TOOL-PART INTERACTION IN COMPOSITES PROCESSING

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ABSTRACT: The ability to process composite structures with a high degree of dimensional control remains a barrier to the further implementation of composite materials in commercial applications. Of the numerous types of process induced deformations which occur, the warpage of flat laminates due to tool-part interaction remains a poorly understood phenomena. The current work presents a combined experimental and modelling effort to develop a fundamental understanding of the mechanics and constitutive behaviour of the tool-part interface during processing. An experimental parametric study indicated that laminate geometry has the most significant effect on part warpage. An instrumented tool technique was used to measure tool-part interfacial shear stress during processing. This study indicated that a sliding interface condition was operative during the time at which residual stresses are expected to accumulate in the part. The results from these two experimental studies provide a basis for improved numerical modelling of the tool-part interaction phenomena.

KEYWORDS: tool-part interaction, warpage, dimensional control, process modelling

INTRODUCTION

A vital aspect of affordable composite manufacturing is the ability to fabricate parts within tight dimensional tolerances. Residual stresses invariably arise during the processing of composite structures and these often result in part dimensional changes. Common manifestations of residual stress are the spring-in of flanges on angled sections and the warpage of parts fabricated on flat tooling. A number of sources of residual stress have been identified in the literature, some of which are intrinsic to the material itself while others are dependant on external process and tooling variables [*1*- *3*].

A common observation amongst composite manufacturers and researchers is that there is a component of shape change which cannot be attributed to the well understood sources of residual stress such as material anisotropy. In particular, thin, balanced laminates fabricated on flat tooling are often seen to exhibit a concave down warpage after processing. The explanation often invoked to account for this deformation is a mismatch between tool and part Coefficient of Thermal Expansion (CTE) [*4*-*5*]. The mechanism put forth considers a low CTE laminate against a tool with a considerably higher CTE. When the tool and part are forced together due to autoclave pressure and subjected to a temperature ramp, a shear interaction between the tooling and the curing part arises which places the laminate in tension. As this occurs prior to any significant degree of resin modulus development, the laminate shear modulus is very low and those plies which are distant from the tooling are not loaded to the same extent as those close to the interface. This non-uniform stress distribution is locked in as the resin cures and upon

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removal from the tooling, the resultant bending moment warps the part away from the tooling (Figure 1).

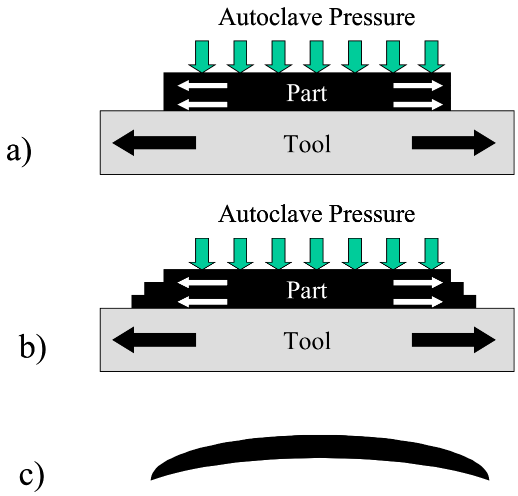

Figure 1: Mechanism for warpage due to tool-part interaction. a) Tooling thermal expansion is communicated to the part via interfacial shear stresses. This induces tensile stresses in the laminate. b) Because the laminate is very soft in shear, plies distant from the tool are not loaded to the same extent as those close to the tool. The resulting stress gradient is locked in when the pre-preg cures. c) Upon removal from the tool the laminate warps away from tool face[5].

It has been noted that this type of dimensional change is highly variable from part to part and can depend on parameters such as pre-preg age, resin viscosity, as well as process variables such as the rate and magnitude of pressure and temperature application [5]. Some experimental work has quantified the warpage demonstrated by laminates fabricated over a range of process conditions [6]. This was compared with the results of a numerical FEM analysis based on experiments which measured the friction coefficients associated with the tool-part interface and interply regions respectively. Other authors have performed experiments examining laminates with different amounts of resin bleeding. They proposed that the warpage of flat laminates is, at least in part, related to the effect which volume fraction (V_F) can have on the interaction between tool and laminate [7].

