Comparison of fatigue limits obtained on thermoplastic composites from SN curve and self-heating method

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ABSTRACT. *To achieve weight reduction of structures, composite materials are used extensively in different industrial applications as aerospace and automotive. Their high mechanical performances and good fatigue durability offer advantages compared to more traditional materials. To be able to design composite parts, it is necessary to characterize their fatigue behavior and specifically to evaluate fatigue limit. All fatigue tests generally used for this determination take long time and are potentially very costly. In this paper we propose to apply on thermoplastic composites, the self-heating method, which has been developed and validated initially on carbon/epoxy composite materials.The material under consideration is a woven made of carbon fibers and PA66 matrix. Fatigue tests are conducted on two stacking sequences ([0°] and [+/-45°]). The results show that during self-heating tests at room temperature, the mechanisms leading to the increase in temperature are different compared with those observed in thermoset matrix composite systems. This means that a new analysis of the results must be developed to obtain the limit of fatigue. The fatigue limit obtained with this method, is successfully compared with results from classical SN curves.*

RÉSUMÉ. *Afin de répondre aux exigences d'allègement, les matériaux composites sont de plus en plus utilisés dans l'industrie automobile ou aéronautique. Leurs bonnes propriétés mécaniques ainsi que leur tenue en fatigue offrent de nombreux avantages par rapport à des matériaux plus traditionnels. Toutefois, la conception et le dimensionnement de structures en composite passe par la connaissance de leur comportement en fatigue et plus précisément par la détermination de la limite d'endurance. Les méthodes classiques, généralement utilisées, sont longues et coûteuses. Dans cet article, nous proposons d'appliquer la méthode d'auto-échauffement qui a été développée sur les matériaux métalliques et validée sur les composites thermodurs. Le matériau considéré est un PA66 renforcé de fibres carbone, tissé. Des essais de fatigue et d'auto-échauffement ont été menés et comparés sur 2 configurations ([0°] et [+/- 45°]). Les résultats obtenus en auto-échauffement montrent que les mécanismes mis en jeu sont différents en fonction de la direction considérée, et également de ceux obtenus sur des thermodurs. Une nouvelle approche est donc développée pour ces matériaux. Les résultats sont en bon accord avec ceux obtenus par la courbe SN.*

KEYWORDS: *fatigue, thermoplastic composites, self-heating.*

MOTS-CLÉS : *fatigue, composites thermoplastique, auto échauffement.*

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1. Introduction

Thermoplastic (TP)-based laminates are becoming more and more attractive to the industry, due to promising alternatives compared to thermoset matrix composites, especially with their reduced curing time and their recycling properties. However, further growth of TP-based composites is directly linked to the knowledge of their long-term behavior (fatigue and creep), for which, experimental campaigns are material- and time-consuming.

The self-heating method, first developed on metallic materials (La Rosa *et al.*, 2000 ; Fargione *et al.*, 2002 ;Chrysochoss *et al.* 2000 ; Doudar *et al.* 2004), is a suitable tool to fast predict the fatigue limit. It has been applied successfully to unidirectional carbon fibre reinforced thermoset matrix laminate (Westphal, 2014).

The challenge now is to adapt this methodology to carbon fibre reinforced thermoplastic matrix woven ply laminate. The weave pattern and the ductility of the matrix represent the two main difficulties of this adaptation work. Indeed, viscous behaviour may influence fatigue resistance and temperature elevations under cyclic loadings. This article compares fatigue strength values obtained by means of classical fatigue tests (SN Curves) and self-heating tests. We propose an interpretation of the self-heating curves in order to determine the fatigue properties of the thermoplastic woven ply laminate.

2. Material

The material of the study is the TEPEX dynalite 201-C200(x)/45% carbon/PA6.6 manufactured by Bond Laminates. It is currently used in automotive and sporting applications. The polyamide 6.6 is reinforced with a carbon fabric of twill type, with balanced warp and fills yarns. In this article we will note this CFRP composite as CF/PA66. According to the constructor's data, the matrix has a glass transition temperature of 70°C.

2.1. Mechanical testing

Two kinds of tests have been performed: classical fatigue tests to build the SN curves, and self-heating tests for fatigue limit determination.

