Numerical prediction of interlaminar stresses in laminated composites

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Abstract. Laminated composite materials are extensively utilised in aerospace, aviation and automobile industries because of their high strength and low weight. When laminates are composed of layers with different orientations, classical lamination theory implies boundary tractions on free edges. Edge delamination in laminated composites has become significant in structural reliability. Due to more inter-laminar shear stresses nearer to the free edges of the laminates, more failure modes are developed in the laminates. Because of the complex fibre/matrix micro structure of laminated composite materials, an evaluation of these stresses becomes very important in composite materials design. Normally free edge inter-laminar stresses arise from the mismatch of elastic properties between two layers. Therefore it is necessary to predict the inter-laminar stresses of laminated composite plates. In this study, the free edge inter-laminar stresses of laminated composite materials are predicted numerically. Numerical prediction of inter-laminar stresses of non-hybrid and hybrid laminated composite plates are predicted. In hybrid category, carbon fibres and glass fibres are combined together and analysed. Numerical analysis of laminates is performed in ANSYS. The inter-laminar shear forces and stress distribution are plotted along thickness.

1. Introduction
Composite materials are made with two different materials with one material with discontinuous phases and other one is continuous phase material. The discontinuous phase material is harder and stronger compared to the continuous phase material and it is called as the reinforcement and the continuous phase material is called the matrix. The mechanical properties of composite materials are strongly influenced by their constituent material properties, their distribution, and the interaction between them. The major advantage of these composites is the ability to control their anisotropy by design and fabrication.
Fibre-reinforced composites are classified into single-layer and multilayer composites. Single-layer composites are mostly made with several distinct layers in which each layer has the same mechanical properties and same fibre orientation. Therefore the above laminate is known as a single-layer composite. Multilayered composites are made of several number of laminae of fibrous composites. Each lamina is considered to be a single-layer composite, and its orientation angle is varied according to their design. Each lamina in the multilayered composite is very thin and it cannot be used directly. Many identical or different layers are stacked together to get multilayered composite for several useful
engineering applications. When the same constituent material is present in each layer, they are termed as laminates. To achieve more balanced properties in a laminate, the continuous reinforcement in a single layer is provided in a second direction. In a woven fabric, the bidirectional reinforcement is provided in mutually perpendicular directions. Here, the strengths in two perpendicular directions are equal. (Agarwal et al 2012)

M. Hajikazemi developed a model for calculating both stress and displacement fields at free edges of general symmetric composite laminate strips under thermo-mechanical loads. By partitioning the total stresses in a composite with free edges into unperturbed and perturbation stresses and using the minimum complementary energy principle, the optimal stress and displacement fields are derived that exactly satisfy equilibrium, compatibility, boundary and continuity conditions. The superiority of the developed method over finite element method, both in terms of accuracy and computational efficiency, is discussed.

Christopher R. Cater developed a model with two-scale FE approach to discuss the effect of stresses and the tendency for initial cracking at the laminate free edge. The laminate stacking sequence and the global stress field under a given loading condition are captured by a meso-model and the local constituent level stresses at the free edge are predicted by a micro-scale model. The two models were coupled one-way through a strain localization rule. This proposed model examines the 90/90 interface in carbon/epoxy composite laminates. Investigation of the effects of thermal and tensile loading was carried out to understand the influence of the inter-laminar stresses at free edges during manufacture and during mechanical loading.

M. Keith Ballard investigated the effect of modeling in unidirectional laminae near a free-edge of a [±45/0/90]s laminate under uniaxial extension. A random fiber arrangement was used for the entire 0° and 90° plies, and the predicted inter-laminar normal stress was compared to the prediction using a classical homogeneous model, where all laminae are treated as homogeneous, orthotropic plies. The displacements along the boundaries of the models matched well, but the inter-laminar normal stress near the free-edge differed significantly between the two models. When fibers and matrix were modeled discretely, the interaction of neighbouring fibers created a complex stress pattern along the ply interfaces, especially the 0-90 ply interface. The inter-laminar normal stress for two paths parallel to the y-axis along the 0-90 ply interface showed that the peak stress occurred at the free-edge for a path near a 90° fiber and occurred about two fiber diameters from the free-edge for a path near a matrix rich region of the 90° ply.

