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Testing and Analysis of Ultra Thick Composites

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ABSTRACT: For the development of a composite main landing gear fitting in carbon fiber reinforced plastics the behavior and performance of Ultra Thick Laminate components is investigated. Material thicknesses exceeds 60mm. For the purpose of validation a test program is arranged using T-cross sections subjected to multiple load cases. The components are manufactured entirely with non crimped fabrics (NCF) using an adapted open mould manufacturing process. In addition to these T-Sections large full scale subcomponents of the entire fitting are manufactured and tested. As main topic of this paper standard FE methods are investigated and validated for thick structures using the generated test results. Due to the presence of transverse shear and normal stresses a 3D modeling approach is chosen. Transverse shear and normal stresses are indentified as main failure cause and failure is mainly initiated in the curved regions. Solid composite brick elements offer an efficient way to model thick structures. These are incapable of calculating accurate shear stresses on a ply level; usable results are however achieved by discretisation of the component with multiple elements over thickness. In addition stress gradients in the failure region are small; stress variations on a ply level are minimal. Out of plane material properties are not available and initial assumptions are made. Material correction factors (degradation) are introduced and discussed.

KEYWORDS: (A) Carbon-carbon composites; (C) Finite element analysis (FEA); Ultra thick laminates

INTRODUCTION

The increasing use of laminated composites is spreading from classical applications such as thin walled covers or beams, to highly loaded and compact fittings and joints. Compact structures are often tied to high loads and limited design space. While the increasing thickness of the material requires the development of suitable manufacturing methods, the analysis is also confronted with numerous challenges. The design and layout of the component is highly influenced by the manufacturing process itself; this will directly link the different engineering disciplines. A possible future example of such an application is illustrated in Figure 1. The composite version of the 'Side Stay Fitting' (SSF) landing gear component is developed by EADS Innovation Works as part of the EU project ALCAS (Advanced Low Cost Aircraft Structures) in close cooperation with Airbus UK . The component serves as a joint between the main landing gear (MLG) and the wing spar; see Figure 1(A). Figure 1(B) illustrates the final composite design. It consists of two lugs, inboard and outboard, carrying a cardan pintle axis. Design constraints such as unchanged kinematics and maintained surrounding design space determine the basic layout. Manufacturing capabilities and methods for the new material place additional restrictions on the new layout.

Figure 1 Main landing gear with metallic Side Stay Fitting (a). Composite Side Stay Fitting (b).

Unlike in any thin structure, significant transverse and normal peeling stresses are expected due to the limited dimensions of the fitting in combination with high multidirectional loads. The failure behavior of Ultra Thick Laminates (UTL) is investigated using 3D stacked brick elements implemented in MSC Marc/ Mentat [2]. Due to the linear shape function of the element, transverse shear stresses can not be calculated accurately on a ply level, as shown by Kuhlmann and Rolfes [3]. A reasonable prediction of these stresses is however achieved by discretising the components over thickness. This work describes the initial phase of the project in which an analysis for characteristic cross sections of the fitting is performed, so called T-Sections. The components are manufactured and tested at full scale. Three load cases are investigated; tension (T-Pull), compression (T-Push) and bending (T-Axial). In addition one half section of the entire fitting is tested. This component is referred to as ‘Double Corner’ and is subjected to combined loads, in contrast to the T-Sections.

TEST COMPONENT DESCRIPTION

An experimental program is implemented using the T-Section as a characteristic cross section of the Side Stay Fitting. This cross section as well as the basic layout is illustrated in Figure 2. Loads are subjected to the central web of the component, whereas the flange is used to be bolted to the adjacent structure. The curved sections of the web enclose the gusset filler.

Figure 2 Typical Side Stay Fitting cross sections and corresponding T-Section nomenclature

The T-Section design parameters are illustrated in Figure 3. During the design process the maximum laminate thickness t_1 is increased from 60mm to 68mm, while maintaining a constant radius of $r_0 = 35mm$. A 6mm bottom laminate (t_2) is used to fully enclose the

gusset filler. As will be shown later the bottom laminate has a large influence on out of plane peeling stresses in the upper gusset corner and the consequential failure load. For the filler different materials are investigated; non- supportive foam fillers as well as load carrying carbon fillers. Refer to Table 1 for detailed dimensions.

