ENHANCED FATIGUE RESISTANCE IN CARBON/EPOXY LAMINATES BY USE OF INTERLEAF LAYERS

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SUMMARY: The effect of interleaf layers incorporated between laminae on the axial fatigue behavior of quasi-isotropic carbon/epoxy laminates was investigated. Two kinds of laminates, with and without interlayers, were compared in this study. Tension fatigue tests were performed on both laminates. It is shown that introducing the interleaf layers remarkably improved the tension fatigue resistance of the laminate. The interlayers delayed the onset of interlaminar delamination from the free edge and impeded the progression of interlaminar delamination until final failure. Discussion is made on how these interlayers work in enhancing the interlaminar toughness and thus improving the axial fatigue properties of $[0/\pm45/90]_S$ carbon/epoxy laminates. Discussion is also made on the optimum interleaf width in case the interleaf films were placed only in a limited local area near free edges, from the viewpoint of the fatigue resistance of quasi-isotropic carbon/epoxy laminates.

KEYWORDS: Interleaf layers, Fatigue, Carbon/Epoxy laminate, Quasi-isotropic laminate.

INTRODUCTION

Quasi-isotropic carbon/epoxy laminates are used as structural materials in a wide range of applications. Various types of fracture occur during loading of quasi-isotropic carbon/epoxy laminates. The main fracture mechanisms are fiber breakage, transverse cracks in the resin, splitting, delamination, and shear fracture [1,2]. In particular, progressive delamination starting from the free edge often occurs under loading in the plane of the laminate as shown in Figure 1. This greatly reduces not only the static tensile properties of the laminate, but also the fatigue properties under cyclic loading. This has prompted many studies for the improvement of the free-edge delamination resistance of laminates, and various solutions have been proposed for this purpose, namely toughening of the matrix [3], stitching [4,5], edge-cap reinforcement [6,7], notched edges [8], discrete critical ply [9], and interleaving [10-15]. Among these solutions, interleaving is a very simple technique to manufacture the laminate, and it gives high interlaminar toughness to the laminate (see Figure 2). Delamination suppression concepts using interleaf films have demonstrated a good potential for significantly increasing both the static strength and the fatigue life of laminates susceptible to delaminations.

In this paper, the effect of incorporating polymer interleaf films between laminae on the axial fatigue behavior of quasi-isotropic carbon/epoxy laminates is investigated. How these interlayers work in enhancing the interlaminar toughness and thus improving the axial fatigue properties of $[0/\pm45/90]_S$ carbon/epoxy laminates is discussed. In addition, the optimum interleaf width, in case the interleaf films are placed only in a limited local area near free edges, is investigated from the viewpoint of the fatigue resistance of quasi-isotropic carbon/epoxy laminates.

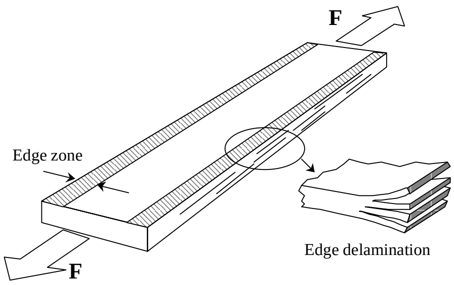


Fig.1: Free-edge delamination.

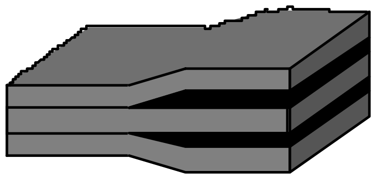


Fig.2: Interleaving concept.

SPECIMEN PREPARATION AND EXPERIMENTAL METHOD

The specimens were fabricated from unidirectional carbon/epoxy prepreg sheet (T800/#2500, TORAY Industries, Inc.) and polyethylene based interleaf films. The interleaf films were approximately 70μm thick and were sandwiched between thermo-adhesive surface layers. CFRP laminates with interleaf films were produced using a vacuum bagging/autoclave curing technique. After cutting and lay-up of the required stacking sequence, the laminates were cured in an autoclave for three hours at 130°C. A postcure process was conducted for melting the thermo-adhesive surface layer of the interleaf film. The cure cycle is shown in Figure 3, where the temperature and applied pressure histories are depicted.

