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Full Length Research Paper

Effect of skew angle on nonlinear static behavior of fiber reinforced plastic (FRP) laminates with circular cutout

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One of the factors influencing the stiffness and stresses of the plate is skew angle of the plate. The present work focused on evaluation of the effect of skew angle on geometric nonlinear behavior of a four layered symmetric cross-ply (0°/90°/90°/0°) skew laminated fiber reinforced plastic (FRP) composite plate with a circular cutout at the geometric centre of the plate. The problem was modeled in ANSYS software and was executed for satisfactory results by performing convergence of the finite element mesh. Results were obtained for a uniform transverse pressure of 0.5 MPa for four different skew angles of the plate. The limitations of the linear assumption and the need for nonlinear analyses are stated.

Key words: Finite element method (FEM), fiber reinforced plastic (FRP) laminate, cutout, geometric nonlinearity, skew angle.

INTRODUCTION

Composite laminates are highly suitable for lightweight applications like aerospace and ship building industries due to their high specific stiffness and strength. The mechanical behavior of these laminated composites depends upon the degree of orthotropy of individual layers and the stacking sequence of the lamina (Jones, 1999). Specific applications of composite skew plates include aircraft wings and aircraft tail-fins. Often these structures are subjected to transverse forces that may cause failure of structure when the magnitude of these forces is not within limits of safe design. Skew composite laminates with cutouts are extensively used in a diverse industrial field, especially, nuclear facilities, aeronautical, mechanical, marine, automotive and civil structures because of their many merits. Cutouts are useful for saving weight, for providing fuel, electrical and hydraulic lines. Skew plates with cutouts are often used in modern structures, despite the mathematical difficulties encountered in their analysis. Hence, due to difficulty to obtain exact solution, numerical methods such as finite element method, finite difference method, Rayleigh-Ritz method, etc., are used to investigate the structural mechanics of skew laminated plates with cutouts. Srinivasan and Ramachandran (1976) presented a theoretical analysis for the large deflection elastic behavior of clamped, uniformly loaded orthotropic skew plates. Buragohain and Patodi (1978) presented a finite difference scheme with triangular mesh for the analysis of skew plate problems with large deflections. Kuppusamy and Reddy (1984) presented a three-dimensional, geometrically nonlinear finite-element analysis of the bending of cross-ply laminated anisotropic composite plates. Reddy and Chandrashekhara (1985) obtained numerical results for geometrically nonlinear analysis of laminated composite shells using a doubly curved shear deformable shell elements. Ajit et al. (1992) analysed nonlinear static behavior of rhombic plates for different skew angles following Banerjee's hypothesis. Kong and Cheung (1995) proposed a displacement-based, three dimensional finite element scheme for analyzing thick laminated plates by treating the plate as a three-dimensional inhomogeneous anisotropic elastic body.

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Liew and Han (1997) presented the bending analysis of a simply supported thick skew plate based on the first-order shear deformation Reissner/Mindlin theory. Duan and Mahendran (2003) developed a new hybrid/mixed shell element using oblique coordinate systems to analyze the large deflection behavior of skew plate with various skew angles, length to width ratios, thicknesses and supported edges under uniformly distributed and concentrated loads. Reddy (2005) reviewed finite element models of the continuum-based theories and two-dimensional plate/shell theories used in the analysis of composite laminates. Khashaba et al. (2007) studied the bending behavior of notched and un-notched angle-ply, $[0/\pm30/\pm60/90]_s$, glass fiber reinforced epoxy composites under static and fatigue loads. Static and fatigue bending properties have been determined for notched and un-notched angle-ply specimens. Shao and Yue (2007) studied the behavior of composite laminate with rectangular cutout by tensile experiments and finite element method (FEM) simulation. Malekzadeh and Fiouz (2007) employed two different differential quadrature approaches based on the thin plate theory and the first order shear deformation plate theory to investigate the large deformation analyses of thin and moderately thick orthotropic skew plates with nonlinear elastic rotationally restrained edges. Park et al. (2008) performed a structural dynamic analysis of skew sandwich plate with laminated composite faces based on the high-order shear deformation plate theory. The effects of skew angles and layup sequences on the dynamic response for various parameters are studied using a nonlinear high-order finite element program developed for the study. Ersin et al. (2009) investigated the effects of hole diameter and hole location on the lateral buckling behavior of woven fabric laminated composite cantilever beams. Wang and Qin (2010) presented a new hybrid finite element formulation for solving two-dimensional orthotropic elasticity problem of a square plate containing a circular hole in the center and under uniaxial tension. Debabrata et al. (2010) investigated the effects of skew angle, aspect ratio and boundary condition on large deflection static behavior of thin isotropic skew plates under uniformly distributed load. From the review of available literature, it is observed that the nonlinear static analysis of skew plates with cutouts using elasticity theory has not been studied. Hence, there is a scope to analyze the effect of skew angle on the geometric nonlinear behavior of skew fiber reinforced plastic (FRP) laminates with circular cutout.

