

Mechanical Properties and Damage Analysis of Laminates with Hybrid Fiber Volume Fraction

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Abstract: This study is concerned with modelling the mechanical behavior and damage of glass fiber composite laminates that exhibit hybrid fiber volume fraction. The Transformation Field analysis (TFA) is implemented in formulation while the composite is modeled using Mori-Tanaka averaging model. The formulation is verified versus an experimental program conducted at the Center for Advanced Materials (CAM) in the British University in Egypt (BUE). The studied laminates are with different lay ups and subjected to uniaxial bending and tension. The investigated lay ups are (0°) glass fiber symmetric laminate with thickness 37.0 mm and consists of 48 plies and a $(0/\pm 45^\circ)$ symmetric laminate comprised of 12 layers of $(0/\pm 45^\circ)$ glass fiber textile resulting in 36 plies with total thickness 10.7 mm. The fiber volume fraction (FVF) is 62% for both lay ups. The hybridization in fiber volume fraction is implemented by assigning low FVF of 40% for some core plies with variable depths. The core depths studied for the (0°) laminate are $t/4$, $t/2$ and $3t/4$ where t is half the thickness of the laminate while the core depths for the $(0/\pm 45^\circ)$ layup are $t/3$ and $2t/3$. A comparison according to different criteria between the results of the above-mentioned lay ups and the results of the same laminate when all plies have the same volume fraction of 62% is conducted. The comparison criteria include longitudinal and flexural stiffness, the tensile strength and bending moment at the onset of failure together with ultimate bending moment the laminate can sustain. For bending case, the results show that for both the (0°) and $(0/\pm 45^\circ)$ laminates, minor reduction in the mechanical properties in both the undamaged and damaged state takes place. The reduction ranges from 0-12% for all recorded variables. For the axial tension, the loss in mechanical properties is more rigorous. For the off-axis layup, laminate may lose 23% of its stiffness for large core depths. The effect is more pronounced for the load capacity where the laminate may lose up to 30% of its strength according to the depth of the low FVF core.

Key words: Laminate, fiber volume fraction, eignstress, failure, rigorous, loss

INTRODUCTION

The composite materials application in industry is now gaining more land. The mechanical properties of a composite depends on the constituent's properties and primarily on the Fiber Volume Fraction (FVF). The technology adopted in the manufacturing process of a composite plays a major role in obtaining a desired fiber volume fraction implemented in the design of a certain structure or part of it. Some researchers investigated the effect of fiber volume fraction on the mechanical properties of a composite. Among them is Salgar Swapnil *et al.* (2017) who conducted an experimental investigation on composite with different volume fractions. They studied the mechanical properties of composite with volume fractions 40, 50 and 60%. They concluded that the best behaviour is obtained with volume fraction 50%. Sureshkumar *et al.* (2014) investigated a glass fiber/polyurethane composite with different volume fraction of 70, 65 and 60%. They stated that increasing

the fiber volume fraction increases the tensile and flexural strength but for higher FVF the composite may suffer lower strength due to lack of adhesive, (Sureshkumar *et al.*, 2014).

Numerical modelling of fibrous composite has taken much interest. The modelling ranges from a macro scale where the overall composite properties are employed in the analysis using some simple models such as rule of mixture. Models that are more precise are found in the literature such as Mori-Tanka (MT) averaging model (Mori and Tanaka, 1973). For which the composite is considered as a fiber inclusion in a matrix medium and the stresses in both fiber and matrix can be obtained from the composite stresses via. some concentration factors. Other micro-mechanical models are now on going where a certain Representative Volume Element (RVE) describes the behaviour of the composite when repeated in a certain pattern. As an example of the RVE Models, is the Periodic Hexagonal Array Model (PHA) (Bahei-El-Din and Botrous, 2003). The challenge in

dealing with these models is to model damage. One of the most effective ways of modelling damage is the transformation field analysis (Dvorak and Benveniste, 1992). In such formulation, all the non-recoverable sources of stresses and strains such as thermal, electrical or damage, are treated as elastic eigen values that affect the behavior of the composite through some influence functions.