There is a large body of anecdotal evidence confirming the occurrence of tool-part interaction but there is still relatively little quantitative data concerning the conditions under which it acts, the extent to which it can influence part shape, or the variability associated with this phenomena. Efforts to incorporate tool-part interaction behaviour into process models have shown that it can have a tremendous influence on the magnitude of predicted deformations [8]. At the present time though, there is a lack of experimental basis for the selection of input parameters for these models [9].

This paper presents an integrated experimental and modelling approach to developing a fundamental understanding of the mechanics and constitutive behaviour of the tool-part interface. Firstly a parametric study examining the magnitude of part warpage demonstrated over various process conditions and part geometries is presented. Secondly some of the results from an experimental technique developed to measure tool-part interfacial shear stress during processing are examined. Finally numerical modelling work is considered with respect to the insight gained from the previous experimental studies.

WARPAGE PARAMETRIC STUDY

In order to quantify the effect of tool-part interaction, a number of uni-directional CFRP samples were fabricated on flat tooling and measured for deformation. To the greatest extent possible, fabrication procedures and part sizes were selected to reflect industrial practice. The following parameters were selected as experimental variables:

- Part thickness – $[0]_4$, $[0]_8$ and $[0]_{16}$ ply lay-ups were examined.
- Part length - 300 mm, 600 mm and 1200 mm part nominal lengths.
- Autoclave Pressure – 103 kPa (15 psi) and 586 kPa (85 psi).
- Tool Surface Condition – 2 plies of FEP and Freekote 700 NC release agent.

All specimens in this study were fabricated from T-800H/3900-2 carbon/epoxy pre-preg and autoclave cured using a standard 180 ^{o}C (355 ^{o}F) cure cycle. All parts were 100 mm in width and were fabricated on aluminum (Al-6061 T-6) tooling. For most of the specimens, deflections due to part self weight were significant with respect to overall warpage. To negate this effect, all measurements were taken with the part on its side. For 300 mm and 600 mm specimens part profiles were captured using a flatbed document scanner. For the 1200 mm parts the warpage profile of these parts was traced onto paper and measured using Vernier callipers.

WARPAGE PARAMETRIC STUDY - RESULTS

Specimens generally deformed in a smooth, symmetrical arc with the concave towards the tooling. A photograph showing the magnitude of warpage which can occur is shown in Figure 2. The maximum warpage, w_{max}, exhibited by a part provided a useful basis for comparison of part shape.

In general, part geometry effects dominated the total amount of warpage observed. Longer parts were seen to warp considerably more than shorter parts, regardless of process conditions or part thickness. Similarly, thinner parts warped considerably more than their thicker counterparts. Autoclave pressure was seen to have a modest effect on warpage while the tool surface condition (FEP versus Release Agent) was not observed to have any significant effect. For the parameters examined, the collective effect on warpage can be expressed by the following proportionality:

$$w_{\max} \propto \frac{P^{0.2} \cdot L^3}{t^2{}_{Lam}} \tag{1}$$

where P is the autoclave pressure, L is the laminate length and t_{Lam} is the laminate thickness. The relationship is illustrated in Figure 3. It is interesting to note that the relationship above suggests that part curvature actually *increases* with part length.

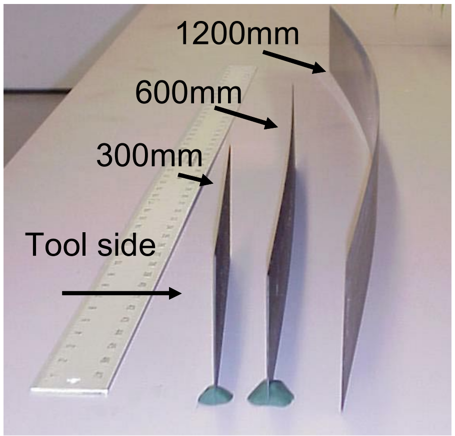

Figure 2: Photograph depicting the magnitude of warpage for 4 ply parts of various lengths. 586 kPa / FEP interface.