Hamidreza Yazdani Sarvestani determined the inter-laminar stresses of cross-ply composite laminates nearer to the free edges. The stresses in the interior and the boundary-layer regions were investigated for the laminates subjected to a bending moment, an axial force, and/or a torque. The computed results were compared with Reddy’s theory and it was observed that the HESL theory predicts the interlaminar stresses near the free edges of laminates precisely.

N. Dhanesh determined accurate free edge stresses in laminates under uniaxial tension, bending, twisting and thermal loading based on three-dimensional elasticity using the mixed-field multi term extended Kantorovich method (MMEKM). MMEKM is a better iterative analytical method and its solution satisfies all the interfacial continuity conditions and boundary conditions at all points, for symmetric cross-ply and angle-ply laminates, the free edge stresses are predicted and compared and it is seen that there is a good convergence of the MMEKM results.

Espadas-Escalante investigated the inter-laminar and intra-laminar stresses at the free-edge of plain woven composite laminates. Considering repeating unit cells simulating finite and infinite width, two-layered laminates with three different shifting configurations were studied. While more number of
layers is considered, it is observed that the stacking sequence influences the free edge effects and the state of stress.

Muhsin J. Jweeg presented an analytical study using the First-Order Shear Deformation Theory (FSDT) to determine the inter-laminar shear stress between every two layers of the laminated composite plates of symmetrical and un-symmetrical, cross ply and angle ply laminated plates. The Navier solutions are also used to find the behaviour of the plates in two dimensions. In model analysis method, the equation of motion for the composite plate is solved and the inter-laminated shearing stress is calculated. The inter-laminar shear stress under effect of the dynamical loads are studied by the effect of material orthotropic, aspect ratio, laminate stacking sequence, number of layer of laminated plate and the plate width-to-thickness ratio. The results of the displacements are compared with numerical program. It is found there is a good agreement between the analytical and numerical results.

Nosier determined the inter-laminar stresses nearer to the free edges in laminated composite materials under axial tension. And the accuracy and effectiveness of the proposed theory were verified with the results of Reddy's layer-wise theory. Reddy’s layer-wise theory is used for numerical and analytical investigations of the boundary-layer stresses within arbitrarily laminated composite plates. The effects of end conditions of laminates, laminate orientation angles, the stacking sequences of the layers within laminates and geometric parameters with the predicted the boundary-layer stresses were discussed.

Rasuo analyzed the stress-strain conditions at the free edges of the laminates using Tsai criteria. In laminated composites, inter-laminar stresses develop at the free edges due to variation of elastic properties between laminates. It is observed that the inter-laminar stresses are important because they have more influence on the failure strengths of composite laminates. Accurate determination of inter-laminar stresses at the free edge is hence crucial and it should be studied to prevent its early failure.

Zaki presented an analytical model for the determination of shear stresses in laminated composite materials at the interface of bonded layers. Here, a new function based on shear stress is developed and that considered the influence of shear lag in laminates which are stacked with adhesively bonded layers of various types and thicknesses.

Based on the literature review stated above, it is observed that the inter-laminar shear stress is an important requirement of laminated composite materials subjected to external loading. This study is concentrated on free edges inter-laminar stresses of (90/60)s composite laminates with different types of fibres and matrix with axial loading. In this work, the numerical analysis of (90/60)s composite plates with Glass Fibre, Carbon fibre, Aramid Fibre, Boron, and Alumina Fibres is carried out.

2. Laminated composite Materials

In this work, (90/60)s layup sequence are considered. The various reinforcements like E-Glass Fibre, S-Glass Fibre, PAN Carbon GY70, PAN Carbon AS1, Aramid Kevlar 49, Aramid Technora, Boron, and Alumina Fibre are considered with unidirectional category. The matrices selected for the study are cast epoxy resin and KIII. The principal material directions in the lamina are used to represent structural element with the mechanical properties in x, y and z directions in which the lamina acts as a single layer material. In a laminate, the bond between two lamina is to be perfect and the laminae cannot move over each other and it is assumed that displacements across the thickness of laminate are continuous. Figure 1 shows a lamina in which Fibres are positioned parallel to each other in a matrix. To describe its mechanical properties, the two-way coordinate systems are defined such as the 1-2-z system and the x-y-z system. Both1-2 and x-y axes are coincided in the ground plane, that is the plane of the lamina, and the z axis is normal to this plane. In the 1-2-z system, axis 1 is along with the Fibre1
and denotes the longitudinal direction of the lamina. The axis 2 is normal to the Fibre and denotes the transverse direction of the lamina. Together, they form the principal material directions of the lamina. 

