Delamination Growth Directionality and the Subsequent Migration Processes - The Key to Damage Tolerant Design

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Abstract

Delamination has been recognised as one of the challenging aspects of laminated composites, and has been the focus of considerable research over the last three decades. This research reported in this paper investigated the influence of ply interface on delamination propagation. Experimental evidence is presented which illustrates that delamination does not grow in a self-similar manner. Instead, delaminations were shown to propagate preferentially in the direction of one ply at the delaminating interface; which ply was dictated by the orientation of the principal stress at the interface region. In conjunction with the experimental studies, an initial methodology for modelling delamination directionality was presented. The results of this study have considerable implications for tailoring stacking sequences to promote delamination migration and thus enhance damage tolerance.

1 Introduction

Delamination is recognised as perhaps the most critical damage process in laminated composites under compressive/bending loading. Delaminations can develop from a number of processes/features such as ply-drop-offs, impact damage, notches and manufacturing defects. Even a simple, single plane defect can result in multiplane delamination growth [1]. Indeed delamination growth is often associated to other secondary processes such as intralaminar or translaminar damage. Modelling approaches tend to simplify the analysis by considering each failure mode independently. This leads to difficulties in the accurate prediction of progressive growth in structures as the delamination may migrate to another ply interface and promote development of other damage modes.

The most successful approach to investigating delamination has focussed on simple tests (DCB, ENF, MMB) to characterise toughness under controlled conditions at unidirectional ply interfaces. However, when these tests investigate multidirectional interfaces (as utilised in structures), difficulties arise. In particular, delaminations migrate from the original defect plane, invalidating the test results [2]. Fractographic observations [3] have illustrated that these migration processes are associated with the inherent directionality of the delamination growth. That is, delaminations preferentially grow along the direction of the fibres at a ply interface, and if forced to grow obliquely to this, migration processes typically ensue. Whether it is the uppermost or lowermost fibres at an interface which dictate the growth direction is controlled by the orientation of the principal stress at the interface region.

The orthotropic nature of composite laminates implies that the majority of mechanical properties (stiffness, strength) are dependent on the direction. Although being a property which is highly influenced by the resin, interlaminar fracture toughness also exhibits directionality [2]. This effect has been studied in mode I and mode II tests on non-zero ply interfaces, and delamination migration via intralaminar ply splitting has been consistently observed. A critical angle to avoid this migration was identified to be 33.5˚ for mode I and between 7.5˚and 10˚ for mode II [2,4]. At the angles where migration did not occur, the effect of fibre orientation on mode I toughness was negligible. However the behaviour under mode II loading was dependent on the nature of the matrix; brittle matrices exhibited higher ply interface dependence than tougher matrices [5]. This migration mechanism can be explained by considering the stress state at the crack tip [1] within the interply resin layer: under pure shear or mixed-mode loading the principal stress is orientated at an angle and microcracks develop ahead of the crack tip (Figure 1a and Figure 1b). As these microcracks coalesce the delamination is directed to the upper or lower ply/interply boundary where it will then propagate. If the fibres of this ply are aligned with the delamination growth direction, the delamination will remain in that plane. However, if the fibre direction does not coincide with this growth direction, the delamination will migrate through the plies until it reaches an interface in which the ply and delamination growth directions are approximately coincident . This mechanism has been verified by fractographic observations; typically the matching faces of delaminated surfaces present either exclusively matrix or fibre dominated morphology, which implies that delamination does not usually grow cohesively through the interply resin-rich region, but interfacially adjacent to one ply of an interface [1]. This implies that fibre orientation may influence its behaviour.