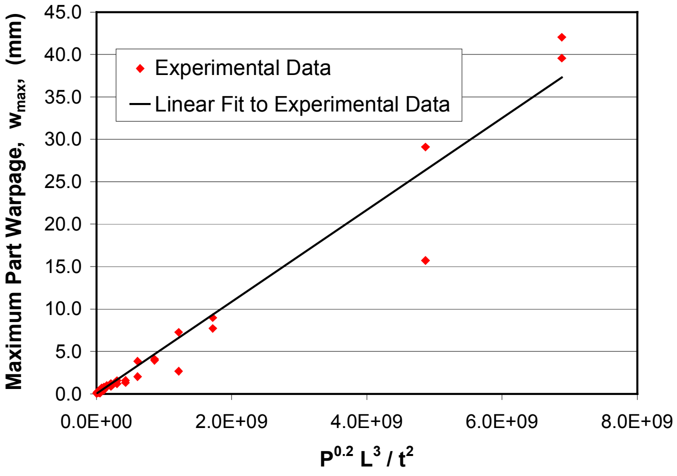

Figure 3: Experimental data compared with empirical relationship predicting maximum warpage.

INSTRUMENTED TOOL EXPERIMENTS

The success with which tool-part interaction can be modelled over a practical range of part geometries and process conditions depends on having an accurate picture of the distribution of tool-part interfacial shear stress. An existing experimental technique was refined, with the goal of quantifying the development of tool-part interface shear stress throughout the cure cycle [*10*].

No stress can be measured directly, but the interfacial shear stress acting on a body may be inferred from the normal strains exhibited by the material close to the interface. When examining this interfacial phenomena one has the option of examining strains from the tool side or from the part side. Strain gage placement in the part itself has been utilized successfully for the examination of residual stresses which arise after part gelation but there are inherent difficulties in this technique [*11*]. For this reason, it was decided to place strain gages on the tool itself. To ensure that the magnitudes of the strain induced in the tool were sufficiently large to be measurable, a thin, compliant tool was used. As the cure cycle progressed, strains measured in the thin tool were recorded. The product of this experimental technique was a history of the in-plane, mechanical strain in the thin tool throughout the cure cycle. From this measurement it was possible to estimate the magnitude and distribution of shear stresses at the tool-part interface. A schematic illustration of the approach is shown in Figure 4.

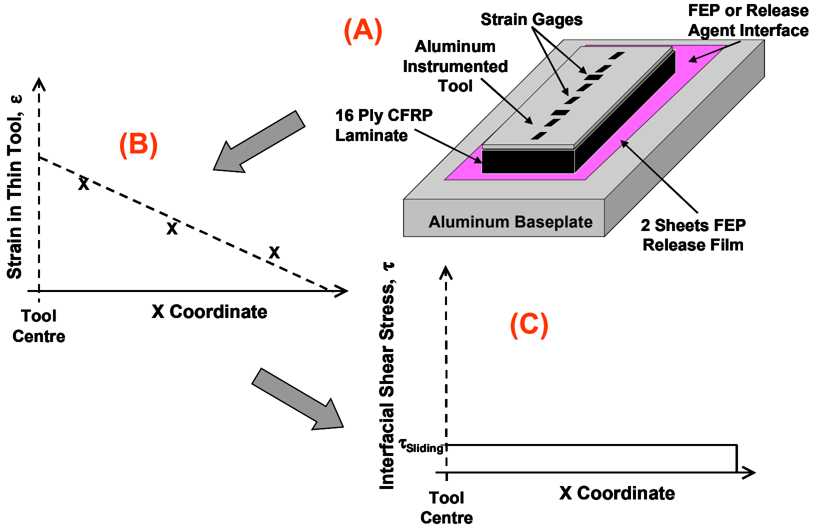

Figure 4: Schematic illustration of the instrumented tool approach. (A) A thin tool is strain gaged, placed adjacent to a part, and subjected to a cure cycle. (B) The strain in the thin tool during the cure cycle is recorded from which (C) the tool-part interfacial shear stress can be estimated.

The instrumented tool was a piece of aluminum (6061-T6) with dimensions of 100 mm x 600 mm x 0.762 mm. Eight strain gages were placed on the tool, 6 oriented longitudinally and 2 transversely. A $[0]_{16}$ CFRP part with the same length and width as the instrumented tool was placed on a 6.35 mm thick aluminum baseplate. Two sheets of FEP separated the part and the baseplate. The instrumented tool was then placed on top of the CFRP part. The assembly was vacuum bagged and subjected to an autoclave cure cycle. As with the warpage specimens, two interface and two pressure conditions were examined:

- 2 plies of FEP, and Freekote release agent.
- 103 kPa and 586 kPa autoclave pressures.