In the \( xyz \) system, \( x \) and \( y \) axes represent the loading directions. The angle between the positive \( x \) axis and the \( 1 \)-axis is called the Fibre orientation angle and is represented by \( \theta \). The sign of this angle depends on the right-handed coordinate system as shown in figure 2. If the \( z \) axis is vertically upward to the lamina plane, \( \theta \) is positive when measured counterclockwise from the positive \( x \) axis (Mallick 2008).

![Figure 1](image1.png) Principal material axes and loading axes for a laminae.  
![Figure 2](image2.png) Right-handed coordinate systems.

### 2.1. Determination of Elastic Properties of Unidirectional Laminae

The unidirectional composite laminae elastic properties are calculated using Fibre volume fraction (\( V_f \)) and the mechanical properties of Fibres and Matrix which are tabulated in Table 1 and 2. Equations (1) to (6) depict the elastic properties of laminae. (Mohammed et al 2003).

\[
E_1 = E_f V_f + E_m V_m
\]

(1)

\[
E_2 = E_m \left( \frac{E_f + E_m + (E_f - E_m)V_f}{E_f + E_m - (E_f - E_m)V_f} \right)
\]

(2)

\[
v_{12} = v_f V_f + v_m V_m
\]

(3)

\[
G_{23} = \frac{E_2}{2(1 + \nu_{23})}
\]

(4)

\[
\nu_{23} = \frac{1 + \nu_m - \nu_{12}}{1 - \nu_m^2 + \nu_m \nu_{12}} \left( \frac{E_m}{E_1} \right)
\]

(5)

\[
G_{12} = G_m \left[ \frac{G_f + G_m + (G_f - G_m)V_f}{G_f + G_m - (G_f - G_m)V_f} \right]
\]

(6)
Indices ‘m’ and ‘f’ denote matrix and fibre, respectively

where

\( E_1 \) Elastic modulus of unidirectional laminae along \( x \) direction (GPa)
\( E_2 \) Elastic modulus of unidirectional laminae along \( y \) direction (GPa)
\( E_3 \) Elastic modulus of unidirectional laminae along \( z \) direction (GPa)
\( \nu_{12} \) Poisson ratio of unidirectional laminae in plane \( x-y \)
\( \nu_{13} \) Poisson ratio of unidirectional laminae in plane \( x-z \)
\( \nu_{23} \) Poisson ratio of unidirectional laminae in plane \( y-z \)
\( G_{12} \) In plane shear modulus of unidirectional laminae (GPa)
\( G_{13} \) Shear modulus of unidirectional laminae along \( x-z \) direction (GPa)
\( G_{23} \) Shear modulus of unidirectional laminae along \( y-z \) direction (GPa)
\( E_f \) Elastic modulus of fibre (GPa)
\( E_m \) Elastic modulus of matrix (GPa)
\( G_f \) Shear modulus of fibre (GPa)
\( G_m \) Shear modulus of matrix (GPa)
\( V_f \) Fibre Volume fraction
\( V_m \) Matrix Volume fraction
\( \nu_f \) Poisson’s ratio of fibre
\( \nu_m \) Poisson’s ratio of matrix

**Table 1. Mechanical Properties of various Fibres.**

| Mechanical Properties | E-Glass Fibre | S-Glass Fibre | PAN Carbon GY70 | PAN Carbon AS 1 | Aramid Kevlar 49 | Aramid Technora | Boron | Alumina Fibre (Al₂O₃) |
|-----------------------|---------------|---------------|-----------------|-----------------|------------------|----------------|-------|-----------------------|
| Elasticity Modulus    | 72.4          | 86.9          | 483             | 228             | 131              | 70             | 393   | 379                   |
| (GPa)                 |               |               |                 |                 |                  |                |       |                       |
| Shear Modulus         | 30.16         | 35.61         | 201.25          | 95              | 48.51            | 25.92          | 163.75| 157.91                |
| (GPa)                 |               |               |                 |                 |                  |                |       |                       |
| Poisson’s ratio       | 0.2           | 0.22          | 0.2             | 0.2             | 0.35             | 0.35           | 0.2   | 0.2                   |