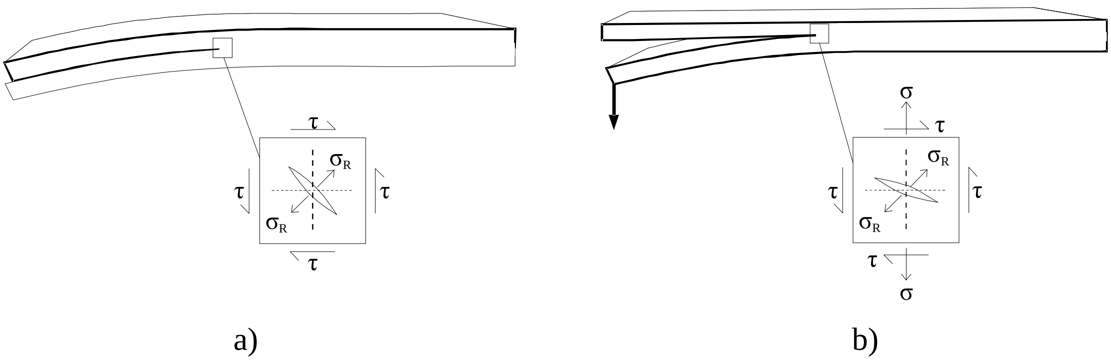

Figure 1. Resolved stresses in (a) pure mode II and (b) mixed-mode test configurations.

It has been shown that surface features of a fibre diameter scale can significantly influence the behaviour in mode I [6] therefore it is expected that features due to the fibres themselves would have a similar effect in the fracture toughness. Another example where this directionality effect caused by the fibres was observed is in woven composites [7]. In this study, the authors tested carbon and glass woven composites in mode I. Plain, twill and 8 harness satin configurations were tested in two directions to verify the effect of the fill direction on the fracture toughness. The results showed that as the crimp increased, so did the difference between the fracture toughnesses in both directions. For plain weave, both directions had similar values; however delamination propagation in the fill direction showed lower resistance than that in the weft direction for twill and satin weave patterns. These results are significant because woven materials do not exhibit the same degree of migration often observed when trying to grow a delamination obliquely to the fibre direction [2].

When delamination problems are approached numerically, these experimental observations are often overlooked. The behaviour of the ply interface is often modelled uniquely with shear and opening delamination modes. Typically, displacement and shear tractions in the two directions on the plane (direction 2 and 3) of the ply interface are accounted together as

$$\delta_{shear} = \sqrt{(\delta_2)^2 + (\delta_3)^2} \tag{1}$$

$$t_{shear} = \sqrt{(t_2)^2 + (t_3)^2} \tag{2}$$

and a single value for the fracture toughness of the interface is used in both directions [8].

The objective of this paper is to present experimental results demonstrating directionality of delamination growth. The approach has been to formulate and conduct simple experiments in which directionality could be observed, and use these to validate predictive models. Furthermore, the effect of using distinct initiation strength and toughness values to model delamination directionality has been briefly presented. These results could be used to support observations from more complicated loading conditions such as buckling induced delamination in laminates under membrane compressive loading [9], and also provide benchmarks for the development of physically based predictive models for delamination.

2 Experimental details

As shown in Figure 2, a novel, yet simple, experimental configuration was proposed to demonstrate delamination directionality (i.e. achieve asymmetric growth, see Figure 3). As shown in Figure 2, this configuration was based on an End Loaded Split **(**ELS**)** width tapered specimen configuration. The stacking sequence was chosen to have a predominant grow direction at the mid-plane to promote the formation of an asymmetric delamination front. This configuration had the advantage of exhibiting stable crack growth and of providing a large fracture area to inspect using fractographic techniques.

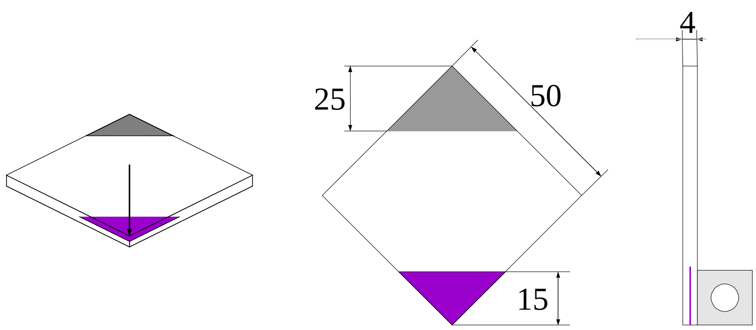

Figure 2. End Loaded Split (ELS) width tapered specimen with end-block. Precrack insert shown in violet and clamping area in grey. Units in mm.