Figure 4 shows the location of interleaf films for four kinds of laminates prepared in the present work. The Type I specimen is a conventional CFRP laminate with symmetric $[0/\pm45/90]_s$ lay-up, which has no interleaf layer. Type II has one interleaf film placed in its middle interlayer. Type IV has two interleaf films which were incorporated into [-45/90] interlayers. The specimens were also prepared in which the interleaf films were placed only in a limited local area near the free edges. The ratio of interleaf width placed near the free edges to the specimen width (let it be called edge interleaf width ratio) were changed in the three different ways, 25%, 50% and 75% (see Figure 5). In Figure 4, Type I_2 and Type IV_2 show the quasi-isotropic carbon/epoxy laminates with sixteen layers. The number of layers is twice as large as above-mentioned specimen and lamination is double repetition for each angle layer. Subscript 2 signifies this type of laminates.

Geometry of the tension fatigue test is illustrated in Figure 6. The tension test was conducted at a speed of 0.5mm/min. Tension fatigue tests were performed by an electro-hydraulic fatigue testing machine at the frequency of 10Hz. Cyclic stress ratio, R, representing a ratio of minimum stress to maximum stress was fixed to 0.1 for the tension fatigue tests.

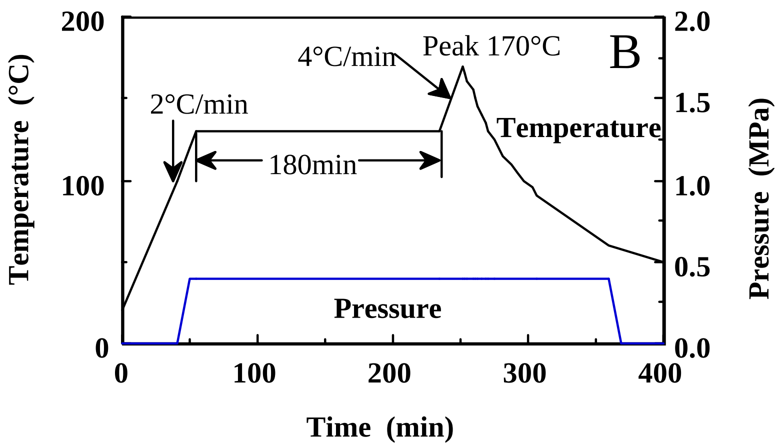
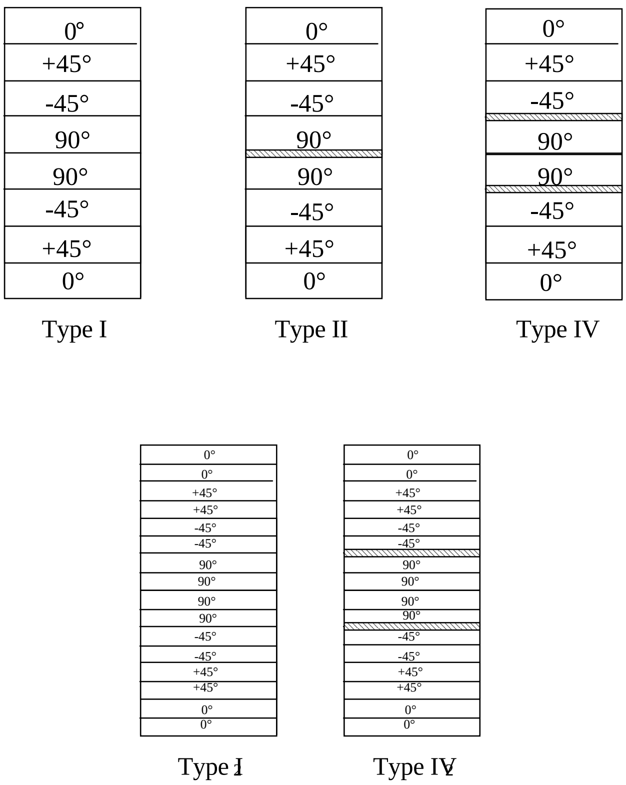


Fig.3: Cure cycle diagram for CFRP/interleaf laminates.