Figure 3 T-Section dimensions l parameters.

Table 1 General T-Section dimensions

T-Section dimensions [mm]	
t_1	60-68
t_2	6
t_3	30-34
h	350
b	100-120
r_0	35

In particular the radius region as well as the gusset corner is subjected to high transverse shear and peeling stresses due to the load transfer from the web to the flange. Initial ideas led in the direction of out of plane reinforcement in the form of stitching or z- pins. According to Schuermann [8] pins cannot prevent the first delamination; purely crack growth will be reduced. In order to effectively counteract the delamination initiation a constant pretension of the fibers is required. In addition any reinforcement will reduce the in plane properties significantly. DeTeresa [11] demonstrated experimentally that through thickness compression enhances the interlaminar shear fatigue lifetime.

Figure 4 illustrates the unreinforced standard T-Section as well as two reinforced variants. (B) shows a reinforcement of the three gusset corners. (C) incorporates a middle laminate

potentially reducing the loads transferred to the curved section. A delamination is considered as first failure, a 3D reinforcement is hence not implemented due to the inability to prevent the delamination onset. The tests also show a significant residual strength of the components.

Figure 4 Possible 3D reinforcement for the UTL T-Section.

The test program is extended from simple T-Sections to a half section of the entire fitting. The component is referred to as ‘Double Corner’ and is illustrated in Figure 5. Maximum laminate thickness is 60mm, similar to the T-Sections. Two load directions are tested. In the context of this work only the inplane load is examined due to its similarity to the T-Section test results.

Figure 5 Double Corner general layout and dimensions.

TEST MATRIX OVERVIEW

Strain gauges are applied in the radius in order to monitor the local deformation. In addition the cross section is monitored using a digital image correlation system (GOM Aramis). The stochastic pattern can be seen in Figure 6. Metallic blocks are used on either side of the web to clamp the flanges to the base plate of the test rig. These are used to simulate one entire bolt row of the landing gear fitting and are thus designed with high stiffness. Three bolts are used to load the web.

Figure 6 60mm T-Section with side installed displacement transducer.

Three characteristic T-Section loadcases are investigated as illustrated in Figure 7: Tension (T-Pull, A), compression (T-Push, B), and bending (T-Axial, C). For Pull and Push the load is transferred with the above described bolts. For Axial bending a single rotating joint is used at a distance c_l from the base, see also the forthcoming chapter ‘T-Axial’ for more details.

Figure 7 Loadcase Illustration

The Double Corner loadcase resembles T-Pull. The load is applied at 28° inclination via a hinged cantilever; see test setup in Figure 8. The test essentially presents an extension to the described T-Pull test with two load direction. In addition the Double Corner presents one half of the above mentioned Side Stay Fitting and is considered as a full scale test.

Figure 8 Double Corner test setup.

ANALYSIS

For the analysis a stacked composite brick element is used (type 149), available in MSC Marc/ Mentat (see MSC Marc ‘Element Library’ [2]). This is an isoparametric 3D 8-node composite brick and for each layer different material properties can be applied. The element presents an efficient way to model thick laminates with a large amount of layers. As investigated by Kuhlmann and Rolfes [3] the stacked brick element yields a satisfactory result for transverse normal stresses σ_{33} . Transverse shear stresses τ_{13} and τ_{23} however contradict the exact solution since the step like displacement distribution over the thickness of composite structures can not be reproduced. The effect on UTL is shown in Figure 9. Here the stacked brick element with 8 plies per element is compared to a high resolution mesh (3 elements/ ply). The fine mesh shows the stress distribution over the individual ply whereas the layered element only can reproduce the global distribution over the component thickness. It also becomes obvious that in the region of highest shear stress the effect of altering ply angles is low in relation to the overall stress level; in addition stress gradients are small. A reasonable transverse shear stress distribution over thickness using the layered element is hence achieved with a discretisation that features multiple elements over thickness. The maximum stress level can be calculated with adequate accuracy. A slight offset of the maximum stress position can be observed, which is believed to be the effect of the coarser mesh.

Figure 9 Transverse shear stress distribution over normalized thickness.

