, 426–434, doi:10.1016/j.ijlmm.2020.06.005.
43. Vijayakumar, A.A.; Zahid, M.; Corvaglia, S.G.; Maffezzoli, A. Skin/Core Fracture Toughness of Sandwich Structures: A Comparison of Different Experimental Arrangements. *Polymer Testing* **2025**, *150*, 108904, doi:10.1016/j.polymertesting.2025.108904.
44. Alliyankal Vijayakumar, A.; Zahid, M.; Kumar, A.; Corvaglia, S.G.; Maffezzoli, A. Impact of Intact Length and Initial Debond on the Mode I Fracture Toughness of Sandwich Structures. *Polymer Composites* **2026**, *47*, 7328–7340, doi:10.1002/pc.70625.
45. Ratcliffe JG, Sizing Single Cantilever Beam Specimens for Characterizing Facesheet/Core Peel Debonding in Sandwich Structure, NASA/TM–2010-216798, NASA Langley Research Center, Hampton, VA, USA., **2010**.
46. Mixed Mode Cracking in Layered Materials. In *Advances in Applied Mechanics*; Elsevier, 1991; Vol. 29, pp. 63–191.
47. Suo, Z.; Hutchinson, J.W. Sandwich Test Specimens for Measuring Interface Crack Toughness. *Materials Science and Engineering: A* **1989**, *107*, 135–143, doi:10.1016/0921-5093(89)90382-1.
48. Hutchinson, J.W. Mixed Mode Fracture Mechanics of Interfaces. *Metal-ceramic interfaces* **1990**, *1990*, 295–306.
49. Prasad, S.; Carlsson, L.A. Debonding and Crack Kinking in Foam Core Sandwich Beams—I. Analysis of Fracture Specimens. *Engineering Fracture Mechanics* **1994**, *47*, 813–824, doi:10.1016/0013-7944(94)90061-2.
50. Lee, S.; Ji, W. Measurement of Pure Mode I Fracture Toughness at a Sandwich Interface and Parametrization of the R-Curve for a Cohesive Element. *Composite Structures* **2022**, *291*, 115599, doi:10.1016/j.compstruct.2022.115599.
51. Ural, A.; Zehnder, A.T.; Ingraffea, A.R. Fracture Mechanics Approach to Facesheet Delamination in Honeycomb: Measurement of Energy Release Rate of the Adhesive Bond. *Engineering Fracture Mechanics* **2003**, *70*, 93–103, doi:10.1016/S0013-7944(02)00024-3.

52. Wei, X.; Xue, P.; Wu, Q.; Wang, Y.; Xiong, J. Debonding Characteristics and Strengthening Mechanics of All-CFRP Sandwich Beams with Interface-Reinforced Honeycomb Cores. *Composites Science and Technology* **2022**, *218*, 109157, doi:10.1016/j.compscitech.2021.109157.
53. Lascoup, B.; Aboura, Z.; Khellil, K.; Benzeggagh, M. Core–Skin Interfacial Toughness of Stitched Sandwich Structure. *Composites Part B: Engineering* **2014**, *67*, 363–370, doi:10.1016/j.compositesb.2014.07.006.
54. Shivakumar, K.N.; Smith, S.A. In Situ Fracture Toughness Testing of Core Materials in Sandwich Panels. *Journal of Composite Materials* **2004**, *38*, 655–668, doi:10.1177/0021998304042392.
55. Weaver, C. Evaluation of Mode I Fracture Mechanics Test Methods for Sandwich Composites. **2010**.
56. Williams, M.L. The Stresses around a Fault or Crack in Dissimilar Media. *Bulletin of the Seismological Society of America* **1959**, *49*, 199–204, doi:10.1785/BSSA0490020199.
57. Erdogan, F. Stress Distribution in Bonded Dissimilar Materials With Cracks. *J. Appl. Mech* **1965**, *32*, 403–410, doi:10.1115/1.3625814.
58. Maleki, F.K.; Toygar, M.E. The Fracture Behavior of Sandwich Composites with Different Core Densities and Thickness Subjected to Mode I Loading at Different Temperatures. *Mater. Res. Express* **2019**, *6*, 045314, doi:10.1088/2053-1591/aafc02.
59. Ramantani, D.A.; de Moura, M.F.S.F.; Campilho, R.D.S.G.; Marques, A.T. Fracture Characterization of Sandwich Structures Interfaces under Mode I Loading. *Composites Science and Technology* **2010**, *70*, 1386–1394, doi:10.1016/j.compscitech.2010.04.018.