INSTRUMENTED TOOL EXPERIMENT - RESULTS

The instrumented tooling experiments yielded both qualitative information about the distribution of interfacial shear stress, and quantitative information regarding the magnitude of those stresses. During the heat-up portion of the cure cycle when part residual stress development due to tool-part interaction is most significant, a sliding friction condition occurred at the tool-part interface. The value of interfacial shear stress associated with this condition, $\tau_{Sliding}$, was seen to increase significantly with degree of cure. A plot of $\tau_{Sliding}$ versus resin degree of cure is shown in Figure 5.

As is apparent in Figure 5, during the heat-up $\tau_{Sliding}$ is of the order of 30 kPa, while at the end of the cure cycle values can reach as high as 165 kPa. This suggests that temperature ramp rate or intermediate isothermal dwells can influence the interfacial shear stress history which a laminate sees and hence change final part shape. Figure 5 also illustrates that at higher degrees of cure the difference in $\tau_{Sliding}$ associated with different autoclave pressures was much greater.

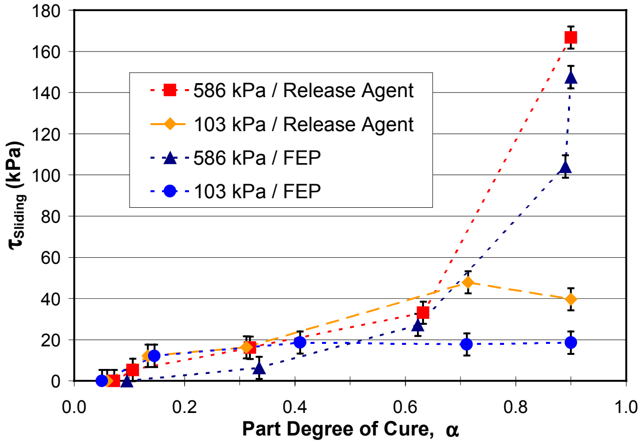

Figure 5: Evolution of interfacial shear stress, $\tau_{Sliding}$, associated with a sliding tool-part interface condition.

Another interesting result of the instrumented tool approach was the fact that at times during the cure cycle, particularly after isothermal dwells, a sticking interface condition occurred between the tool and part, despite the use of release agent on the tool. Furthermore, the shear stress associated with tool-part debonding, τ_{Debond}, as the sliding interface condition resumed was as high as 3-4 MPa. A schematic illustration of the interface tool-part interface behaviour which this implies is shown in Figure 6.

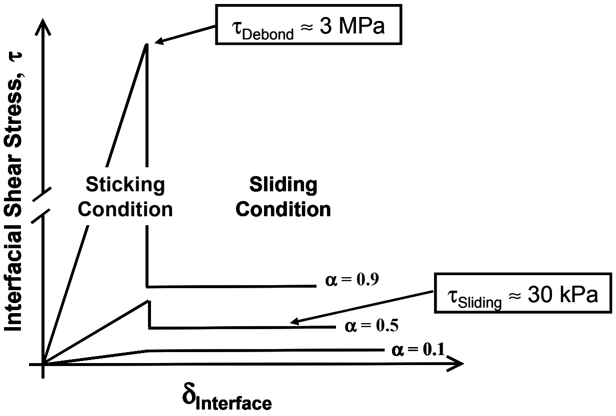

Figure 6: Schematic illustration of interfacial shear stress versus tool-part interface displacement. The results are for a release agent interface.

NUMERICAL MODELLING

The ultimate goal of the current work is to improve the ability of finite element based process models to accurately predict the development of residual stresses in composite structures. Towards that end the ability of an existing process model to simulate the tool-part interaction phenomenon was examined. COMPRO is a 2-dimensional, plane-strain finite element code which considers the heat transfer and thermochemical aspects of the autoclave process, compaction and flow of the material, and finally the development of residual stresses in the part. Material property development is captured using a cure hardening instantaneous linear elastic approach. The reader is referred to [*12*] and [*13*] for complete model details.