Problem statement

The objective of the present work is to predict the geometric nonlinear behaviour of a four layered symmetric cross-ply laminate with a central circular cutout subjected to uniform transverse pressure for different skew angles using a three dimensional finite element approach.

Skew laminate

The term 'skew' in skew laminate refers to oblique, swept or parallelogram. In the case of skew plate, the angle between the adjacent sides of the plate is not equal to 90°. If opposite sides of the plate are parallel, it becomes a parallelogram and when their lengths are equal, the plate is called a rhombic plate. In the present analysis a skew laminated plate of skew angle α is considered as shown in Figure 1.

Nonlinearities in structures

The term "stiffness" defines the fundamental difference between linear and nonlinear analysis. Stiffness is a property of a part or assembly that characterizes its response to the applied load. A number of factors like shape, material and part support, etc., affect stiffness of a structure. When a structure deforms under a load its stiffness changes, due to one or more of the earlier listed factors. If it deforms a great deal, its shape can change. On the other hand, if the change in stiffness is small enough, it makes sense to assume that neither the shape nor material properties change at all during the deformation process.

That means that throughout the entire process of deformation, the analyzed model retain whatever stiffness it possessed in its undeformed shape prior to loading. Regardless of how much the model deforms, whether the load gets applied in one step or gradually, and no matter how high the stresses that develop in response to that load may be, the model retains its initial stiffness. This assumption generally simplifies problem formulation and solution. We recall the fundamental finite element analysis (FEA) equation:

$$[F] = [K] \times [d]$$

where [F] is the known vector of nodal loads, [K] is the known stiffness matrix and [d] is the unknown vector of nodal displacements.

This matrix equation describes the behavior of FEA models. The stiffness matrix [K] depends on the geometry, material properties and restraints. Under the linear analysis assumption that the model stiffness never changes, those equations are assembled and solved just once, with no need to update anything while the model is deforming. Thus, linear analysis follows a straight path from problem formulation to completion.

Everything changes upon entering the world of nonlinear analysis, because nonlinear analysis requires engineers to abandon the assumption of constant stiffness. Instead, stiffness changes during the deformation process and the stiffness matrix [K] must be updated as the nonlinear solver progresses through an iterative solution process. Those iterations increase the amount of time it takes to obtain accurate results.

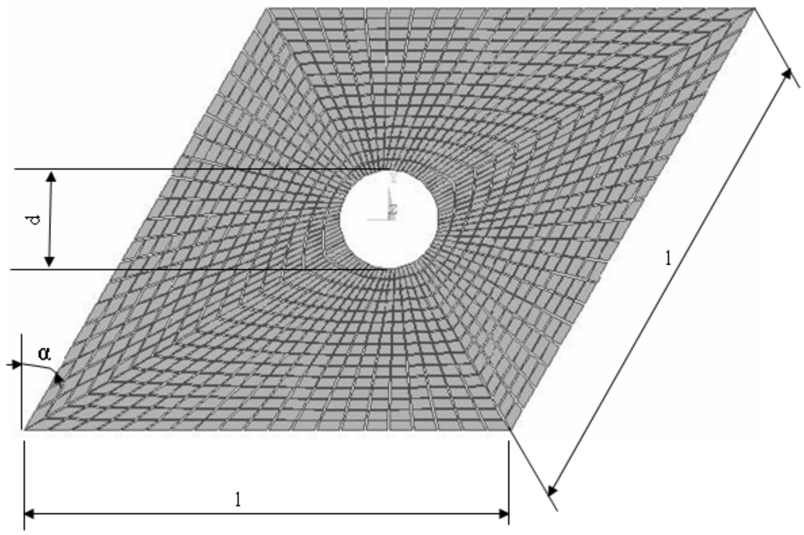

Figure 1. Skew laminated Composite plate with a circular cutout.