For every element a local element coordinates system is defined, also referred to as the ‘preferred system’. Figure 10 shows the excerpt from the curved section of the T-Section radius. Three base vectors, denoted x_1 , x_2 and x_3 , define the orientation of the ply within the element. Stresses are calculated in the local ply direction. In addition a thickness direction is used in order to define the stacking direction. For the laminate the stacking direction coincides with x_3 . Each element has four integration points per layer. Element thickness is determined by ply thickness and the number of layers per element. A maximum of 8 plies is used for one element. Element width and length is subsequently calculated as a multiple of the height. Here a maximum multiple of 4 is not exceeded.

Figure 10 The curved radius section requires the definition of local element coordinates.

MATERIAL AND PROCESS

The final landing gear fitting is subjected to loads in different directions. As a first approach and based on common design rules a standard biaxial NCF is chosen, with a quasi isotropic stacking sequence $[(0/90/-45/45)_s]_n$. Optimizing the stacking sequence is recognized as a way to further improve and optimize the structure, but this is not

considered in the initial T-Section test program. The chosen material is Tenax HTS 12K (Saertex) (+45/-45, -45/+45, 0/90) biaxial NCF and is applied in combination with RTM6 (Hexcel) resin and PA1541 binder fleece. A fiber volume fraction of 58% is measured.

The components are manufactured using an adaptation of the standard open mould vacuum assisted process (VAP). Due to the large wall thickness the process is separated into two or more infiltration steps; the outer section of the laminate is pre-cured and subsequently used as an outer tooling. In a final step the inner laminate is infiltrated and cured. Due to the combination of cured components and dry performs the process is also referred to as ‘Integrated Tooling Concept’ [10].

For the analysis the full 3D mechanical properties of the transversely isotropic material are required. The constitutive equation yields

$$(\boldsymbol{\varepsilon}) = [\boldsymbol{S}](\boldsymbol{\sigma})$$

$$\begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 = \gamma_{23} \\ \varepsilon_5 = \gamma_{31} \\ \varepsilon_6 = \gamma_{12} \end{pmatrix} = \begin{bmatrix} 1/E_{11} & -\nu_{21}/E_{11} & -\nu_{31}/E_{33} & 0 & 0 & 0 \\ -\nu_{12}/E_{11} & 1/E_{22} & -\nu_{32}/E_{33} & 0 & 0 & 0 \\ -\nu_{13}/E_{11} & -\nu_{23}/E_{22} & 1/E_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{23} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{31} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{12} \end{bmatrix} \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 = \tau_{23} \\ \sigma_5 = \tau_{31} \\ \sigma_6 = \tau_{12} \end{pmatrix} \quad 1$$

Only a limited number of material properties are available, namely E_{11} , E_{22} and G_{12} . E_{33} is calculated with an empirical correction factor $k_3 = 0.7$ in order to gain comparable deformations as the tests have shown. Additional statements for the material are

$$\begin{aligned} E_{33} &= k_3 E_{22} \\ G_{12} &= G_{13} \\ \nu_{12} &= \nu_{31} \\ G_{23} &= \frac{E_2}{2(1 + \nu_{23})} \end{aligned} \quad 2$$

ν_{12} is primarily based on sources found in the literature, [3], [9]. Similar properties as for G1157 with RTM6 are assumed; see [12] and Table 2.

Table 2 Material properties for G1157 with RTM6.

E_{11} [MPa]	E_{22} [MPa]	E_{33} [MPa]	ν_{12}	ν_{23}	ν_{31}	G_{12} [MPa]	G_{23} [MPa]	G_{31} [MPa]
136000	9400	6580	0.30	0.52	0.015	5400	3100	3100

T-PULL

The pull test setup is illustrated in Figure 11. The T-Section (3) is attached via the test rig brackets (2) to the hydraulic cylinder (1). Two clamps (5) serve as connection to the base plate (4).

Figure 11 T-Pull test setup.

The 60 mm thick T-Section delaminates in the upper gusset corner where the two radii converge, see Figure 12. Here the stresses are dominated by σ_{33} . Due to the strong mesh dependency the peeling stress σ_{33} is not examined in a single point but along a path φ . The interfacing foam is highlighted with a dotted line. Due to its low stiffness the foam is omitted in the finite element analysis.