To permit a means of tailoring the amount of shear stress transfer at the tool-part interface a layer of elements, referred to as a shear-layer, is incorporated into the FE mesh between the tool and part. Depending on the value of elastic modulus assigned to the shear layer, a range of tool part interface conditions can be simulated. At the one extreme, if the properties of the shear layer are the same as the tooling, high shear stresses arise between the tool and part. At the other extreme, by giving the shear layer low values for E_{11} and G_{13}, relatively little stress is transferred between tool and part.

A parametric study was performed using COMPRO (Version 2.42) to examine the effect of varying shear layer and part properties over the range of part geometries examined experimentally. The following parameters were examined in the numerical study:

- Shear layer stiffness – with the exception of E_{11} and G_{13}, the shear layer properties were always the same as that of the aluminum tool and the shear layer geometry was held constant. Values of E_{11} and G_{13} were lowered by identical order of magnitude decrements to create an increasingly soft shear layer

- Part shear modulus - COMPRO uses standard micromechanics equations to calculate the properties of a laminate based on its constituents properties. By using a lower initial elastic modulus for the resin, G_{13} of the laminate is reduced substantially while E_{11} remains virtually unchanged. The nominal value for initial resin modulus is 4.1×10^7 Pa. In a similar fashion to the shear layer, resin modulus was lowered by order of magnitude decrements from its nominal value of 4.1×10^7 Pa. The final resin modulus was held constant at 4.1 GPa.

- Part length – 300mm, 600 mm and 1200 mm part lengths were examined.

- Part thickness – 4, 8 and 16 ply laminates were modelled.

NUMERICAL MODELLING - RESULTS

Both shear layer modulus and initial resin modulus can cause part warpage to vary over many orders of magnitude. The warpage demonstrated by a single part geometry can be matched by appropriate selection of the shear layer and resin modulii as shown in Figure 7, moreover there are several combinations of the two parameters which can reasonably approximate the actual part shape.

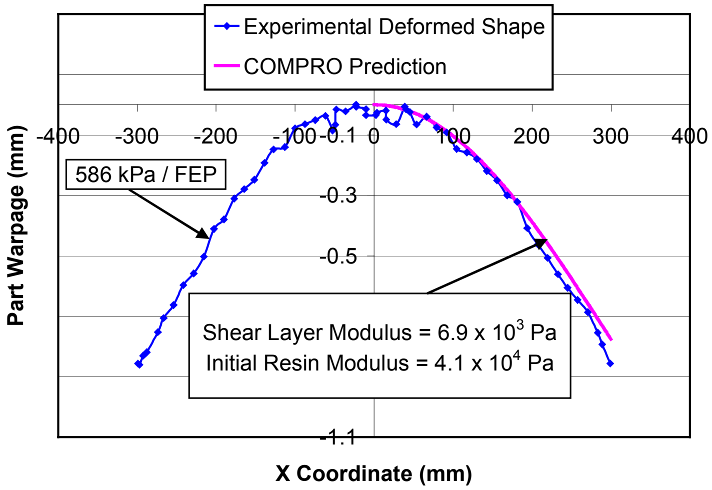

Figure 7: Comparison of experimental deformed shape with COMRPO numerical modelling result. Note that only half the part was modeled due to symmetry.

Of greater importance than matching part shape, is the ability to predict the trends in warpage with respect to part geometry. The success with which the model can capture warpage trends with respect to part length depends largely on the interfacial shear stress distribution which the model yields, while trends with respect to thickness depend to a greater extent on the in-plane stress distribution through the thickness of the part. The model inputs which affected these two stress distributions principally, were the modulus of the shear layer and the shear modulus of the part respectively.

The distribution of interfacial shear stress predicted by the model for two different shear layer stiffness is shown in Figure 8. Recalling the instrumented tool experiments, the results suggested that the interfacial shear stress during the heat-up portion of the cure cycle (when tool-part interaction induced residual stresses are building) was on the order of 30 kPa (Figure 5).