Two 250 x 200 mm panels were manufactured with Hexcel IM7/8552 0.125mm thick pre-preg using the stacking sequences shown in Table 1. The stacking sequences were chosen to minimise bending-twisting coupling and ensure similar bending stiffnesses in the arms. To maintain the same elastic properties while achieving a different delamination interface, +45°/-45° for configuration 1 and -45°/+45° for configuration 2, the two configurations differed only in the sequence of the +45° and -45° plies. A 10μm PTFE film acting as a crack starter was inserted at the mid-plane during lay-up and the panels were then fabricated following the manufacturers recommended cure schedule. Three specimens of each configuration were cut from the two panels, the faces to be bonded were sandblasted and end blocks bonded with Araldite 2011. The specimens were tested in an Instron universal testing machine with a 100 kN load cell at a loading rate of 2 mm/min until the delamination had reached the clamp. After testing, time-of-flight (TOF) C-Scans were performed to determine the growth directions and sites of the delamination. C-Scans were done with a 10 MHz ultrasonic probe coupled to an ANDSCAN v3.1 full waveform capturing device. A TOF gate was centred on the defect to monitor the depth of the delamination. The specimens were scanned upside down to avoid any interference of the ultrasonic signal with the glue left after removal of the end-block. Specimens were then exposed for fractographic examination using a S-3400N Hitachi scanning electron microscope (SEM) at magnifications of between x100 and x400 at an acceleration voltage of 15 kV.

Configuration 1 Interface 45/-45	[(45°/90°/0°/-45°)$_s$(45°/0°/90°/-45°)$_s$//(-45°/0°/90°/45°)$_s$(-45°/90°/0°/45°)$_s$]
Configuration 2 Interface -45/45	[(-45°/90°/0°/45°)$_s$(-45°/0°/90°/45°)$_s$//(45°/0°/90°/-45°)$_s$(45°/90°/0°/-45°)$_s$]

Table 1. Stacking Sequences for the two configurations studied

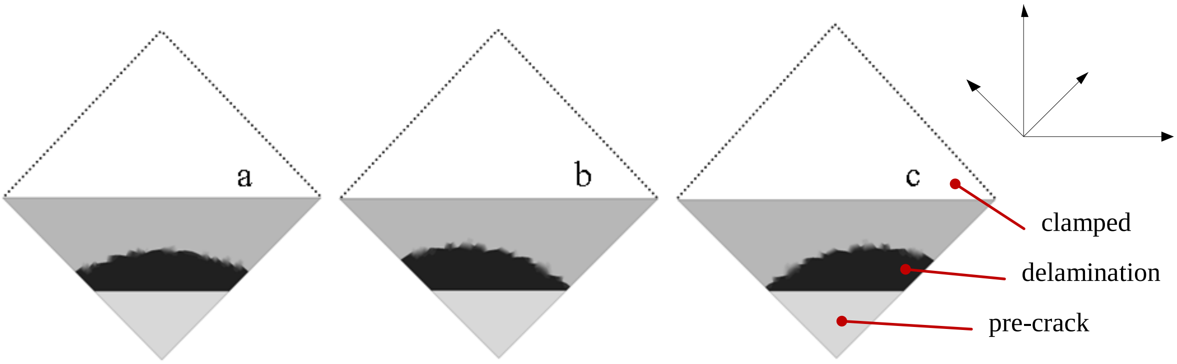

Figure 3. Predicted delamination with a) nominal properties, b) enhanced properties transverse to fibres for configuration 1 and c) configuration 2.