60. Shivakumar, K.; Chen, H.; Smith, S.A. An Evaluation of Data Reduction Methods for Opening Mode Fracture Toughness of Sandwich Panels. *Jnl of Sandwich Structures & Materials* **2005**, *7*, 77–90, doi:10.1177/1099636205047085.
61. Williams, J.G. The Fracture Mechanics of Delamination Tests. *The Journal of Strain Analysis for Engineering Design* **1989**, *24*, 207–214, doi:10.1243/03093247V244207.
62. Weidmann, F.; Ziegmann, G.; Wieser, J. A Review of Mode I Dominant Interfacial Fracture Toughness Test Methods of Skin-Core Bonding for Thermoplastic Composite Sandwich Structures. *Journal of Thermoplastic Composite Materials* **2023**, *36*, 2643–2673, doi:10.1177/08927057221083493.
63. ASTM D5528-21, Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites, ASTM International, West Conshohocken, PA, (accessed on 27 May 2024).
64. Rinker, M.; Ratcliffe, J.G.; Adams, D.O.; Krueger, R. *Characterizing Facesheet/Core Disbonding in Honeycomb Core Sandwich Structure*; NASA Technical Report, 2013;
65. Carlsson, L.A.; Sendlein, L.S.; Merry, S.L. Characterization of Face Sheet/Core Shear Fracture of Composite Sandwich Beams. *Journal of Composite Materials* **1991**, *25*, 101–116, doi:10.1177/002199839102500105.
66. Carlsson, L.A.; Prasad, S. Interfacial Fracture of Sandwich Beams. *Engineering Fracture Mechanics* **1993**, *44*, 581–590, doi:10.1016/0013-7944(93)90100-7.
67. Li, X.; Carlsson, L.A. Elastic Foundation Analysis of Tilted Sandwich Debond (TSD) Specimen. *Jnl of Sandwich Structures & Materials* **2000**, *2*, 3–32, doi:10.1177/109963620000200101.
68. Liechti, K.M.; Marton, B. Delamination of a High-Temperature Sandwich Plate. *Experimental Mechanics* **2002**, *42*, 206–213, doi:10.1007/BF02410885.
69. Kanninen, M.F. An Augmented Double Cantilever Beam Model for Studying Crack Propagation and Arrest. *Int J Fract* **1973**, *9*, 83–92, doi:10.1007/BF00035958.
70. Williams, J.G. End Corrections for Orthotropic DCB Specimens. *Composites Science and Technology* **1989**, *35*, 367–376, doi:10.1016/0266-3538(89)90058-4.
71. Wilk, J. Investigation of the Applicability of Single Cantilever Beam Test for the Evaluation of Fracture Toughness of Sandwich Composites. *Engineering Fracture Mechanics* **2023**, *281*, 109075, doi:10.1016/j.engfracmech.2023.109075.
72. Saseendran, V.; Berggreen, C. Mixed-Mode Fracture Evaluation of Aerospace Grade Honeycomb Core Sandwich Specimens Using the Double Cantilever Beam–Uneven Bending Moment Test Method. *Jnl of Sandwich Structures & Materials* **2020**, *22*, 991–1018, doi:10.1177/1099636218777964.
73. Saseendran, V. Fracture Characterization and Analysis of Debonded Sandwich Composites, 2017.

74. Saseendran, V.; Berggreen, C.; Krueger, R. Mode Mixity Analysis of Face/Core Debonds in a Single Cantilever Beam Sandwich Specimen. *Jnl of Sandwich Structures & Materials* **2020**, *22*, 1879–1909, doi:10.1177/1099636218788223.
75. Sørensen, B.F.; Horsewell, A.; Jørgensen, O.; Kumar, A.N.; Engbæk, P. Fracture Resistance Measurement Method for in Situ Observation of Crack Mechanisms. *Journal of the American Ceramic Society* **1998**, *81*, 661–669, doi:10.1111/j.1151-2916.1998.tb02387.x.
76. Bridging Law Determination in Short Fibre Composites by a DCB-Test. In *European Structural Integrity Society*; Elsevier, 2000; Vol. 27, pp. 73–82.
77. Disbond of Sandwich Structures - DoSS - EASA\_REP\_RESEA\_2016\_2 | EASA Available online: <https://www.easa.europa.eu/en/document-library/research-reports/easarepresea20162> (accessed on 26 September 2024).
78. Li, X.; Carlsson, L.A. The Tilted Sandwich Debond (TSD) Specimen for Face/Core Interface Fracture Characterization. *Jnl of Sandwich Structures & Materials* **1999**, *1*, 60–75, doi:10.1177/109963629900100104.