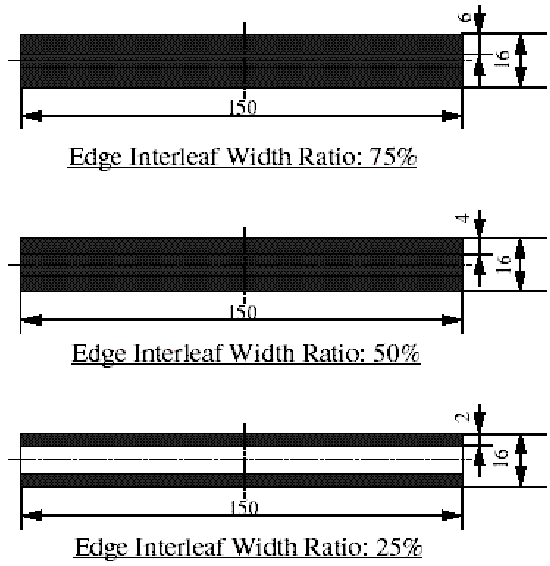


Fig.4: Stacking sequence for various CFRP/interleaf laminates.

Fig.5: Geometry of interleaf film in each edge interleaf width ratio.

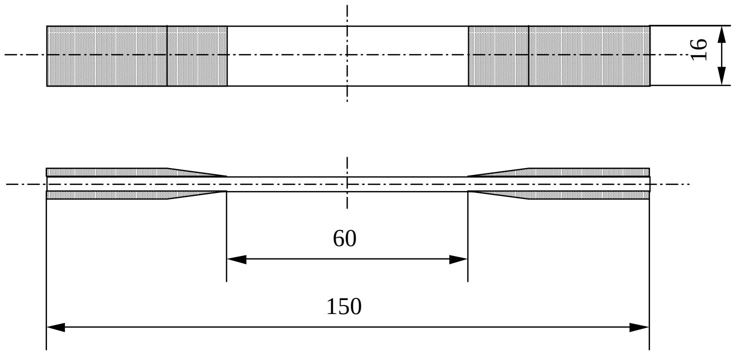


Fig.6: Geometry of tension fatigue test specimen.

EXPERIMENTAL RESULTS AND DISCUSSION

Tensile Properties

Tensile test result is shown in Table 1 for the quasi-isotropic carbon/epoxy laminates with sixteen layers. The ultimate load (UL) value of Type IV_2 was 30.2 KN and is 15% larger UL value, in comparison with the conventional CFRP value, 26.3 KN. The coefficient of variation (CV), which is related to the tensile strength reliability, is also listed in Table 1. The CV value for CFRP/interleaf laminate, Type IV_2 is much lower than that for the laminate without interleaf layer, Type I_2. This result suggests that the CFRP/interleaf laminates have high reliability, in regard to the tensile strength.

The fracture mode for CFRP/interleaf laminates was found to be quite different from that for conventional CFRP. In conventional CFRP, the delaminations between -45° and 90° angle layers were generated at about 80% load of U_L. The ultimate failure occurred in a catastrophic fashion with multiple longitudinal splits (broom straw effect). Ultrasonic C-scan inspection and fracture appearance have shown that the fracture process is remarkably different in each laminate [12]. Dominant failure mode in CFRP/interleaf laminates depends strongly upon the location of interlayer, in which the interleaf films are incorporated. That means, the failure mode in CFRP laminate is changeable by choosing the most appropriate interplies to incorporate the interleaf films. Experimental results showed that interleaf film incorporated at the -45/90 interlayer can suppress the delamination damage in the CFRP laminate. On the other hand, an interleaf film is effective for suppressing the multiple splitting in the 0° angle layer, when it has been sandwiched between 0° and +45° layers.

According to our previous work [14], it was observed that increasing the number of interleaf films results in a decrease in tensile modulus. This fact may be inherent demerit in this delamination-suppression method. In order to overcome this problem, authors attempted to change the geometry of interleaf film [14]. The interleaf films were placed not over the whole width of the specimen flat area, but only in a limited local area near the free edges. The ratio of interleaf width placed near the free edges to the specimen width, edge interleaf width ratio, were changed in the three different ways, 25%, 50% and 75% (see Figure 5). As shown in Figure 7, the tensile modulus decreases with increasing edge interleaf width ratio, except for 25%. Largest reduction in tensile modulus is found for 100% edge interleaf width ratio, in which the interleaf film was placed over the whole width of the specimen flat area. The tensile modulus for CFRP/interleaf laminate with edge interleaf width ratio of 25% is slightly larger than conventional CFRP laminate with 0% edge interleaf width ratio. That means, the

CFRP/interleaf laminate with 25% edge interleaf width ratio can improve the tensile strength without losing elastic modulus, in comparison with conventional CFRP laminate. This point is extremely important in practical application of this concept.