This study is concerned with investigating the mechanical behaviour of composite laminates that possess hybrid fiber volume fraction. The investigation covers the undamaged stage and progressive damage phase. The MT averaging model is employed and to model damage the TFA is implemented. Section 2 is assigned to materials and methods. In this section the TFA formulation for composite that exhibits damage together with the implemented failure criteria are presented in conjunction with the MT Model. In subsection verification of the model, the model is verified against experimental results. The proceeding section is assigned to present the investigated laminates with regards to geometry, fiber volume fraction, layup, materials properties and loading conditions. Results and discussion are presented in sections 3 and 4 respectively. Conclusion of the results is presented in section 5.

MATERIALS AND METHODS

Averaging model formulation: Let us consider a composite laminate with number of N plies and thickness $2t$. The laminate is subjected to normal force N and bending moment M as shown in Fig. 1. The individual ply stress can be expressed as function of the laminate properties and loads as follows:

$$\hat{\sigma}_i(z_i) = P_i N + Q_i M + \sum_{j=1, n} U_{ij} \hat{\lambda}_j \quad (1)$$

The coefficient matrices P_i and Q_i denote stress distribution factors of ply i that depend on the ply properties and the ply distance from the mid plane. U_{ij} denotes stress transformation influence functions that takes into account the effect of any source of non-recoverable stresses $\hat{\lambda}_j$ that occur in any other ply j on the stress state of ply i . These non-recoverable stresses may be due to thermal, plastic or, as in the case of this work, damage. All matrices are function of elastic moduli, fiber volume fraction of the laminas and the laminate layup. A closed form of these matrices can be found in Micheal and Bahei-El-Din (2017).

In averaging models, any ply i comprises of two phases, fiber and matrix. The phase stresses are linked to the ply stresses through a certain stress concentration factor in addition to the effect of any non-recoverable source of stress that takes place in the other phase. Implementing the Transformation Field Analysis (TFA)

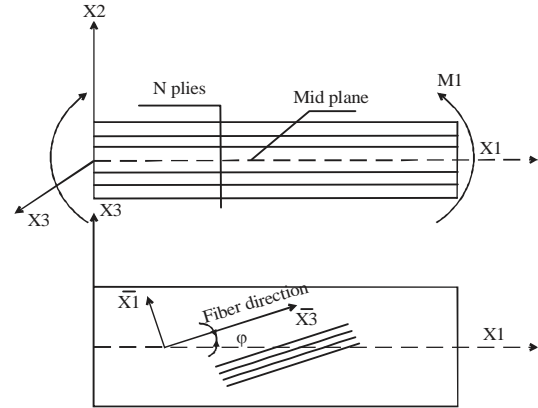


Fig. 1: Geometry and load of a fibrous laminate

in the formulation the phase stresses and strains can be written as follows (Bahei-El-Din and Botrous, 2003):

$$\sigma_r = B_r \bar{\sigma} + \sum_{s=f, m} F_{rs} \lambda_s \quad r = f, m \quad (2)$$

$$\varepsilon_r = A_r \bar{\varepsilon} + \sum_{s=1, Q} D_{rs} \mu_s \quad r = f, m \quad (3)$$

In analogy to the ply stress, the phase stress and strain σ_r and ε_r depend on the ply stress $\bar{\sigma}$ and strain $\bar{\varepsilon}$ where the upper dash denoted the fields in the local coordinate system \bar{X} in addition to the eignstress λ_s and eignstrain μ_s encountered in the phases.

B_r and A_r are the stress and strain concentration factors while F_{rs} and D_{rs} are the stress and strain influence functions. They too are function of the elastic properties of the phases and can be found in closed form for Mori and Tanaka (1973) averaging model of composites. Their expressions are given in Bahei-El-Din and Botrous (2003).

The strain ε_0 and curvature κ of the mid plane of the laminate can be expressed as follow:

$$\varepsilon_0 = A'N + B'f' \quad (4)$$

$$\kappa = C'N + D'M + g' \quad (5)$$

The first two terms in Eq. 4 and 5 represent the strain and curvature due to the mechanical loads. The third term represents the effects caused by the laminas eignstresses λ_i :

$$f' = \sum_{i=1, n} t_i \lambda_i, g' = \sum_{i=1, n} (t_i z_i) \lambda_i \quad (6)$$

The lamina eignstress is function of the phases' counterparts of eigenvalues λ_i as follows:

$$\bar{\lambda}_i = \sum_{r=1,Q} v_r A_r^T \lambda_r^{(i)} \quad (7)$$

Again, the upper dash relates the eigen fields in the local coordinates of the ply. This should be transformed to the global coordinate system before applying into Eq. 6.