Table 1. A few computed values of stresses on free surfaces (Bottom surface).

x-Position (mm)	y-Position (mm)	σ_{zz} (MPa)	τ_{yz} (MPa)	τ_{zx} (MPa)
-0.57172	-3.77549	-0.0000029288	0.0055260	0.0058589
0.57172	3.77549	-0.0000029284	-0.0055260	-0.0058589

Table 2. A few computed values of stresses on top surfaces (Top surface).

x-Position (mm)	y-Position (mm)	σ_{zz} (MPa)	τ_{yz} (MPa)	τ_{zx} (MPa)
-0.57172	-3.77549	-0.50038	0.0076090	0.0067750
0.57172	3.77549	-0.50038	-0.0076090	-0.0067750

PROBLEM MODELING

The in-plane dimensions of the laminate considered for the present analysis is as shown in Figure 1. The dimensions for 'l' are taken as 20 mm. The value of d was determined from the ratio of d/l. The value of 'h' is determined from the length to thickness ratio l/h (s).

Laminate consists of four layers of equal thickness (h/4). The present work considers a skew plate with a central circular cutout of fixed d/l = 0.2 and 's' value of 40 for both linear and nonlinear analysis.

The finite element mesh is generated using a three dimensional brick element 'SOLID 95' of ANSYS. This element is a structural solid element designed based on three-dimensional elasticity theory and is used to model orthotropic solids. The element is defined by 20 nodes having three degrees of freedom per node: translations in the nodal X, Y and Z directions. The element may have any spatial orientation. The stacking sequence of the laminate is taken as 0°/90°/90°/0°.

All the edges of the cross-ply laminated skew plate are clamped that is all the three degrees of freedom (Displacements in global x-, y- and z- directions) of the nodes attached to the side faces of the plate are constrained. A transverse pressure of 0.5 MPa is applied on the top surface of the plate in ten equal steps.

The material properties of the composite made of graphite-epoxy are as furnished as shown in Table 4.

VALIDITY OF THE PRESENT ANALYSIS

To validate the finite element results, a skew four layered FRP cross-ply laminate having a circular cutout at the centre with clamped edges and applied pressure (0.5 MPa) on the top surface was considered.

A few computed values of stresses at top and bottom surfaces of the plate are obtained after conducting a number of convergence tests by varying mesh size (Tables 1 and 2). The values of σ_{zz} are nearly equal to zero at the bottom surface of plate and equal to applied pressure load at the top surface of plate. The shear stresses τ_{yz} and τ_{zx} are nearly equal to zero at both surfaces of the plate.

RESULTS AND DISCUSSION

Results are obtained by varying uniform transverse pressure upto 0.5 MPa for four different skew angles α = 0°,15°, 30° and 45°. The results show that there is a variation of deflection from linear to nonlinear.

Transverse deflection of the skew plate with respect to the applied load is as shown in Figure 2. Magnitude of

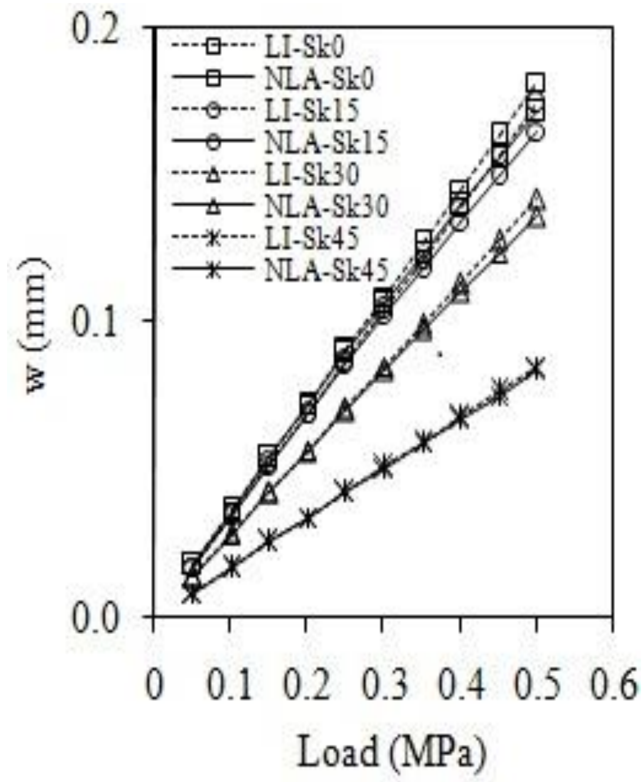

Figure 2. Variation of 'w' with respect to Load.