Figure 12 The crack develops at the tip of the converging radii.

It is found that the initially calculated strains in the upper gusset corner are significantly higher than measured values. To improve the accuracy of the calculated results the interface between the two radii is modeled with a 0.4mm thin layer of elements with pure resin properties to account for undulations found in that region.

Figure 13 shows the measured (Aramis) as well as calculated strain across the upper corner. The image illustrates the results for two T-Sections, namely TS04 and TS07, as well as the calculated values.

Figure 13 Peeling strain across the upper gusset corner according to optical strain measurement and FEA.

Bottom Plate Influence for T-Pull

Every T-Section includes a 6mm bottom laminate. The removal of the bottom laminate is only tested for a larger sample measuring 68x120mm. The results are illustrated in Figure 14. Here the peeling stress is displayed along φ . Peak peeling stress is decreased by approximately 20%. Omitting the bottom laminate enables the radii to move in lateral direction, thus reducing the stress diverted to the upper gusset corner. The bottom

laminate should hence be kept as thin as possible to decrease upper corner peeling stresses.

Figure 14 T-Section test configuration with and without bottom laminate.

Double Corner

Due to similarities of the results the Double Corner is also presented in the context of the T-Section. Deflection is measured at the central axis. Figure 15 illustrates the deformation as measured and calculated up to 580kN failure load. First failure is comparable to the T-Pull specimen; a delamination of the converging upper gusset corner. The load carrying capability of the Double Corner is however virtually unaffected and the delamination does not spread significantly. The load is increased to 1000kN after which a sudden and complete delamination of the web is observed followed by a load drop. Irregularities in the graph are caused by halts in the load application in order to manually store the test data. In addition Figure 14 illustrates the calculated deflection.

Figure 15 The calculated deflection is marked with a dotted line.

For the analysis equal element size is used as for the T-Section. Due to the compact dimensions of the component and the given proximity of the load introduction to fixation bolts, it is found that boundary conditions have a large influence on the overall deformation of the component. Fixation bolts are modeled with line elements through the thickness of the laminate to simulate a certain bending stiffness. A pintle axis is used to apply the load. The limited contact region of the pintle to the laminate is approximated with rigid body elements connected to the compression side of the laminate hole.

T-Pull and Double Corner Failure Analysis

The delamination of the upper gusset corner observed both for T-Pull and the Double Corner is the effect of the discontinuity and can be characterized as a free edge effect. It is of great interest to directly transfer the obtained test data to the final component for sizing. Stresses at the free edge are however highly mesh dependent. In addition to a maximum stress criterion the Kim Soni delamination criterion is applied, see also [4]. Here the peeling stress is examined along a characteristic length φ . This criterion is specifically related to the failure mode and failure location of T-Pull.

$$\bar{\sigma}_z = \frac{1}{b_0} \int_0^{b_0} \sigma_z(\varphi, 0) d\varphi \quad 3$$

Choosing the characteristic length b_0 is crucial. Since the stress peak is expected to initiate the crack, b_0 should be as small as possible in order to best account for the stress concentration. In addition mesh related deviations should be reduced. The criterion can be applied to three individual test results: The 60mm T-Pull, the 68mm T-Section with removed bottom laminate and the Double Corner. The calculated average stress leading to failure should be equal for all three test results. Figure 16 illustrates the calculated results for all tests for the corresponding failure load. Equal average stress values are achieved for $b_0 = 20mm$. The critical average normal peeling stress is thus calculated to $\bar{\sigma}_z = 15MPa$.

Figure 16 Average normal peeling stress for 60/68mm T-Sections and Double Corner.

T-PUSH

In addition the T-Sections are subjected to compression loads, referred to as loadcase T-Push. Here the web is pushed downwards, subjecting the radius to shear and compression loads. Figure 17 illustrates T-Push at 320kN.

Figure 17 Enlarged delamination region, cracks are highlighted white.