Failure criteria and modelling: To detect damage in averaging model, the average phase normal stresses in lamina local axis found in Eq. 2, should be checked against the ultimate material strength for $\sigma_{ut}^{(r)}$ tension or compression $\sigma_{uc}^{(r)}$. These failure criteria for normal stresses can be written as (Micheal and Bahei-El-Din, 2017):

$$\bar{\sigma}_{ii}^{(r)} = \sigma_{ut}^{(r)} \text{ if } \bar{\sigma}_{ii}^{(r)} > 0, \bar{\sigma}_{ii}^{(r)} = \sigma_{uc}^{(r)} \text{ if } \bar{\sigma}_{ii}^{(r)} < 0, r = f, m, i = 1, 3 \quad (8)$$

If this failure criterion is satisfied, stresses in failed directions should vanish. Matrix shear may attain an ultimate value τ_u^m which causes matrix to slip transversely or longitudinally with respect to fibers. Taking into account the existence of friction between fiber and matrix due to surface asperities, these failure criteria can be written as follows:

$$\frac{1}{2} |\bar{\sigma}_{11}^m - \bar{\sigma}_{22}^m| + \frac{1}{2} \eta_T (\bar{\sigma}_{11}^m + \bar{\sigma}_{22}^m) = \tau_u^m \quad (9)$$

$$\bar{\sigma}_{13}^m + \eta_L (\bar{\sigma}_{22}^m) = \tau_u^m \quad (10)$$

where, η_T and η_L are coefficients of friction for matrix slip in the transverse and longitudinal direction, respectively and $(x) = x$ if $x < 0$, $(x) = 0$ if $x \geq 0$. If failure criteria Eq. 9 is satisfied both $\bar{\sigma}_{11}^m$ and $\bar{\sigma}_{22}^m$ should set to zero and satisfying Eq. 10 requires $\bar{\sigma}_{13}^m$ to vanish.

If damage takes place, there should be additional eigenstresses, which are the unknowns that should be added to the system to fulfill the condition of vanishing stresses. Isolating the stress components that should vanish after damage in a reduced version of Eq. 2 and giving them a value of zero, the equation can be solved for the unknown eigenstresses.

The eigenstresses can then be applied back in the full version of Eq. 2 and the phase stresses due to damage is super-positioned with non-damage stresses. The procedure should be repeated until full saturation of failure at a certain load level is attained. Applying back the resulting eigenstresses in Eq. 7, 6, 4 and 5, the laminate mid plane strain and curvature are obtained.

Verification of the model: To verify the previously mention model for composite laminate damage, a bench mark problem is solved and compared with experimental results. The experimental program is conducted on a composite laminate of 4 layers of glass fiber textile ($0/\pm 45^\circ$) ETXL1200-SBIL with thickness 2.5 mm, width 25 mm and length 250 mm with a symmetric layup ($+45/-45/0/+45/-45/0/0/-45/+45/0/-45/+45$) and manufactured using vacuum infusion. The Fiber Volume Fraction (FVF) of the specimen is 0.56 and the matrix is Araldite LY 1567. Six specimens are tested and the average results are implemented in the comparison. The specimens are manufactured at the Centre for Advanced Materials (CAM) in the British University in Egypt (BUE) and tested under tension using a Universal Testing Machine with loading rate 2 mm min^{-1} according to ASTM standard with the designation D3039/D3039M-00 (ASTM, 2017). The experimental program results can be found in the work published by Bahei El-Din YA 2011. The same problem is solved using the TFA averaging model presented in the previous section. The material properties implemented in the analysis are as given in Table 1.

The comparison of the results are given in Fig. 2. The compatibility of the undamaged part of the two curves is clear. The onset of failure in the model takes place at stress 460 MPa in the off axis plies due to matrix tensile failure according to the failure criteria depicted in Eq. 8-10 while the experiment shows earlier onset of failure. However, for the TFA Model, failure results in large increase in strains at onset of failure then for subsequent behavior both the analytical and experimental results show good agreement.