79. Cantwell, W.J.; Davies, P. A Test Technique for Assessing Core-Skin Adhesion in Composite Sandwich Structures. *J Mater Sci Lett* **1994**, *13*, 203–205, doi:10.1007/BF00278162.
80. Glaessgen, E.H.; Reeder, J.R.; Sleight, D.W.; Wang, J.T.; Raju, I.S.; Harris, C.E. Debonding Failure of Sandwich-Composite Cryogenic Fuel Tank with Internal Core Pressure. *Journal of Spacecraft and Rockets* **2005**, *42*, 613–627, doi:10.2514/1.5567.
81. McGarva, L.D.; Åström, B.T. Experimental Investigation of Compression Moulding of Glass/PA12-PMI Foam Core Sandwich Components. *Composites Part A: Applied Science and Manufacturing* **1999**, *30*, 1171–1185, doi:10.1016/S1359-835X(99)00028-7.
82. Charalambides, M.; Kinloch, A.J.; Wang, Y.; Williams, J.G. On the Analysis of Mixed-Mode Failure. *Int J Fract* **1992**, *54*, 269–291, doi:10.1007/BF00035361.
83. Cantwell, W.J.; Davies, P. A Study of Skin-Core Adhesion in Glass Fibre Reinforced Sandwich Materials. *Appl Compos Mater* **1996**, *3*, 407–420, doi:10.1007/BF00133683.
84. Irvén, G.; Duncan, A.; Whitehouse, A.; Carolan, D.; Fergusson, A.; Dear, J.P. Impact Response of Composite Sandwich Structures with Toughened Matrices. *Materials & Design* **2021**, *203*, 109629, doi:10.1016/j.matdes.2021.109629.
85. McGarva, L.D.; Tomas  $\diamond$ str  $\diamond$ m, B. COMPRESSION MOULDING OF THERMOPLASTIC COMPOSITE SANDWICH COMPONENTS. Presented at the 12nd International Conference on Composite Materials (ICCM-12), 1999.
86. Viana, G.M.; Carlsson, L.A. Influences of Foam Density and Core Thickness on Debond Toughness of Sandwich Specimens with PVC Foam Core. *Jnl of Sandwich Structures & Materials* **2003**, *5*, 103–118, doi:10.1177/1099636203005002020.
87. Fracture Mechanics of Sandwich Structures Available online: <https://soar.wichita.edu/items/7604739a-7cbb-429c-9911-2205c7f65b5d> (accessed on 3 February 2026).
88. Alliyankal Vijayakumar, A.; Zahid, M.; Corvaglia, S.G.; Montagna, F.; Lionetto, F.; Maffezzoli, A. Characterisation of Thermoplastic Sandwich Panels Manufactured by Continuous Ultrasonic Welding of Skins to the Core. *Composites Part B: Engineering* **2025**, *307*, 112927, doi:10.1016/j.compositesb.2025.112927.
89. Trucillo, P.; Vijayakumar, A.A.; Zahid, M.; Maffezzoli, A.; Di Maio, E. Manufacturing of PP-Based Composite Sandwich Panels via Simultaneous Foaming and Skin-Core Bonding. *Polymer Composites* **2025**, *46*, doi:10.1002/pc.70287.
90. Drake, D.A.; Ratcliffe, J.R.; Vieira de Carvalho, N.; Paris, A.J. On the Calculation of the Strain Energy Release Rate for Thin-Gage Facesheet Sandwich Structures Using the J-Integral Method. *Jnl of Sandwich Structures & Materials* **2026**, *28*, 701–719, doi:10.1177/10996362251396612.
91. Drake, D.A.; Ratcliffe, J.G.; Carvalho, N.V. de; Paris, A.J. Computational Assessment of the Opening Mode Facesheet-to-Core Fracture Toughness of a Thin-Gage Facesheet Sandwich Structure.; San Diego, CA.
92. Quispitupa, A.; Berggreen, C.; Carlsson, L.A. On the Analysis of a Mixed Mode Bending Sandwich Specimen for Debond Fracture Characterization. *Engineering Fracture Mechanics* **2009**, *76*, 594–613, doi:10.1016/j.engfracmech.2008.12.008.

93. Spies, G.J. The Peeling Test on Redux-bonded Joints: A Theoretical Analysis of the Test Devised by Aero Research Limited. *Aircraft Engineering* **1953**, *25*, 64–70, doi:10.1108/eb032268.
94. Moore, D.R. An Introduction to the Special Issue on Peel Testing. *International Journal of Adhesion and Adhesives* **2008**, *28*, 153–157, doi:10.1016/j.ijadhadh.2007.01.001.