**Table 2. Mechanical Properties of Cast Epoxy Resin and K III resins.**

| Mechanical Properties | Cast Epoxy Resin | K-III |
|-----------------------|------------------|-------|
| Elasticity modulus    | 4                | 3.76  |
| (GPa)                 |                  |       |
| Shear modulus         | 1.50             | 1.50  |
| (GPa)                 |                  |       |
| Poisson’s ratio       | 0.33             | 0.36  |

The calculated elastic properties of unidirectional laminae are given in table 3
Table 3. Elastic Properties of unidirectional composite laminae.

| Elastic Properties | E-Glass Epoxy Composites | Carbon KIII composites |
|--------------------|--------------------------|------------------------|
| $V_f$              | 0.3                      | 0.35                   | 0.4          | 0.45         | 0.3   | 0.35   | 0.4   | 0.45   |
| $E_1$ GPa          | 24.52                    | 27.94                  | 31.36        | 34.78        | 147.53| 171.49 | 195.45| 219.41 |
| $E_2$ GPa          | 6.93                     | 7.65                   | 8.46         | 9.39         | 6.91 | 7.71  | 8.64 | 9.74  |
| $E_3$ GPa          | 6.93                     | 7.65                   | 8.46         | 9.39         | 6.91 | 7.71  | 8.64 | 9.74  |
| $v_{12}$           | 0.29                     | 0.28                   | 0.27         | 0.27         | 0.31 | 0.30  | 0.29 | 0.29  |
| $v_{13}$           | 0.29                     | 0.28                   | 0.27         | 0.27         | 0.31 | 0.30  | 0.29 | 0.29  |
| $v_{23}$           | 0.41                     | 0.40                   | 0.39         | 0.39         | 0.49 | 0.48  | 0.46 | 0.45  |
| $G_{12}$ GPa       | 2.62                     | 2.89                   | 3.21         | 3.57         | 2.76 | 3.08  | 3.45 | 3.89  |
| $G_{13}$ GPa       | 2.62                     | 2.89                   | 3.21         | 3.57         | 2.76 | 3.08  | 3.45 | 3.89  |
| $G_{23}$ GPa       | 2.45                     | 2.72                   | 3.02         | 3.377        | 2.31 | 2.60  | 2.94 | 3.34  |

3. Numerical Model of laminate
In this study, Finite Element Analysis based numerical simulation software, ANSYS is used. ANSYS Parametric Design Language (APDL) module is selected for prediction of inter-laminar shear stress and it executes the input commands given by the users to predict the required output. The composite plate is modelled in ANSYS software and meshed with SOILD 186 element. It has 20 nodes and three degrees of freedom at each node. The degrees of freedom are translation at each node in three perpendicular axes and rotational degrees of freedom about those axes. The coordinate system used in this element, the location of the nodes in the element and the element geometry are shown in Figure 3. The SOLID 186 element supports stress stiffening, creep, hyper-elasticity, large deflection, plasticity, composite material modelling and large strain capabilities. The numerically modelled [90/60], composite plate has shown in figure 4.
3.1. Prediction of Inter-laminar Shear Stress

Inter-laminar stresses are known as out of plane stresses which are developed at the interface between the two laminates. The magnitude of the stresses induced in the interface depends upon the orientation of the fibres, material used in the phases. When the composite material is subjected to an external loading, intra-laminar and inter-laminar stresses between the layers are developed. The delamination of the laminates usually commences at the vicinity of the free edges of the material, which is due to the induced inter-laminar stresses. Hence, the prediction of the inter-laminar stress that plays a vital role in the failure of the laminated composite materials. In this study, the inter-laminar stresses \( \tau_{xz}, \tau_{yz} \) and \( \sigma_{zz} \) are predicted between the two layer composites when it is subjected to tensile loading. In this study, the entire laminated are subjected to axial strain of 0.01. Figure 5 shows the inter-laminar shear stress distribution along YZ direction of S glass KIII composites. The maximum inter-laminar stress near edges is predicted using this numerical program. The predicted inter-laminar stresses for all laminates with four different values of fiber volumetric fraction as tabulated in tables 4-11.