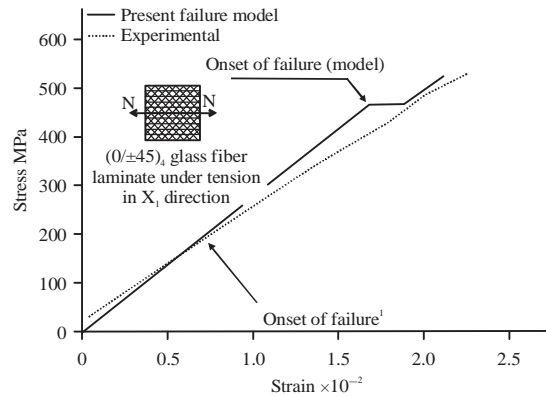


Fig. 2: Verification of damage model (ASTM, 2017)

Table 1: Material properties

Materials	E (GPa)	ν	σ_{ut} (MPa)	σ_{uc} (MPa)	τ_u (MPa)	η_L	η_T
Araldite LY 1564 epoxy	3.35	0.35	72	115	60	0.268	0.268
Glass fiber	73.00	0.21	1900	---	---	---	---

Glass fiber composite laminates with hybrid volume fraction: The model presented in the previous sections is implemented in the analysis of a composite laminates with hybrid fiber volume fraction and compared with the results of conventional ones. Two values of fiber volume fraction are studied 62 and 40%. From the practical point of view, low values of the FVF can be found when a composite is manufactured using hand layup while the higher values are obtained for manufacturing using vacuum infusion or prepreg techniques (Bahei El-Din, 2011).

The first layup to be studied is a laminate with total thickness of 36mm and comprised of 48 layers of (0°) plies of glass fiber/epoxy matrix with the properties presented in Table 1. The single ply thickness is 0.75 mm and the laminate is subjected to bending moment in X₁ direction as given in Fig. 1.

For comparison, firstly, a problem is solved when the volume fraction of all plies is maintained at 62% whose designation is Type I. Then, the same laminate is analysed under same loading and assigning a lower value of FVF of 40% for core plies with thickness t/4, t/2 and 3t/4 where t is the laminate half thickness as shown in Fig. 3-5. This core thickness can be attained by assigning the lower FVF value for 12, 24, 36 plies for core thickness t/4, t/2, 3t/4, respectively as given in Table 2.

The comparison criteria include flexural stiffness, bending moment at the onset of failure and the ultimate bending moment the laminate can sustain. The flexural modulus of the laminate E_f is calculated using the relation:

$$E_f = M/\kappa I \quad (11)$$

$I = b(2t)^3/12$ where, b is the width of the laminate which is a unit length. κ is the curvature of the laminate at bending moment M according to Eq. 5.

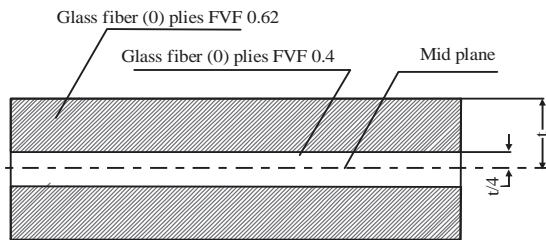


Fig. 3: (0°) laminate layup type II with core plies with thickness t/4 of FVF 40%

The same procedure is followed to check the effect of hybrid volume fraction on the behaviour of off-axis laminates. The investigated laminate is 12 layers of glass fiber textile with layup (0/±45°) for each layer resulting in 36 plies symmetric laminate with total thickness 10.7 mm. The thickness assigned for the 0° plies is 0.443 mm and for the off-axis plies is 0.222 mm. The fiber volume fraction of all plies is kept at 62% and analysed under bending moment in the global X₁ direction. As for the case of (0°) laminates, the bending moment at onset of failure and at complete failure together with the flexural rigidity E_f are recorded. This layup is given a designation of Type V. Then, two cases of hybrid volume fraction are investigated, designated Type VI and VII. For Type VI, a core of t/3 is assigned to a lower volume fraction of 40%. This thickness can be achieved by assigning this low volume fraction to 12 plies. A core of thickness 2t/3, which represents 24 plies, designated Type VII is assigned a low FVF of 40%. The different hybridization is presented in Fig. 6 and 7.