Table 1: Tensile properties of CFRP/interleaf laminate with 16 layers.

Specimen	Ultimate load U_L (kN)	Load ratio $U_L/U_{L(\text{Type I})}$	Coefficient of variation C_V (%)
Type I_2	26.3	1.00	4.0
Type IV_2	30.2	1.15	0.6

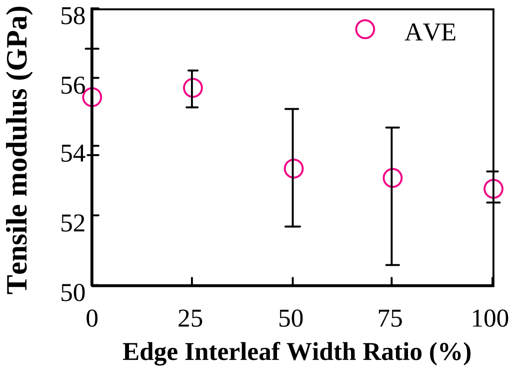


Fig. 7: Variation of tensile modulus for CFRP/interleaf laminates with edge interleaf width ratio.

Fatigue Properties

Figure 8 shows a comparison of the tensile fatigue properties for two types of CFRP/interleaf laminates (Type II and Type IV) and conventional CFRP laminate (Type I), in which the maximum cyclic load was plotted as a function of the number of cycles to fatigue failure. As a result, Type II and Type IV exhibit longer fatigue life when compared with Type I. It should be pointed out here that Type IV laminate which is a CFRP laminate with interleaf films incorporated between -45° and 0° layer enhances not only the static load carrying capability but also the fatigue resistance under tensile fatigue, as a result of suppressing the onset and propagation of delamination damage.

Figure 9 shows comparisons of the tensile fatigue properties for Type II CFRP/interleaf laminates with different edge interleaf width ratios. As a result, the tensile fatigue strengths of Type II CFRP/interleaf laminates for edge interleaf width ratios of 25%, 50%, 70% and 100% were significantly higher in any cases than that of the conventional CFRP laminates without interleaf layers (edge interleaf width ratio of 0%). From the viewpoint of the fatigue resistance, the optimum edge interleaf width ratio in Type II CFRP/interleaf laminates was found to be 75%.

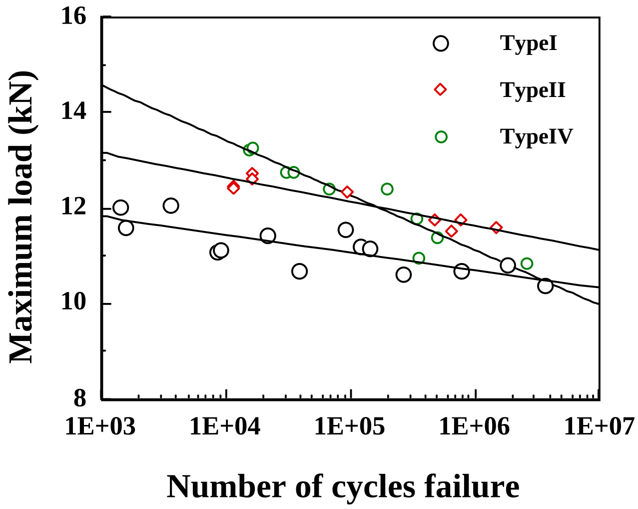


Fig. 8: Comparison of tensile fatigue properties between CFRP/interleaf laminates (Type II and Type IV) and a conventional CFRP laminate (Type I).