4. Results and discussions

From tables 4 to 11, it is observed that inter-laminar stress along yz-direction (\( \tau_{yz} \)) influences more than the other two stresses (\( \tau_{xz} \) and \( \sigma_{zz} \)).

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**Figure 3.** SOLID 186 Element.

**Figure 4.** Meshed Model of composite plate.

**Figure 5.** Inter-laminar stress distribution (\( \tau_{YZ} \)) of (90/60)\(_{S}\) composite laminates.
Table 4. Maximum Inter-laminar stress of Kevlar 49 Epoxy Composites and Kevlar 49 K-III Composites for various volumetric fractions.

|                  | Kevlar 49- Epoxy Composites | Kevlar 49 K-III Composites |
|------------------|-----------------------------|-----------------------------|
| V_f              | 0.3 0.35 0.4 0.45           | 0.3 0.35 0.4 0.45           |
| \( \tau_{xz} \)  | -8.7625 -10.017 -11.29 -12.594 | -9.0476 -10.316 -11.617 -12.966 |
| \( \tau_{yz} \)  | 15.374 17.491 19.688 21.991  | 14.6 16.629 18.732 20.937   |
| \( \sigma_{zz} \) | -7.5541 -8.5467 -9.6027 -10.743 | -7.2845 -8.246 -9.2657 -10.364 |

Table 5. Maximum Inter-laminar stress of Technora Epoxy Composites and Technora K-III Composites for various volumetric fractions.

|                  | Technora Epoxy Composites | Technora KIII Composites |
|------------------|---------------------------|--------------------------|
| V_f              | 0.3 0.35 0.4 0.45         | 0.3 0.35 0.4 0.45        |
| \( \tau_{xz} \)  | -4.874 -5.586 -6.279 -6.952 | -5.3863 -6.1351 -7.2484 -7.6067 |
| \( \tau_{yz} \)  | 9.7488 11.071 12.404 13.759  | 9.195 10.465 11.33 13.052  |
| \( \sigma_{zz} \) | -5.2621 -5.9507 -6.6596 -7.397  | -5.0223 -5.6845 -6.2533 -7.0845  |

Table 6. Maximum Inter-laminar stress of E-Glass Epoxy Composites and E-Glass K-III Composites for various volumetric fractions.

|                  | E-Glass Epoxy Composites | E-Glass KIII Composites |
|------------------|--------------------------|-------------------------|
| V_f              | 0.3 0.35 0.4 0.45        | 0.3 0.35 0.4 0.45      |
| \( \tau_{xz} \)  | -5.1117 -5.878 -6.6309 -7.3701 | -5.6262 -6.4299 -7.3701 -8.0357 |
| \( \tau_{yz} \)  | 9.947 11.274 12.66 13.977  | 9.3562 10.633 11.601 13.22  |
| \( \sigma_{zz} \) | -5.2496 -5.9073 -6.5803 -7.277  | -4.9769 -5.6079 -6.1535 -6.9137  |

Table 7. Maximum Inter-laminar stress of S-Glass Epoxy Composites and S-Glass K-III Composites for various volumetric fractions.

|                  | S-Glass Epoxy Composites | S-Glass KIII Composites |
|------------------|--------------------------|-------------------------|
| V_f              | 0.3 0.35 0.4 0.45        | 0.3 0.35 0.4 0.45      |
| \( \tau_{xz} \)  | -6.1564 -7.0714 -7.9807 -8.8866 | -6.6132 -7.5608 -8.5162 -9.4836 |
| \( \tau_{yz} \)  | 11.468 13.019 14.598 16.216  | 10.828 12.314 13.68 15.371  |
| \( \sigma_{zz} \) | -5.9061 -6.6522 -7.4247 -8.235  | -5.6263 -6.3421 -7.0801 -7.8516  |

Table 8. Maximum Inter-laminar stress of PAN Carbon AS1 Epoxy Composites and PAN Carbon AS1 K-III Composites for various volumetric fractions.
Table 9. Maximum inter-laminar stress of PAN Carbon GY70 epoxy composites and PAN Carbon GY70 K-III composites for various volumetric fractions.