The other loading case to be studied is tensile load. For the tensile loading, the relation between axial stress and axial strain for the mid plane, Eq. 4, is plotted for the

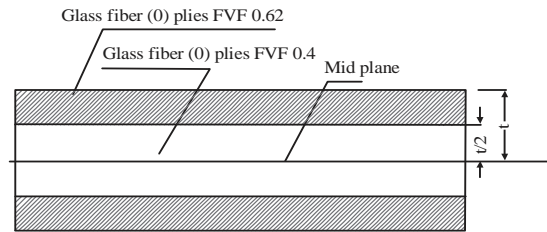


Fig. 4: (0°) laminate layup type III with core plies with thickness t/2 of FVF 40%

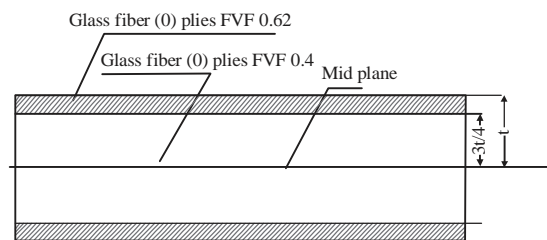


Fig. 5: (0°) laminate layup type IV with core plies with thickness 3t/4 of FVF 40%

Table 2: Results of (0°) plies composite laminates with variable volume fraction under bending moment in X₁ direction

Designation	Reduced FVF core thickness fraction	Reduced FVF core thickness (mm)	Reduced FVF core number of plies	BM at onset of failure (kN m m ⁻¹)	BM at failure (kN m m ⁻¹)	E _f (GPa)
Type I	0	0.00	0	238	288	58.16
Type II	t/4	9.00	12	238	288	57.87
Type III	t/2	18.0	24	225	275	56.05
Type IV	3t/4	27.0	36	225	250	51.06

cases of hybrid FVF and compared with the laminate where all plies enjoy higher volume fraction of 62%. The same two layups investigated under bending are utilised for axial loading.

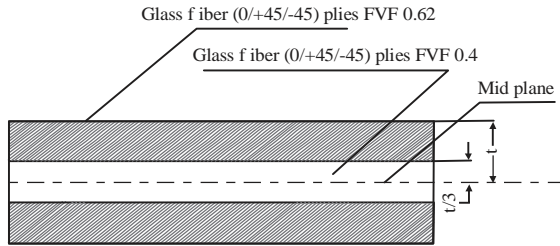


Fig. 6: (0/±45°) laminate layup type VI with core plies with thickness t/3 of FVF 40%

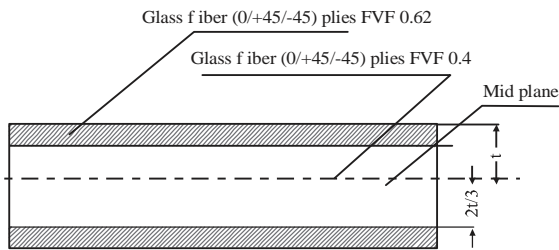


Fig. 7: (0/±45°) laminate type VII with core plies with thickness 2t/3 of FVF 40%

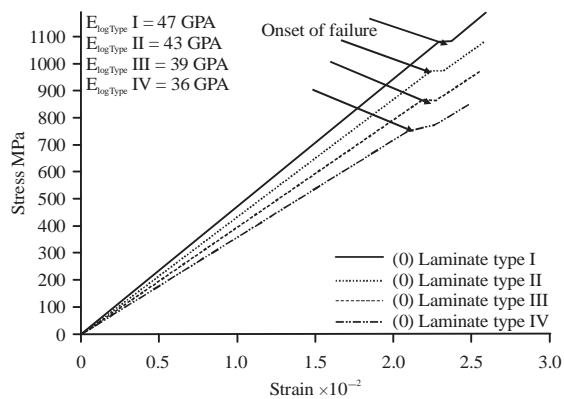


Fig. 8: Stress strain relationship for (0°) plies composite laminates with variable volume fraction under tension X_1 direction

RESULTS AND DISCUSSION

The results of the (0°) laminate presented in the previous section under bending are shown in Table 2. Comparing the results, it can be concluded that the effect of reduced core FVF on the mechanical behaviour of the axial laminates under bending is not significant. The reduction in any property ranges from 0% for narrow core to 12% for large core. The results of the (0/±45°) laminate are shown in Table 3. The same phenomenon depicted in the (0°) is repeated here with slight reduction in any of the studied variables. For example, the reduction in the bending moment at the onset of failure may reach 18.2% when assigning low FVF for two thirds of the thickness.