3 Preliminary numerical analysis

Prior to testing, some preliminary analyses were conducted in Simulia Abaqus/Standard [10]. The unclamped portion of the square plate shown in Figure 3 was modelled with one layer of continuum shell elements per half plate thickness and laminate definition as per Table 1. Cohesive elements were inserted in the mid-plane, but were omitted in the triangular pre-crack area. Transverse displacement was applied at the tip of both plate halves to avoid contact modelling. Mechanical material properties for IM7/8552 were taken from[11], only the cohesive parameters are repeated here: Initiation stress, S_{IC} = 62.3MPa, S_{IIC} = S_{IIIC} = 92.3MPa, and critical SERR, G_{IC} = 277J/m^2, G_{IIC} = G_{IIIC} = 788J/m^2. Only the mode II values were of particular relevance here but realistic mode I values must still be specified in the cohesive law. The Abaqus cohesive element uses the vector sum of II and III values to evaluate the actual mode II (sliding) response, as shown in Eq. 1. It is customary to use similar values since it is generally difficult to distinguish between the two modes from a modelling perspective. In the present analysis the II subscript indicated sliding along a neighbouring ply direction and the III subscript indicated sliding perpendicular to the fibre in the delamination plane. For consistency, it is currently necessary to manually define a material orientation for the cohesive layer such that it is aligned with a chosen fibre orientation. Here, this direction is -45° for configuration 1 and +45° for configuration 2, see Table 1 and Figure 3. Predicted delamination with nominal cohesive values is shown in Figure 3a. For modelling of the anticipated directionality, values were modified such that $S_{IIIC} = 2 \times S_{IIC}$ and $G_{IIIC} = 4 \times G_{IIC}$ to mimic the higher resistance to growth perpendicular to fibres. The enhanced values were chosen somewhat arbitrarily merely to illustrate the potential behaviour. Results are shown in Figure 3b for configuration 1 and Figure 3c for configuration 2. It was assumed that the delamination would remain in the same plane, but as is presented in the following paragraphs, the tests showed significant, yet highly repeatable, migration. Ply damage was not modelled here but examination of matrix stresses at delamination initiation revealed that stresses were close to matrix strength thus indicating the possibility of ply splits formation, thus leading to migration. This will be addressed in more detailed modelling.

4 Test results

The load-displacement curves are shown in Figure 4; for clarity only two representative specimens from each configuration are shown. The test configuration was very sensitive to the initial crack length which caused an inconsistency in the specimen compliance specimens. However, it should be noted that the fracture processes were highly reproducible and the fracture surfaces shared major similarities (Figure 5a and Figure 5b). The two configurations had mirrored morphologies such as the location and number of ply splits.