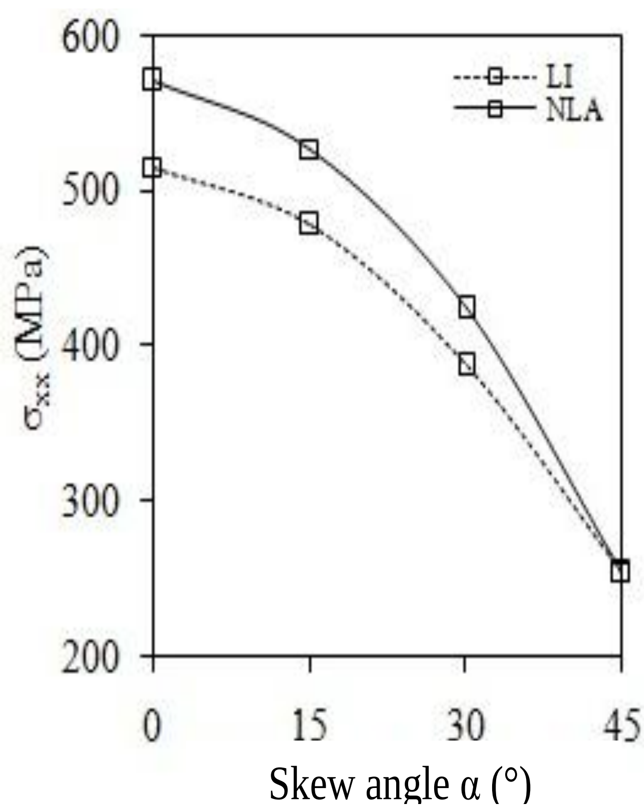

Figure 3. Variation of σ_{xx} with respect to α.

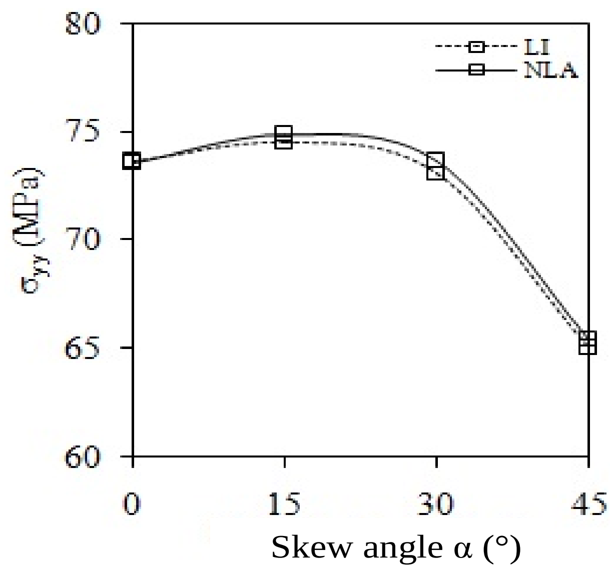

Figure 4. Variation of σ_{yy} with respect to α.

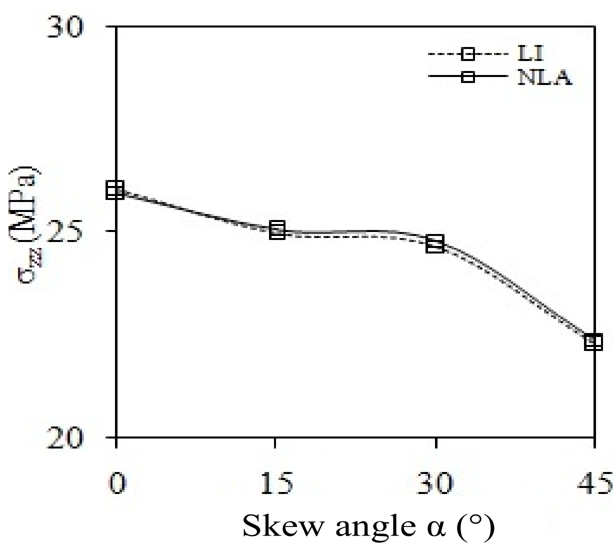

Figure 5. Variation of σ_{zz} with respect to α.