2.1.1. SN tests

Symmetrical rectangular CF/PA66 specimens of nominal dimensions 250x30 millimeters with end tabs (ASTM D3039, ISO 527) (Figure 1) have been used for fatigue tests. Three Representative Elementary Volume are contained in the specimen width. Two stacking sequences are tested: $[45]_8$ and $[0]_8$.

No environmental preconditioning is performed and specimens are kept in an ambient condition (RH50).

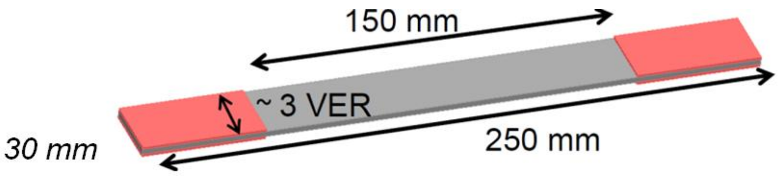

Figure 1. Specimen used for fatigue tests

Tests conditions are as followed:

– Load control

– End of test: rupture or 5.10^5 cycles

– Frequency: 10Hz (with forced air cooling system)

– Load ratio: R=0,1

– $[0]_8$ and $[45]_8$ laminates have been tested

Curves were built with 15 to 20 specimens located on 3 or 5 load levels.

2.1.2. Self-heating tests

2.1.2.1. Methodology

A self-heating test consists in applying successive series of cycles for different increasing maximal stresses keeping the same stress ratio. For each maximal stress, the change of temperature variation, $\theta(t) = T(t) - T_0$ (where $T(t)$ is the mean temperature on the surface and T_0 is his initial value) is recorded. The mean temperature becomes stable after a fixed number of cycles depending on the stress level and loading frequency and equals$\theta_{stabilized}(\sigma_{max})$. (Figure 2) It is observed that, beyond a given stress level, the stabilized temperature starts to increase significantly. From this variation, fatigue limit can be determined as the intersection point between $\theta_{stabilised}$ axis and σ_{max} axis (Figure 3).

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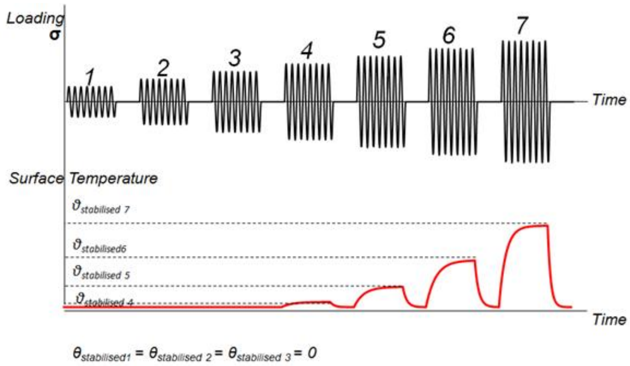

Figure 2. Description on the self-heating method

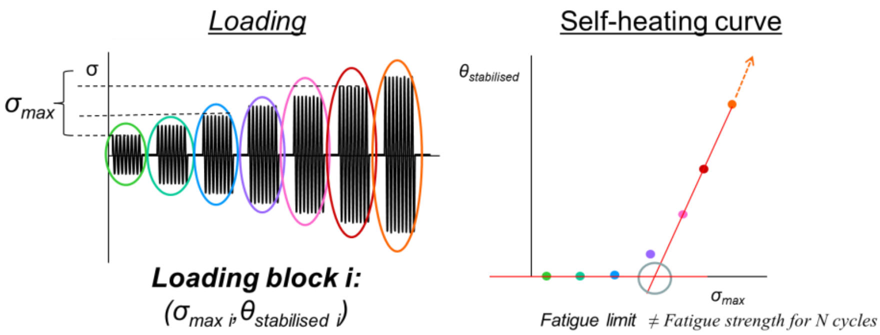

Figure 3. Explanation of fatigue limit determination: block of loading and self-heating curve

Both $[0]_8$ and $[45]_8$ laminates have been tested with this methodology to determine the fibre and shear direction behaviours of the woven ply.