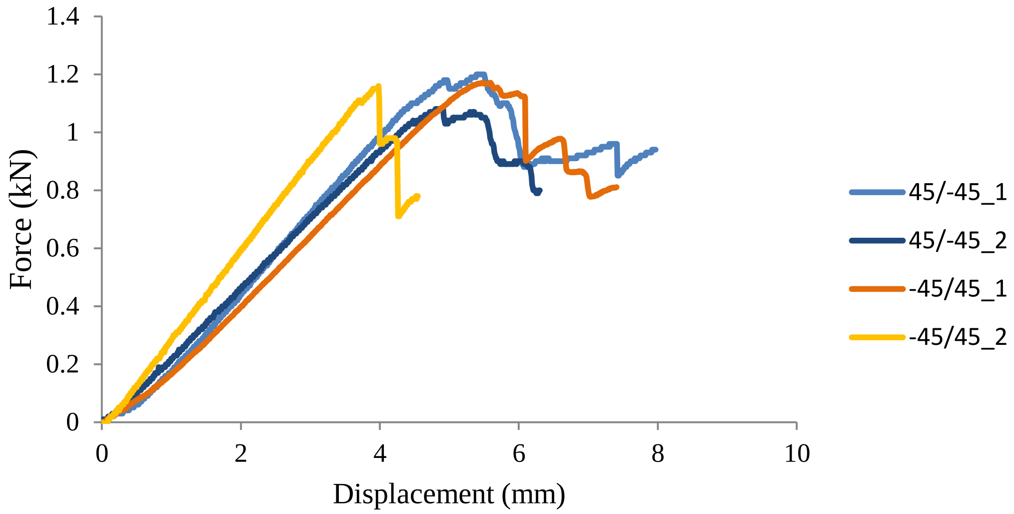

Figure 4 Load displacement curves for the four specimens

Figure 5 should be interpreted accordingly to the scanning direction. Because of the scan being upside down angles and depth values are inverted. In the four cases, the delamination migrated towards the lowermost face as was expected from the orientation of the principal stress (Figure 1). It was apparent that the delamination had grown at four different ply interfaces starting from the mid-plane (depth 2.00 mm from the back surface; lilac) changing to the following interface $17^{th}/18^{th}$ (depth 1.88 mm; pink) and migrating twice more to interface $18^{th}/19^{th}$ (depth 1.76 mm; orange) and $19^{th}/20^{th}$ (depth 1.63 mm; yellow). However, all specimens exhibited a band (Figure 5) where the delamination did not migrate, which corresponded to the area in which preferential growth had been anticipated (i.e. the growth and lower ply directions were coincident). Detailed inspection of this band close to the insert is shown in the electron micrograph (Figure 6). This surface corresponded to the upper matching surface of a +45˚/-45˚ interface at the initial delamination plane; hence, as expected, it was matrix dominated [3] as the delamination had propagated parallel to the lowermost ply. Cusps and gouges were seen perpendicular to the fibre imprints (Figure 6); the latter are a typical fractographic feature found at interfaces with a relative ply orientation of 90˚ and both features are indicative of a mode II component [3]. In the micrograph, the direction of the cusps was not aligned with the insert boundary as would be expected if self-similar growth had occurred. Instead the cusps were orientated perpendicular to the fibre imprints from the upper surface, indicating that the local growth had been parallel to the 45˚ ply. Although the global delamination had appeared to have been radial (Figure 5), it was evident from the fractographic observations that the local growth directions had followed the orientation of the lower ply. Furthermore, main delaminated area (indicated in orange in Figure 5) was at the 18th/19th ply interface (0˚/90˚) which corresponded to the interface at which the direction of the lower ply (90˚) matched the global growth direction. It should be noted that the original delamination had migrated through three plies (16th, 17th and 18th) to reach this interface.

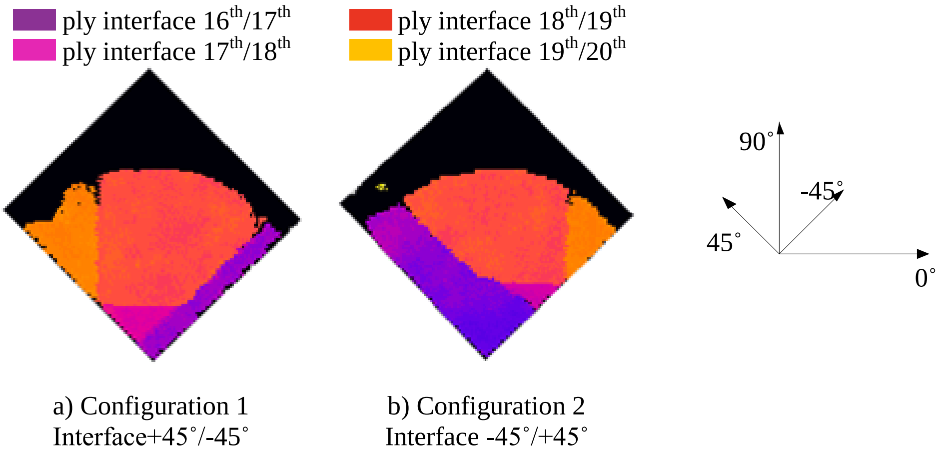

Figure 5. Time of flight C-Scan showing the delamination propagating at different interfaces