the transverse deflection and the difference between results from the two analyses types increase with an increase in load indicating that nonlinear analysis is required to study the exact behavior of the structure under consideration. The values of deflection decreases as the skew angle of the FRP laminated composite plate increases, because of increase in stiffness of the plate due to reduction in the length of shorter diagonal of the plate. The nonlinear behavior was observed beyond 0.3 MPa for skew angles of α = 0°,15°, 30° and 0.45 MPa for α = 45°.

The values of normal stresses σ_{xx}, σ_{yy} and σ_{zz} (Figures 3 to 5) decrease with increase in skew angle α for both linear and nonlinear analysis.

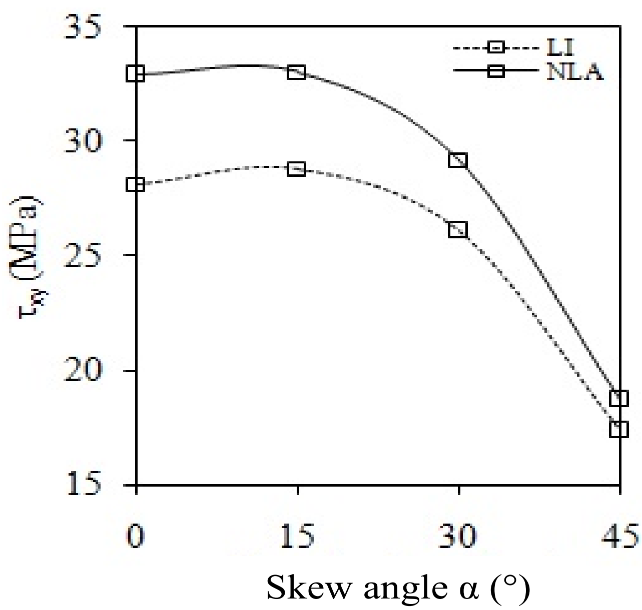

Figure 6. Variation of τ_{xy} with respect to α.

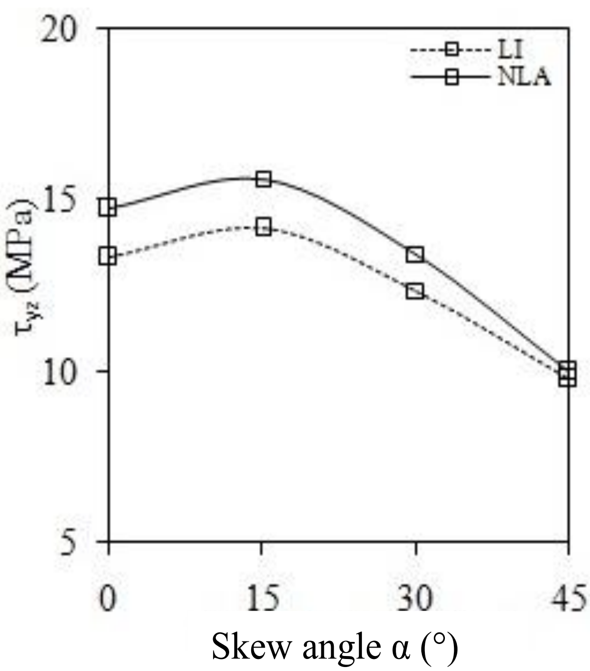

Figure 7. Variation of τ_{yz} with respect to α.