Each loading block consists of three steps: the first one is a displacement-controlled loading at 2mm/min to reach the mean stress, the second one is a cyclic loading of 5000 cycles at constant maximal stress and the last one is displacement-controlled and corresponds to the return to zero stress value. The cyclic loading step is performed in load control with sinusoidal waveform constant amplitude and a loading frequency of 5 Hz. After each block, the stress has been entirely relaxed for 15 minutes to again yield the thermal equilibrium. The maximum stress increases from one block to another and are chosen in order to keep constant the stress ratio R=0,1.

2.1.2.2. Temperatures measurements

During self-heating tests, we are interested in the changes of the specimen's mean temperature. Two methods to determine the temperature have been tested here.

The first one is with an infrared camera, placed belong the specimens and permits to measure temperature precisely all along the test (Figure 4).

The second one is with K-type thermocouples equitably allocated on the specimens. The thermocouples are glued on one specimen face and on each machine grip. The thermal problem is supposed unidimensional thus the thermocouples are positioned on the specimen's median line as seen on Figure 5.

From thermocouples or infrared camera data recorded at a time t, it may be possible to determine the mean temperature at the surface of the specimen $\overline{\mathbf{T}}(t)$ and the temperatures of the upper and lower grips $T_u(t)$ and $T_l(t)$. These three measures are employed to calculate the mean temperature changes of the laminates $\theta(t)$ during the self-heating tests thanks to equation (1).

$$\theta(t)=\overline{T}(t)-\overline{T}(0)-\left[\frac{T_u(t)+T_l(t)}{2}-\frac{T_u(0)+T_l(0)}{2}\right] \tag{1}$$

This correction allows taking into account the temperature variation of the servo-hydraulic machine during the experiment.

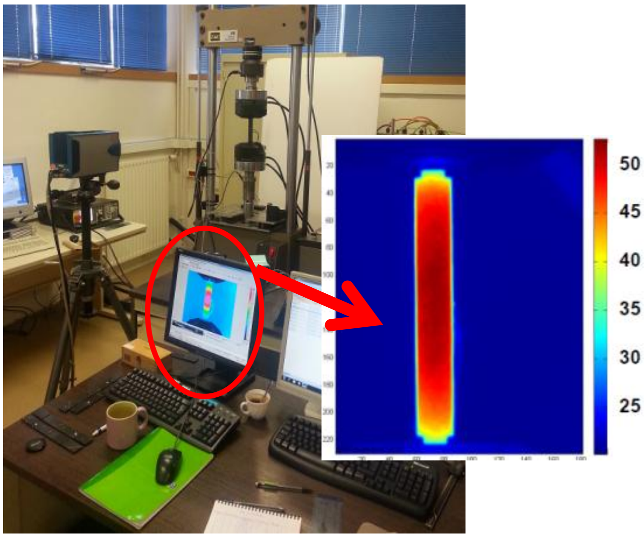

Figure 4. Temperature measurement with infrared camera

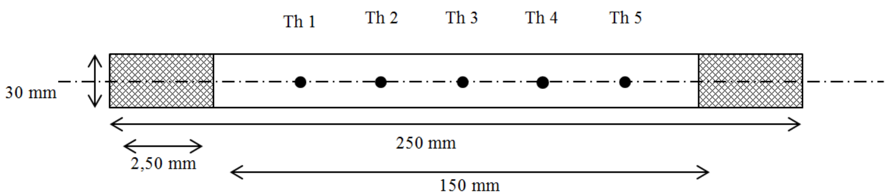

Figure 5. Specimen geometry and thermocouples location

3. Results and discussion

3.1. Temperatures measurement

In this present work, the accuracy of both temperatures measurement methods has been studied. As shown in Figure 6, the two methods, one with infrared camera and the other with thermocouples, are equivalent. It could be explain by the number of thermocouples in the specimens, which give a good idea of the temperature on the surface. They are also less influenced by ambient perturbations.

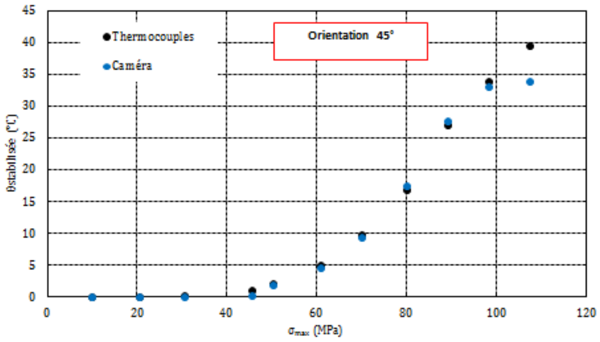

Figure 6. Comparison of temperature measurement methodology

3.2. SN Curves

Results obtained from tests described in §2.1.1 are plotted on Figure 7 and Figure 8 respectively for 0° and 45°.