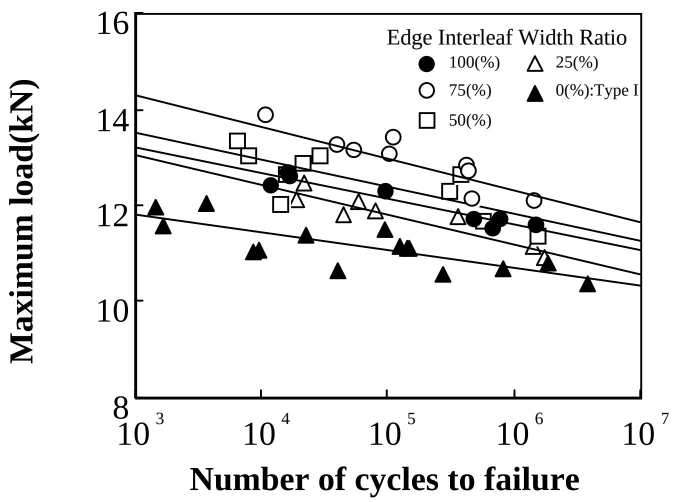


Fig. 9: Comparison of tensile fatigue properties for Type II CFRP/interleaf laminates with different edge interleaf width ratios.

During the tension fatigue test, the progress of fracture was observed by a high-resolution CCD camera in order to investigate the effect of the interleaf layers. In the conventional CFRP laminate (Type I), the edge delamination occurred at the +45° and the 90° interlayers in early stage of fatigue process, and the delaminated area extended progressively towards the center of the laminate with increasing fatigue cycles. In addition, some splitting failure occurred in the 0° layers. The final failure was caused mainly by the delamination progressed in the laminates. Figures 11 and 12 show the fracture process of the CFRP/interleaf laminates for the edge interleaf width ratios of 50% and 75%, respectively. Although a similar edge delamination occurred in the CFRP/interleaf laminates as in the conventional CFRP laminates, the onset of delamination from the free edge was much delayed in CFRP/interleaf laminates, and it progressed much more slowly. This effect seems more remarkable in the laminate with 75% edge interleaf width ratio than that in the laminate with 50% edge interleaf ratio. Splitting failure begins to occur in the outermost layer, 0° angle layer and the damage increases gradually until fatigue failure. From the difference of the fatigue fracture process between laminates with and without interleaf layers, it is apparent that the interleaf layers work to delay the onset of delamination from the free edge and impeded the progression of interlaminar delamination until final failure.

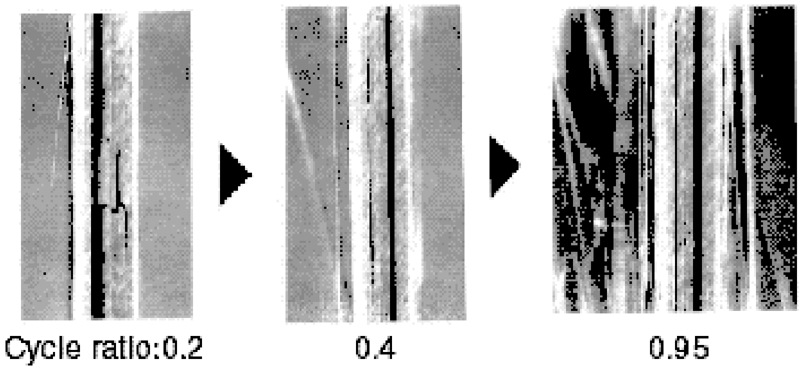


Fig. 11: Fracture process of Type II CFRP/interleaf laminate with 50% edge interleaf width ratio under tension fatigue test (maximum load: 12.65kN, fatigue life: 15500).

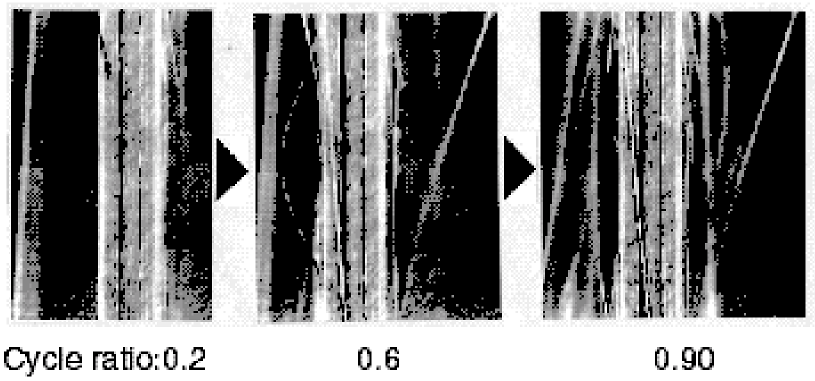


Fig. 12: Fracture process of Type II CFRP/interleaf laminate with 75% edge interleaf width ratio under tension fatigue test (maximum load: 13.44kN, fatigue life: 110100).