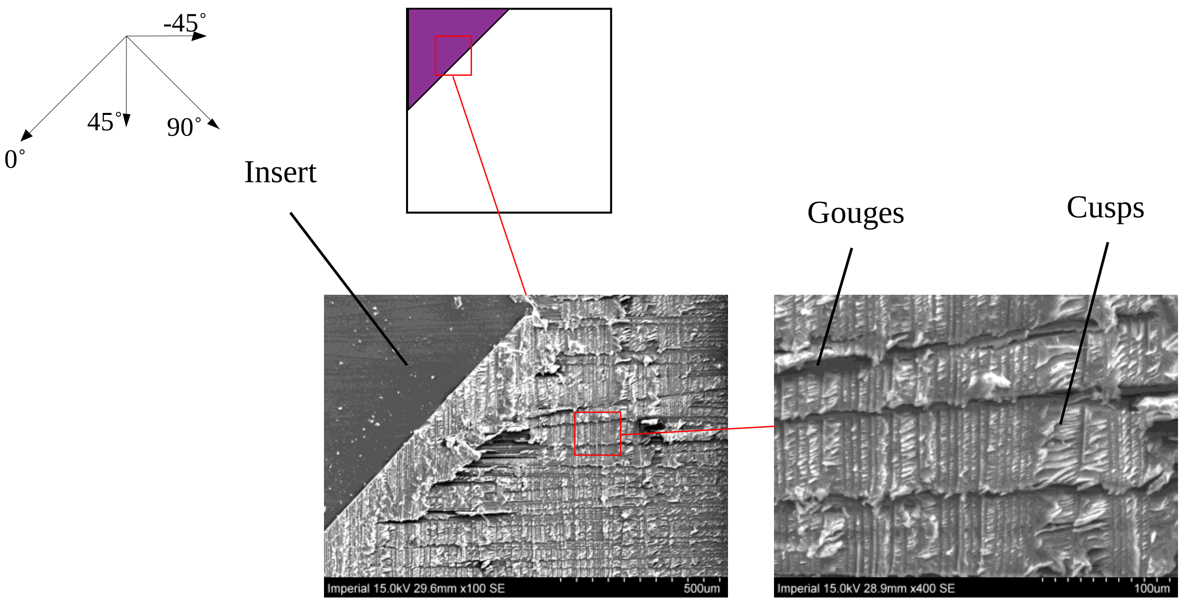

Figure 6. SEM Micrograph specimen 1 (45˚/-45˚ ply interface)

6 Discussion

Delamination has been recognised as one of the challenging aspects of laminated composites, and has been the focus of considerable research over the last three decades. Much of this research has characterised the fracture toughness under different loading modes, or combinations thereof, in unidirectional coupons. However, it has proved to have been difficult to translate this coupon data into the behaviour observed in structures containing embedded delaminations or in-service damage. The fractographic observations reported here and elsewhere [1] have demonstrated that this difficulty is attributed to the fundamental processes by which delaminations grow. In essence, delamination growth exhibits directionality, with the lowest toughness associated with growth parallel to the fibre orientation at a ply interface; whether this is the upper or lower ply of a particular interface is dictated by the sense of the shear stress. If a delamination is driven to propagate obliquely to the ply direction, migration will ensue, continuing until the delamination reaches a preferable interface.

To date, this is a fundamental behaviour associated with delamination in composites has been neglected in predictive models. However, finite element methods have now reached a level of fidelity in which the detailed processes which develop at a ply level (directional delamination growth and migration) could be modelled and therefore accurate prediction of damage growth should be achievable. In the research reported here, a methodology for imposing delamination directionality in predictive models has been presented, and this provides a starting point for further study. The challenge is to link the cohesive material parameters to the adjacent plies and correctly calculate the ply interface along which preferential growth will occur.

In the experimental studies reported here, a simple test configuration was presented which illustrated directionality of delamination growth. Although global growth appeared to have been radial from the insert boundary, locally delamination extension had occurred at four different ply interfaces; delamination had grown parallel to the lowermost ply orientation of each of these interfaces. Since this test exhibited a high level of reproducibility, it could be used to validate models for predicting delamination migration and intralaminar cracks. Finally, it was notable that the multilevel delamination lobes (Figure 5) reported here were very similar to those observed in impact damage, as reported by Hull [12]; these had also been attributed to preferential delamination growth along the ply direction.

Identification of this fundamental directionality/migration process has considerable implications for damage tolerant design of composite structures. If a delamination is located at a preferable interface (i.e. the ply and growth directions coincide), then rapid damage growth will ensue. However, if the stacking sequence is tailored to promote migration (i.e. plies orientated in the direction of growth are avoided), this will lead to massive tow bridging of the crack faces which will tend to increase the tortuosity of the crack path and thus constrain damage extension. Clearly, through careful design there is the opportunity to exploit this mechanism to produce more robust and durable composite structures.

7 Conclusions

An experimental method has been presented to probe the effect of fibre orientation in fibre reinforced composite materials. To accurately study the influence of the ply orientation on the fracture toughness, delamination migration needs to be prevented. However, a delamination will always migrate if not propagating at the appropriate interface. This renders almost impossible to determine the fracture toughness of these interfaces as other energy dissipating mechanism will participate in the process. Therefore, if the fundamental effect of the fibres in the delamination path is to be studied, there is a need to dissociate delamination with its intrinsically linked migration through the plies. For this purpose a material containing the same interfacial features but preventing migration should be used. The authors anticipate that this could be done by replicating the interfacial features of a CFRP ply in an isotropic media or using a composite material which is resistant to intralaminar splitting.

Numerical models accounting for directionality effects on the delamination growth have been presented. It has been shown that by manually defining the orientation of the cohesive elements in the ply interface it is possible to dictate a preferential growth direction. The method presented needs to be extended to include the orientation of the ply interface into the cohesive material parameters.

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