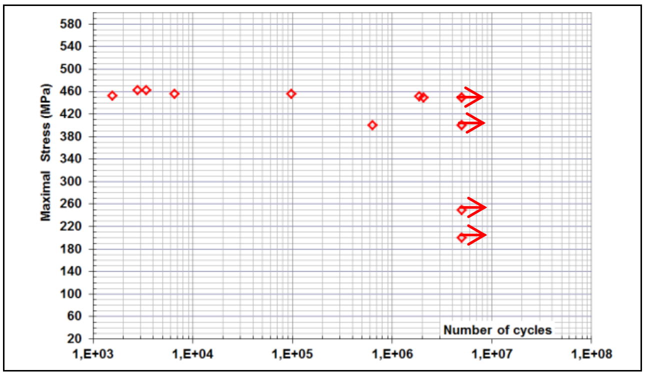

Figure 7. Experimental results for fatigue test on 0° composite

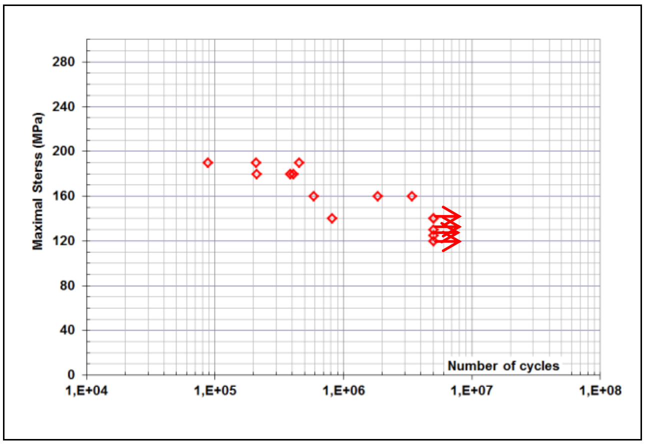

Figure 8. Experimental results for fatigue test on 45° composite

From these points, mean fatigue curves have been determined using Basquin model

$$log(N) = C + m.log(\sigma)$$

This model allows calculating the fatigue strength for 5.10^6 cycles. These values, as well as model parameters, are given in Table 1. The curves are presented on Figure 9 and Figure 10.