For tensile load, the stress-strain relationship of the mid plane of the laminate for the (0°) and the (0/±45°) layups are given in Fig 8 and 9, respectively. From Fig. 8, it can be concluded that the reduction in the laminate stiffness due to the three hybridisation systems, when compared to Type I, is 8.5, 15.8 and 23.7%. For the off-axis (0/±45°) laminate, Fig. 9, the loss in the stiffness is 10% for t/3 core thickness (Type VI) when compared with Type V. The reduction reaches 23% for 2t/3 core thickness with volume fraction of 40% (Type VII).

Comparing the stress at the onset of failure for both layups, it is noticed that the onset of failure for Type I occurs at stress level of 1081 MPa while for hybrid FVF

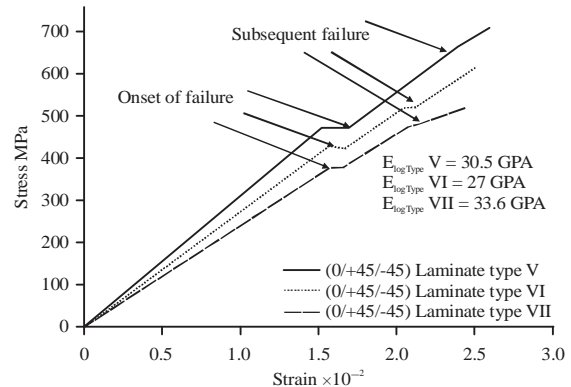


Fig. 9: Stress strain relationship for 0/±45° plies composite laminates with variable volume fraction under tension in X_1 direction

Table 3: Results of (0/±45°) plies composite laminates with variable volume fraction under bending moment in X_1 direction

Designation	Reduced FVF core thickness fraction	Reduced FVF core thickness (mm)	Reduced FVF core number of plies	BM at onset of failure (kN m m^{-1})	BM at failure (kN m m^{-1})	E_r (GPa)
Type V	0	0.00	0	11	16	32.4
Type VI	t/3	3.55	12	10	15	32.0
Type VII	2t/3	7.10	24	9	15	29.0

laminate Type II, III and IV occurs at 973, 865 and 757 MPa respectively. This represents 10, 20 and 30% lower than the onset of failure stress of Type I. The same reduced percentages can be noticed for the failure stress for the three laminates. From Fig. 9 and for $(0/\pm 45^\circ)$ laminate, the onset of failure occurs at stress 467, 420 and 374 MPa for Type V, VI and VII. This represents 10% and 20% reduction due to lower FVF in the core plies. For the failure stress, the reduced percentages attain higher values of 18.7, 31%. It is noticed that the loss in the onset of failure stress and the ultimate stress for such layup is more pronounced than the case of the (0°) layup due to the off-axis plies which give failure that is more tolerant.

It can be concluded from the results under bending and tension, that the behaviour of a hybrid FVF laminate, which contains some plies with reduced volume fraction, is much affected if it is subjected to tensile load rather than bending load. The results reveal that, under bending, the fiber volume fraction of the skin plies is what primarily controls the strength of the laminates especially for uniaxial laminates. This conclusion may be beneficial in the assessment of the reliability of some laminates that suffer suspicious in the fiber volume fraction due to manufacturing process. Such laminates behaviour can be enhanced by applying skin plies with higher fiber volume fraction which can be achieved using another manufacturing process. The overall behaviour in such a case is more reliable under the case of bending rather than tensile loads. It may be worthy to say that the effect of high stiffness skin layers can compensate the weak core plies especially for uniaxial laminates.

CONCLUSION

An investigation is presented on the behaviour of composite hybrid laminates in which some embedded plies suffer lower values of fiber volume fraction. The investigation includes laminates with different layups and with embedded core plies with different thicknesses that contain low values of fiber volume fraction. These laminates are investigated against bending moment and tensile load. It is concluded that the effect of low fiber volume fraction in some plies affects the tensile behavior in a more rigorous way than in bending. However, the effect goes to axial and flexural stiffness in addition to strength in bending and tensile loads.

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