The maximum shear stress level at failure is calculated to $\tau_{31,crit} = \pm 37 \text{ MPa}$. Each element contains eight plies and only the layer with the highest stress is plotted. For the radius a local cylindrical coordinate system is defined, where $r_0 = 35 \text{ mm}$ is the initial radius and t is defined as the laminate thickness, see Figure 18 (A). The angle γ defines the position on the radius. Figure 18 (B) illustrates the calculated shear stress distribution. The maximum stress is plotted for $\gamma = 20^\circ$. The image also indicates that by using solid elements transverse shear stresses do not vanish at the free surfaces of the structure and are discontinuous at layer interfaces since transverse shear stresses are obtained directly from the displacement field.

Figure 18 Transverse shear distribution over thickness for T-Push

Calculated stresses for the failure region are summarized in Table 3 for $\gamma = 20^\circ$. Allowables are given in parenthesis, based on the available material data sheet [12].

Table 3 Calculated stresses for T-Push.

σ_{11} [MPa]	σ_{22} [MPa]	σ_{33} [MPa]	τ_{31} [MPa]	τ_{23} [MPa]
-76	-2.6	-8	37	0
(1970/-990)	(67,-240)	(67,-240)	(62)	(62)

For the transverse allowable the following assumption is made

$$S_{3i} = S_{12} \quad i = 1, 2 \quad 4$$

Stresses are dominated by transverse shear and the influence of inplane stresses is therefore neglected in the analysis. The calculated shear stress is used to extract a correction factor according to

$$k_{3i} = \frac{S_{3i}}{\tau_{3i}} \quad i = 1, 2 \quad 5$$

The shear correction factor is calculated to $k_{31} = 1.9$. It indicates that the actual transverse shear allowable is significantly lower despite the negligence of possible stress interactions. As mentioned previously (see Figure 9) high resolution meshes with multiple elements per ply have confirmed the correctness of the maximum transverse shear stress level. The used

material is undergoing additional coupon/ material tests in the near future to generate reliable properties for UTL.

Application of a Supportive Carbon Gusset Filler

The current foam gusset filler provides minimum support to the structure. Under compression the flux of the load is via the web through the radius section. Here the load is redirected by 90°, causing mainly transverse shear stress concentrations in that particular region. Due to its low stiffness the gusset filler does not attract major loads; it does not serve any structural purpose in its current form. In order to support the radii a monolithic CFRP filler is introduced. This CFRP filler is essentially a partially cured laminate that is milled into the appropriate shape. It is co- cured with the remaining preform in a final infiltration. No failure of the reinforced T-Sections is monitored up to the maximum load level of the test rig (400kN). Figure 19 illustrates the calculated transverse shear stress for the foam equipped T-Section at 320kN failure load, compared to the reinforced T-Section at 400kN. A large portion of the load is diverted to the gusset; shear stresses are reduced by approximately 50%. Downward displacement of the web is also reduced significantly due to direct support of the carbon filler. The highest shear value is moved to the interface region filler/ radius. The effect is caused by the sudden increase in stiffness. For increasing loads the co- cured gusset/ radius interface becomes critical. The CFRP filler is hence implemented in the new design.

Figure 19 Shear stresses are reduced significantly with the CFRP gusset filler..

T-AXIAL

The third load case T-Axial is an asymmetric bending load. One side of the radius is subjected to tension and the opposite side to compression. Figure 20 illustrates the T-Axial

test setup. In contrast to T-Pull and T-Push the T-Section is mounted vertically due to the position of the hydraulic cylinder. The applied load F has a cantilever c_l thus creating a bending moment. The load is applied as a pulling load.

Figure 20 T-Axial test setup.

Under axial bending load, a more complex stress combination can be found. The radius on the tension side of the specimen delaminates at $1/3^{\text{rd}}$ of the laminate thickness. The failure is illustrated in Figure 21. A delamination of surface layers occurs after the first failure.

Figure 21 T-Axial failure mode. Arrows highlight the delamination.

Table 4 summarizes measured as well as calculated strain and displacement values for the samples TS14/15/17. The values highlight that calculated deformations and strains are in line with measured values using the adjusted material properties. Strains are measured on both sides of the radii and displacement is extracted from the load insertion.