95. Sacchetti, F.; Groupe, W.J.B.; Warnet, L.L.; Fernandez Villegas, I. Interlaminar Fracture Toughness of 5HS Carbon/PEEK Laminates. A Comparison between DCB, ELS and Mandrel Peel Tests. *Polymer Testing* **2018**, *66*, 13–23, doi:10.1016/j.polymertesting.2017.12.005.
96. Kok, T.; Groupe, W.J.B.; Warnet, L.L.; Akkerman, R. Effect of Ply Orientation on Bond Strength in Fiber-Placed Composites.; January 1 2015.
97. Satheesh, B.; Tonejc, M.; Potakowskyj, L.; Pletz, M.; Fauster, E.; Kaynak, B.; Schledjewski, R. Peel Strength Characterisation on Ply/Ply Interface Using Wedge and T-Peel/Pull-Type Tests. *Polymers and Polymer Composites* **2018**, *26*, 431–445, doi:10.1177/0967391118809205.
98. Su, Y.; de Rooij, M.; Groupe, W.; Warnet, L. Characterisation of Metal–Thermoplastic Composite Hybrid Joints by Means of a Mandrel Peel Test. *Composites Part B: Engineering* **2016**, *95*, 293–300, doi:10.1016/j.compositesb.2016.03.055.
99. Su, Y.; de Rooij, M.; Groupe, W.; Akkerman, R. The Effect of Titanium Surface Treatment on the Interfacial Strength of Titanium – Thermoplastic Composite Joints. *International Journal of Adhesion and Adhesives* **2017**, *72*, 98–108, doi:10.1016/j.ijadhadh.2016.10.007.
100. Breslauer, E.; Troczynski, T. The Peel Adhesion Test for Metal-Ceramic Interfaces. *Key Engineering Materials* **1997**, *132–136*, 452–455, doi:10.4028/www.scientific.net/KEM.132-136.452.
101. Martiny, Ph.; Lani, F.; Kinloch, A.J.; Pardoen, T. Numerical Analysis of the Energy Contributions in Peel Tests: A Steady-State Multilevel Finite Element Approach. *International Journal of Adhesion and Adhesives* **2008**, *28*, 222–236, doi:10.1016/j.ijadhadh.2007.06.005.
102. Sexsmith, M.; Troczynski, T. Peel Adhesion Test for Thermal Spray Coatings. *JTST* **1994**, *3*, 404–411, doi:10.1007/BF02658986.
103. Dolah, R.; Matsuda, M.; Miyagi, Z. *L18 Optimization of T-Peel Test Method for Flexible Packaging Film*; 2012;
104. Bamps, B.; De Ketelaere, B.; Wolf, J.; Peeters, R. Evaluation and Optimization of the Peel Performance of a Heat Sealed Topfilm and Bottomweb Undergoing Cool Processing. *Packaging Technology and Science* **2021**, *34*, 401–411, doi:10.1002/pts.2562.
105. Lamnawar, K.; Maazouz, A. Rheological Study of Multilayer Functionalized Polymers: Characterization of Interdiffusion and Reaction at Polymer/Polymer Interface. *Rheol Acta* **2006**, *45*, 411–424, doi:10.1007/s00397-005-0062-2.
106. Nettles, A.T.; Ratcliffe, J.G. Mode I Toughness Measurements of Core/Facesheet Bonds in Honeycomb Sandwich Structures 2006.
107. Breslauer, E.; Troczynski, T. Determination of the Energy Dissipated during Peel Testing. *Materials Science and Engineering: A* **2001**, *302*, 168–180, doi:10.1016/S0921-5093(00)01370-8.
108. Kinloch, A.J.; Lau, C.C.; Williams, J.G. The Peeling of Flexible Laminates. *Int J Fract* **1994**, *66*, 45–70, doi:10.1007/BF00012635.
109. ASTM D1781-98, Standard Test Method for Climbing Drum Peel for Adhesives, ASTM International, West Conshohocken, PA (accessed on 3 August 2024).
110. Nettles, A.T.; Gregory, E.D.; Jackson, J.R. Using the Climbing Drum Peel (CDP) Test to Obtain a GIC Value for Core/Face Sheet Bonds. *Journal of Composite Materials* **2007**, *41*, 2863–2876, doi:10.1177/0021998307079974.
111. Nettles, A.T. Measuring Core/Facesheet Bond Toughness in Honeycomb Sandwich Structures 2006.
112. Okada, R.; Kortschot, M.T. The Role of the Resin Fillet in the Delamination of Honeycomb Sandwich Structures. *Composites Science and Technology* **2002**, *62*, 1811–1819, doi:10.1016/S0266-3538(02)00099-4.

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