| $V_f$ | 0.3  | 0.35 | 0.4  | 0.45 | 0.3  | 0.35 | 0.4  | 0.45 |
|-------|------|------|------|------|------|------|------|------|
| $\tau_{xz}$ | -18.376 | -14.917 | -16.872 | -18.96 | -13.063 | -14.905 | -16.859 | -18.962 |
| $\tau_{yz}$ | 17.957  | 24.378 | 27.489 | 30.81 | 20.401 | 23.257 | 26.247 | 29.415 |
| $\sigma_{zz}$ | -7.7405 | -10.404 | -11.646 | -13.016 | -8.9298 | -10.024 | -11.204 | -12.504 |

Table 10. Maximum inter-laminar stress of Al$_2$O$_3$ epoxy composites and Al$_2$O$_3$ K-III composites for various volumetric fractions.

| $V_f$ | 0.3  | 0.35 | 0.4  | 0.45 | 0.3  | 0.35 | 0.4  | 0.45 |
|-------|------|------|------|------|------|------|------|------|
| $\tau_{xz}$ | -18.829 | -21.398 | -24.195 | -27.663 | -18.377 | -20.882 | -23.622 | -26.669 |
| $\tau_{yz}$ | 32.401 | 36.912 | 41.718 | 46.434 | 30.993 | 35.314 | 39.917 | 44.894 |
| $\sigma_{zz}$ | -11.269 | -12.594 | -14.081 | -15.596 | -10.948 | -12.212 | -13.625 | -15.236 |

Table 11. Maximum inter-laminar stress of Boron epoxy composites and Boron K-III composites for various volumetric fractions.

| $V_f$ | 0.3  | 0.35 | 0.4  | 0.45 | 0.3  | 0.35 | 0.4  | 0.45 |
|-------|------|------|------|------|------|------|------|------|
| $\tau_{xz}$ | -17.005 | -19.354 | -21.886 | -24.662 | -16.702 | -19.002 | -21.497 | -24.246 |
| $\tau_{yz}$ | 28.543 | 32.526 | 36.747 | 41.285 | 27.289 | 31.103 | 35.146 | 39.491 |
| $\sigma_{zz}$ | -10.737 | -12.026 | -13.455 | 15.07 | -10.406 | -11.636 | -12.995 | -14.525 |

Figure 6 shows the comparison of inter-laminar stress $\tau_{yz}$ and volumetric fraction of fibers ($V_f$) for different types of reinforcements with epoxy resin. From figure 6, it is observed that Technora epoxy composites and E-glass epoxy composites induce minimum stress, whereas Carbon epoxy composites induce maximum stress. It is also observed that as volumetric fraction of fibre increases, the inter-laminar stresses also increases. Figure 7 shows the comparison of inter-laminar stress $\tau_{yz}$ and volumetric fraction of fibers ($V_f$) for different types of reinforcements with K-III resin and it is observed that stress Carbon GY70 epoxy composites exhibits maximum inter-laminar stress comparing to other laminates.
Figure 6. Comparison of inter-laminar stress $\tau_{yz}$ and volumetric fraction of fibers ($V_f$) for different types of reinforcements with epoxy resin.

Figure 7. Comparison of inter-laminar stress $\tau_{yz}$ and volumetric fraction of fibers ($V_f$) for different types of reinforcements with K-III resin.
Figure 8. Comparison of inter-laminar stress $\tau_{yz}$ for Glass, Technora and Kevlar fibres with Epoxy and K-III resins.

Figure 8 shows the comparison of inter-laminar stress ($\tau_{yz}$) for Glass, Technora and Kevlar fibres with Epoxy and K-III resins and it is observed that the inter-laminar stresses induced in Technora composites are less than E-glass, S-glass and Kevlar Composites.

5. Conclusions
A numerical study is performed to predict the inter-laminar shear stress distribution of two layer composites with various reinforcements, matrix and volumetric fraction of fibres. Based on the results obtained, the following conclusions are arrived.

- Inter-laminar stress along yz-direction ($\tau_{yz}$) influences better than other two inter-laminar stresses.
- As volumetric fraction of fibre increases, the inter-laminar shear stresses also increases.
- K-III composites developed less shear stress compared to Epoxy composites in Glass, Kevlar, Carbon and Alumina fibres.
- Technora K-III composites induce minimum inter-laminar shear stress compared to other composites.

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