Table 4: Test specimen overview

Specimen Name	Strain [$\mu m / m$]	Displacement [mm] (at load insertion c_l)
TS 14	+/-3900	5.1
TS 15	+/-4000	5.3
TS 17	+/-3900	5.2
FEA	+3700/-3550	5.6

In the failure region the maximum peeling stress σ_{33} is calculated to 26MPa, see Figure 22. As the stress distribution indicates, the maximum stress occurs at 1/3rd of the laminate thickness, at the position of the first failure.

Figure 22 In the radius peeling stress strongly resembles the shear stress distribution.

In addition to σ_{33} significant shear stress τ_{31} is present. Figure 23 illustrates relevant stresses in the delamination interface. Transverse shear is reduced to a minimum in the region of highest peeling stress. The failure is hence dominated by peeling stress.

Figure 23 Mid Laminate stresses on radius tension side on crack surface.

The well known Tsai-Hill failure criterion [15] is applied in the region of the crack.

$$\begin{aligned} & \frac{\sigma_1^2}{X^2} + \frac{\sigma_2^2}{Y^2} + \frac{\sigma_3^2}{Z^2} - \left(\frac{1}{X^2} + \frac{1}{Y^2} - \frac{1}{Z^2} \right) \sigma_1 \sigma_2 - \left(\frac{1}{Y^2} + \frac{1}{Z^2} - \frac{1}{X^2} \right) \sigma_2 \sigma_3 \\ & - \left(\frac{1}{Z^2} + \frac{1}{X^2} - \frac{1}{Y^2} \right) \sigma_1 \sigma_3 + \frac{\tau_{12}^2}{S_{12}^2} + \frac{\tau_{23}^2}{S_{23}^2} + \frac{\tau_{31}^2}{S_{31}^2} \geq 1 \end{aligned} \quad 6$$

In addition to the empirical correction factor for transverse shear (see equation 5) an additional factor for normal peeling stresses is applied. With the assumptions of negligible inplane stresses $\sigma_1 \sim 0, \sigma_2 \sim 0$ the criterion is reduced to

$$\frac{(\sigma_{33} k_{33})^2}{Z^2} + \frac{(\tau_{31} k_{31})^2}{S_{31}^2} = 1 \quad 7$$

Equation 7 is applied to the known delamination zone and the correction factor for the stated allowable in transverse normal direction is calculated to $k_{33} = 2.1$.

The correction factor can be used for sizing of the final component but does not explain the reduced strength of the material in third direction when compared to thin coupon data. The conducted calculations indicate a significant drop in transverse shear and peeling strength for UTL compared to the material data derived from thin coupon data, see [12]. As suggested by Shephard et al. [13] the fall off is connected to quality differences between thin and thick laminates, e.g. void content and fiber misalignment. Here a similar degradation is observed for bone shaped thick coupons. E_{33} is reduced by 30% in the analysis to gain reasonable strain values and deformations.

CONCLUSIONS

The lack of reliable full three dimensional material properties is a shortcoming and for a transition period empirical correction factors are implemented to enable the sizing of an all composite main landing gear fitting. Additional material tests are currently work in progress to help refine future analysis. These will also serve as basis for a detailed validation of available failure criteria applied on UTL.

The presented work describes the implementation of available procedures and methods in order to evaluate CFRP with an extreme field of application. The described tests seek to support the design process of a main landing gear fitting in CFRP.

The stacked composite brick element, provided in numerous commercial FE codes, presents an efficient way to model thick and ultra thick laminates. For the investigation the 8 noded brick element type 149 is used, provided in MSC Marc/Mentat. Similar elements are also available in Ansys (Type Solid191), Abaqus (C3D8/20) etc. It should also be noted that due to the linear shape functions of the element the transverse shear stress does not vanish at the free surfaces of the structure and are discontinuous at the layer interfaces. In order to gain reasonable stress results a discretisation of the geometry over thickness is necessary. The main goal of this study and the performed tests is to gain valuable insight into the behavior of UTL. For the purpose of analyzing large scale UTL structures, semi empirical correction factors are extracted. The calculated overall stiffness of the components is in agreement with the performed tests. Transverse shear and normal stresses are identified as main failure reason. Only limited stress interaction is observed for the described application, partially enabling the application of single non interactive failure criteria. Significant material property degradation is indentified for UTL. The investigation of the effect is subject to future studies.

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