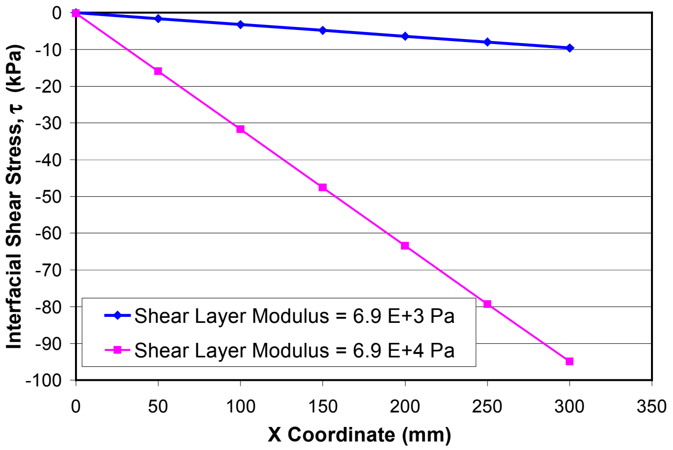

Figure 8: Interfacial shear stress distribution predicted by COMPRO for two different shear layer stiffnesses. The distribution considered is at a time during the isothermal hold portion of the cure cycle.

The COMPRO result is of a similar order of magnitude, however, the distribution associated with the COMPRO model differs from that suggested by the instrumented tool experiments. Under the circumstances that the tool-part interface is sliding, the shear stress should be constant along the entire interface length. The soft elastic assumption implicit in the shear layer modelling approach is unable to represent this "plastic" interface condition. This affects the ability of COMPRO to accurately predict warpage magnitudes over the full range of part lengths.

In order to correctly match the warpage trends with respect to part thickness, it is necessary to use a low initial part shear modulus, ~ 10^4 Pa. The low initial modulus causes the stress induced in the part to be concentrated in the elements close to the tool surface. This severe gradient in stress results in the bending moment which in turn warps the part. By appropriate selection of shear layer and part properties reasonable agreement between modelling and experimental results could be achieved over the full range of part geometries (Figure 9).

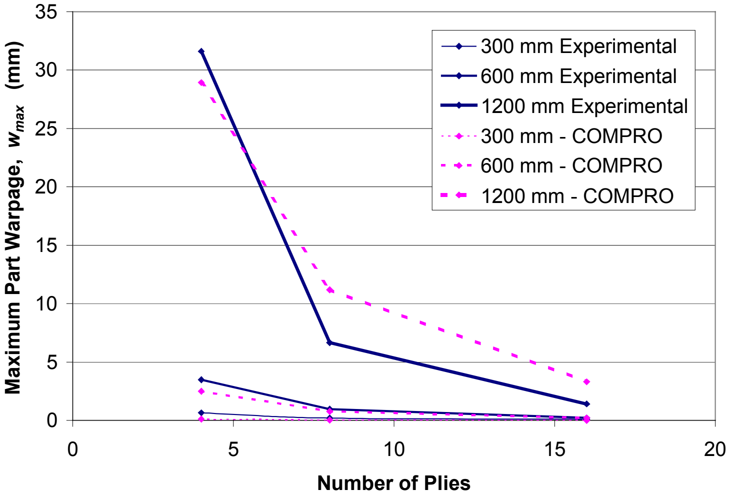

Figure 9: Comparison of COMPRO warpage predictions with experimental results over a range of part lengths and thicknesses. Shear Layer Modulus = 6.9 x 10^3 Pa, Part Initial Resin Modulus = 4.1 x 10^4 Pa.

CONCLUSIONS

A parametric study of tool-part interaction induced warpage has been performed. The results are embodied in a single empirical equation which indicates that of the parameters studied, laminate geometry has the greatest influence on part warpage. A second experimental study was performed using an instrumented tool approach to measure tool-part interfacial shear stresses during the cure cycle. A sliding interface condition is in effect for the majority of the process cycle. The interfacial shear stress was quantified and is seen to increase with resin degree of cure. Finally, a numerical model was used to model tool-part interaction induced warpage. The soft elastic shear layer approach currently used is unable to represent the sliding interface condition which was experimentally observed. Reasonable agreement between modelling and experimental results can be achieved however, by selecting shear layer properties which yield similar magnitudes of interfacial shear stress to those determined experimentally.

ACKNOWLEDGEMENTS

The authors wish to thank the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Boeing Commercial Airplane Group (Seattle) for their financial support, and past and current members of the Composites Group at The University of British Columbia for their contribution to our current knowledge of composites process modelling and the development of software tools for process analysis.

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