The different fracture processes between the conventional CFRP laminates and interleaved CFRP laminates were reflected in the different temperature rise on the surface of the samples, which was measured during fatigue testing at room temperature. The temperature on the surface of the specimen increases progressively until final failure with increasing cycle ratio *n/N*, representing the fraction of the fatigue life. The temperature rise on the surface of the laminates is higher in the conventional CFRP laminates than that in the CFRP/interleaf laminates. The temperature rise on the surface of CFRP/interleaf laminate with 75% edge interleaf width ratio is lower than those of the CFRP laminate without interleaf layers and interleaved CFRP laminate with 100% edge interleaf width ratio. It is interesting to notice that the laminates with lower surface temperature have a higher fatigue resistance.

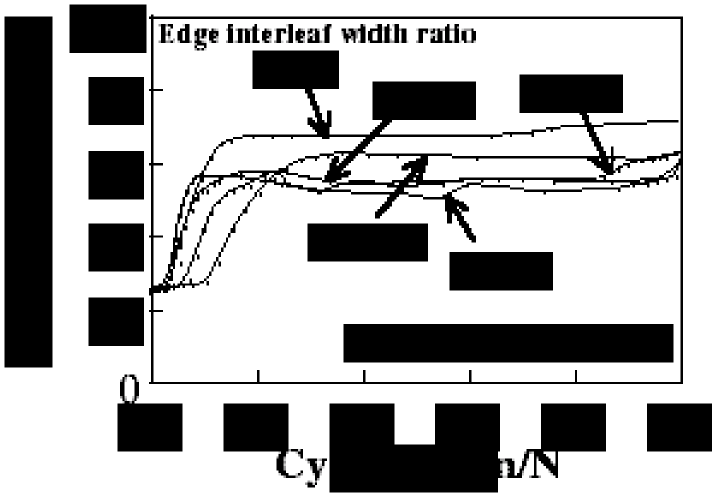


Fig. 13: Variation of temperature with cycle ratio during tension fatigue tests for Type II CFRP/interleaf laminates with different edge interleaf width ratios.

Author's previous work [14] also indicated that visco-elastic properties of interleaf material affects significantly the fatigue fracture process in CFRP/interleaf laminate. When the CFRP/interleaf laminate is subjected to cyclic loading, ductility of interleaf material in service temperature, which reflects the glass transition temperature of the interleaf material will probably be a key in fatigue performance.

It is emphasized in conclusion that the optimum interleaf design such as interlayer location to incorporate interleaf films, edge interleaf width ratio and glass transition temperature of interleaf material should be determined totally from the standpoints of static load carrying capability, fatigue performance, elastic properties, vibration damping capability and so on.

CONCLUDING REMARKS

The present investigation on CFRP/interleaf laminates led to the following conclusions:

1. The CFRP/interleaf laminate has been shown to increase the ultimate load. The mechanical properties of the CFRP/interleaf laminate depend strongly upon the interlayer locations to incorporate interleaf films. The Type IVlaminate, in which the interleaf was incorporated only in a very narrow area near the free edge at -45/90 interlayers, enhanced not only the static load carrying capability but also elastic modulus. This point is extremely important in practical application.
2. The interleaf films incorporated at either 90/90 interlayer (Type II) or -45/90 interlayer (Type IV) can delay the onset of delamination and furthermore mitigate the subsequent progress of delamination between layers under fatigue loading, and thus improved the axial fatigue properties of $[0/\pm45/90]_S$ carbon/epoxy laminates. From the viewpoint of the fatigue resistance, the optimum edge interleaf width ratio in Type CFRP/interleaf laminates was found to be 75%.

Delamination-suppression concept by use of interleaf layers is concluded to have a good potential for significantly increasing both static strength and fatigue life of delamination-susceptible laminates. Optimum interleaf design such as determinations of adequate interlayers to be sandwiched and interleaf width near free edges, and probably selection of the most appropriate interleaf material with different glass transition temperatures corresponded to the actual application, is the most important key issues for a successful application of this concept.

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