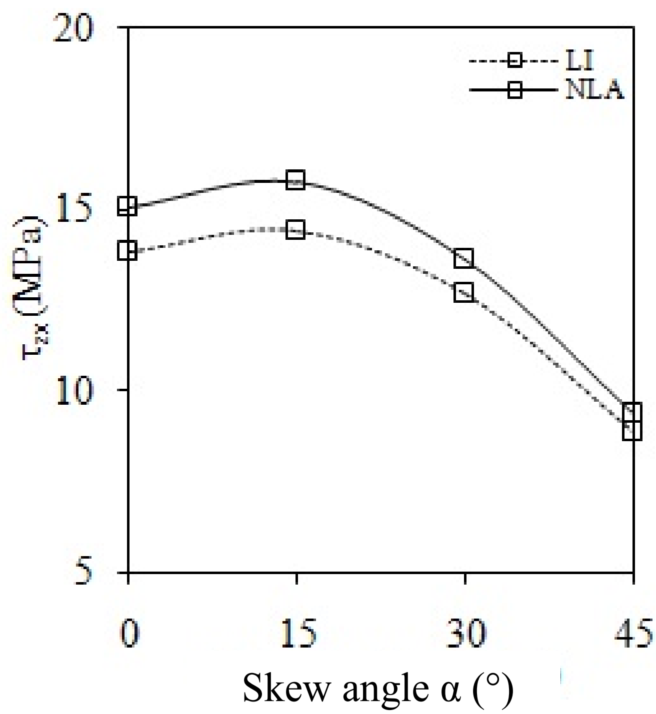

Figure 8. Variation of τ_{zx} with respect to α.

Table 3. Percentage variation of linear and nonlinear results of the critical stress (σ_{xx}).

Skew angle (α) in degrees	Percentage variation (σ_{xx})
0	10.57
15	10.357
30	9.3
45	0.05

Table 4. Components Graphite-Epoxy.

E_1 (GPa)	141.68
$E_2 = E_3$ (GPa)	12.384
$v_{12} = v_{13}$	0.25772
v_{23}	0.42057
G_{23} (GPa)	4.360
$G_{12} = G_{13}$ (GPa)	3.880

The magnitude and difference between linear and nonlinear results was observed to be more for σ_{xx}, but very less for σ_{yy} and σ_{zz} for all skew angles under consideration. The magnitude of σ_{yy} increases upto 15° and then decreases.

The values of shear stresses τ_{xy}, τ_{yz} and τ_{zx} (Figures 6 to 8) decrease with an increase in skew angle for both linear and nonlinear analysis. The magnitude and difference between linear and nonlinear results was observed to be nearly same for τ_{yz} and τ_{zx}, but less when compared with τ_{xy} for all skew angles under consideration.

Table 3 shows the percentage variation of linear and nonlinear results of the critical stress (σ_{xx}) with respect to skew angle. It was found that at α = 0°, the percentage variation is maximum and at α = 45° it is minimum.

CONCLUSIONS

A four layered symmetric skew FRP cross-ply laminate having a circular cutout at geometric centre with clamped edges and applied pressure (0.5 MPa) on the top surface has been analyzed for four different skew angles for linear and geometric nonlinear analysis options. Three-dimensional finite element model has been generated with governing boundary conditions for the evaluation of the deflection, normal and shear stresses. The following conclusions were drawn:

1. Nonlinearity was observed at higher load for deflection at skew angle of $\alpha = 45°$ as compared to $\alpha = 30°$, 15° and 0°.
2. The magnitude of normal stresses, shear stresses and deflection decreases with an increase in skew angle α because of increase in stiffness of the plate.
3. The magnitude of both normal and shear stresses were observed to be more for nonlinear analysis when compared with linear analysis, so for safe design of the structure nonlinear analysis is much needed.
4. It was observed that $\alpha = 45°$ is the optimum skew angle for strength and stiffness point of view in the considered range of skew angles.

Nomenclature: **E_1,** Young's modulus of the lamina in the fiber direction; **($E_2 = E_3$),** Young's modulus of the lamina in the transverse direction of the fiber; **($G_{12} = G_{13}$),** shear modulus in the longitudinal plane of the fiber; **G_{23},** shear modulus in the transverse plane of the fiber; **($v_{12} = v_{13}$),** Poisson's ratio in the longitudinal plane of the fiber; **v_{23},** Poisson's ratio in the transverse plane of the fiber; **α,** skew angle; **s,** length (l)/thickness (h) of the plate; **l,** length or width of the plate; **h,** total thickness of the plate; **d,** diameter of circular cutout.

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