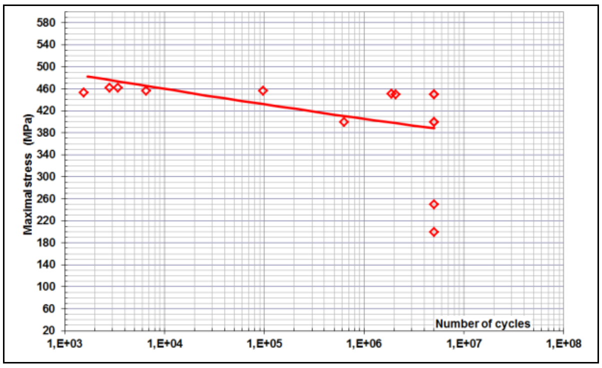

Figure 9. Basquin curve for 0° composite

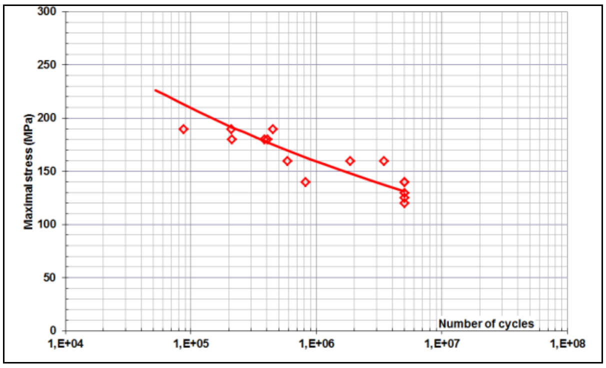

Figure 10. Basquin curve for 45° composite

Table 1. Fatigue strength

	Fatigue strength at 5.10^6 cycles	m	C
0°	388 MPa	-36	101
45°	131 MPa	-8	24

3.3. Self-heating curves

This paragraph presents the self-heating curves obtained for the CF/PA66 woven laminates. The stabilized mean temperature changes in function of maximal axial stress are shown on Figure 11. The self-heating curve of $[0]_8$ laminate presents a typical profile of the one obtained for UD $[0/90]_S$ carbon/epoxy laminated composite (Westphal, 2014). Despite the difference of matrix nature and behaviour, the temperature increments are of the same scale, only few degrees. The presence of fibers in the loading axis can explain this similar result. The superposition of results obtained for two different specimens shows the good reproducibility of the thermal results.

As shown on Figure 11, it may be determined three different mechanisms during the heat build-up test. On the curve the mechanism are easy to see and it is possible to discriminate two characteristics points, here at 150MPa and the second one at 360MPa. The fatigue limit is determined by the cross link between the two tangents of the two last one mechanism as it shows on Figure 12. The fatigue limit is evaluated to ~390MPa.The difficulty here is to correlate heat build-up with physical degradation like fibre break down or delamination. It will be necessary to determine implicated mechanisms to understand well the heat build-up method.

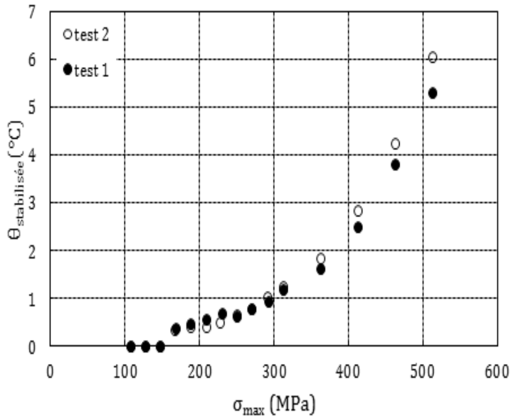

Figure 11. Self-heating curves of a [0]8 CF/PA66 woven laminated composite

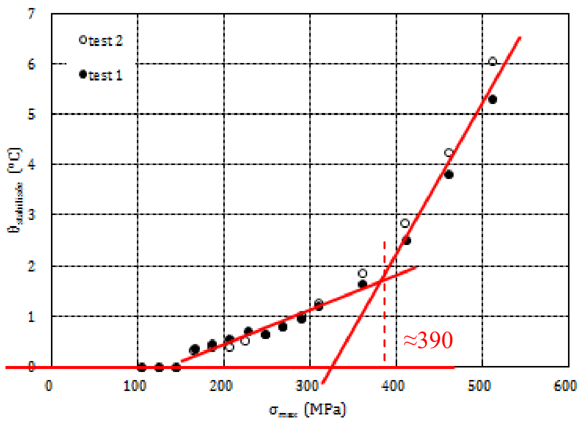

Figure 12. Determination of the fatigue limit of a PA66 $[0]_8$

The self-heating curve obtained for the $[45]_8$ CF/PA66 woven laminated composite is shown in Figure 13. It may be seen that the increase temperature is quite important more than 80°C. Two shift points are clearly observable around maximal stress of 50 MPa and 130 MPa. They illustrate thermal response changes under cyclic loading. The temperature rise around maximal stress of 50 MPa may be due to the activation of dissipation mechanisms like damage or viscoelastic nature of the thermoplastic matrix. For maximal stress superior to 130 MPa, mean stabilized temperature tends to decrease, revealing a diminution of the heat dissipation source with increasing stress amplitude. At these stress amplitudes, the mean stabilized temperature measured at the specimen's surface is superior to the glass transition temperature of the bulk resin (Tg= 70°C). Degradation mechanism for this temperature is really different than at ambient temperature. Higher than the glass transitions temperature the matrix is amorphous and does not play his linker fibre role. So the matrix behaviour permits fibres reorientations along loading axis and that could explain changes of dissipative phenomena. So it may be possible to evaluate a fatigue limit at 125MPa (Figure 14).

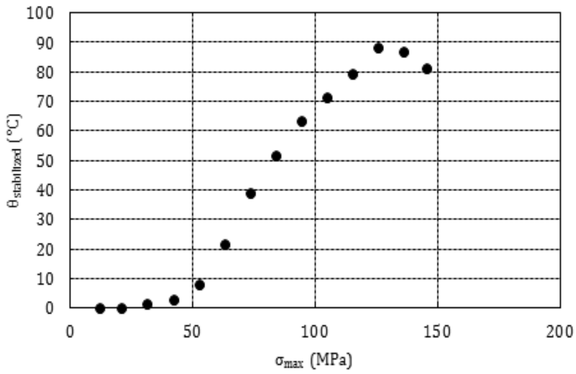

Figure 13. Self-heating curve of a [45]8 CF/PA66 woven laminated composite

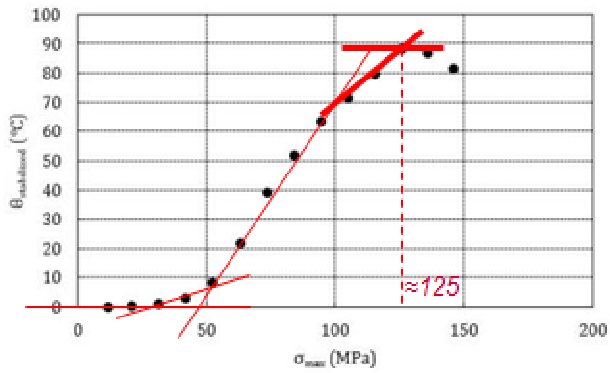

Figure 14. Determination of fatigue limits of a [45]8 CF/PA66 woven laminated composite

As we can see in Table 2, the fatigue strength at 5.10^6 cycles is equal or higher than the fatigue limit determined by the self-heating method as expected. In fact, the self-heating method gives the fatigue limit, while the classic SN curve gives fatigue strength for a given number of cycles. This value is, generally superior to the fatigue limit as shown on Figure 15.

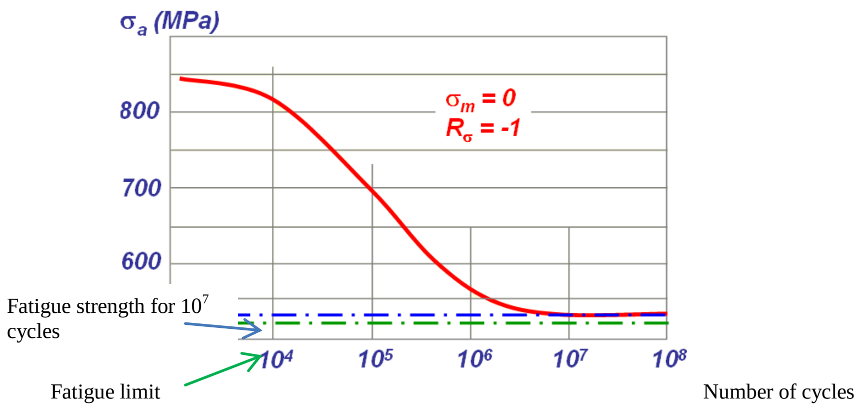

Figure 15. Difference between fatigue limit and fatigue strength

For the $[0]_8$ CF/PA66 the two methods give quite the same value, and for the $[45]_8$ CF/PA66 the difference is around 5%. The results obtained with this promotive method are close to the results obtained with a classical SN curves.

Table 2. Comparison between standard method and self-heating method

	$[0]_8$	$[45]_8$
5.10^6 cycles fatigue strength with SN curves (MPa)	388	132
Fatigue Limits with self-heating (MPa)	390	125

4. Conclusion

In summary, the self-heating method is an easy going set up method. It can be setting up with thermocouples or with infrared camera. Both measurement temperature techniques give good results with same accuracy. Self-heating method can be adapted to any kind of fatigue machine in any laboratory.

It's an easy method but it's also a faster method to have the fatigue limit. An SN curves is built with 25 points of fatigue and takes at least one month, the self-heating method takes 1 day.

The ongoing researches are looking for evaluate the self-heating methods to other materials with different fibers or matrix and particularly different fiber orientations. The understanding of the mechanism degradation in the composites and the correlation with the self-heating curves is necessary to develop this method. Other investigation on the reliability of the results should be also carried out.

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