MODELLING OF DELAMINATION IN LAMINATED COMPOSITES UNDER INTERLAMINAR MODE II FRACTURE LOADINGS

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ABSTRACT

Delamination is one of the dominant failure modes in fiber-reinforced laminated composites. It can substantially decrease the stiffness and strength of the laminates and result in catastrophic composite structural failures. Thus, accurate predictive modelling and simulation approaches are essential to understand the delamination failure mechanism and determine the residual strength of the damaged structures. In the present paper, delamination in unidirectional laminates under static interlaminar mode II fracture loadings is investigated using finite element (FE) modelling of the standard end-notched flexure (ENF) test. Among several commonly used FE modelling methods, the cohesive zone modelling (CZM) technique has been widely used to predict damage onset and evolution in composite bonded joints, and is selected to carry out this research. First, the ENF tests were conducted on G40-800/5276-1 carbon fiber reinforced composite laminate coupons following the ASTM D7905/D7905M standard. The objective of these tests was to determine the mode II fracture toughness (G_{IIC}), required for defining the cohesive element constitutive law. The test coupons were then modelled with embedded cohesive elements for fracture tests with and without precracks. The biggest challenge to ensure the computational convergence and solution accuracy of a CZM model is the determination of relevant parameters. To this end, comprehensive parametric studies were conducted to explore the effects of the traction-separation laws, cohesive element penalty stiffness, interfacial strength, mesh density, as well as the data reduction schemes, to obtain the most efficient and robust solution compared with the test results. The crack propagation in the fracture tests without precracks was also compared with the predictions from the FE models. This study indicates that a reliable CZM strategy has been achieved for the effective prediction of mode II damage behavior of laminated composites.

1 INTRODUCTION

With the increasing use of fiber-reinforced composites in almost all structural applications in recent decades, it is more crucial to well understand and predictively model the failure behavior of these materials. Failure modes in composite materials are typically more complex than metals, which may include matrix cracking, fiber breakage, fiber kinking, and delamination. Interlaminar delamination is one of the catastrophic damage modes in fiber-reinforced composites where material fractures into constituent layers. One of the major causes of the laminated composite delamination is attributed to their low fracture toughness in the thickness direction of the laminates. The objective of the present paper is to study the delamination in unidirectional laminates under interlaminar mode II fracture loadings using finite element (FE) modelling with dedicated test validations. There are three major test methods commonly employed to determine composite mode II interlaminar fracture toughness: the end-notched flexure (ENF) test, the end-loaded split (ELS) test, and the four-point end-notched flexure (4ENF) test. Because the ELS test requires accurate crack propagation monitoring and the 4ENF test is sensitive to geometrical nonlinearity associated with the changes in roller contact points and loading point rotation [1, 2], the ASTM standard ENF test was thus selected in this study due to its advantage of simplicity in the test setup. Two data reduction schemes, the compliance calibration method (CCM) standardized by ASTM D7905/D7905M [3] and the compliance-based beam method (CBBM) suggested in [4], were compared to determine the mode II fracture toughness (G_{IIc}), which is one of the most important parameters to use in the FE models. To model interlaminar delamination, two finite element based approaches are widely used. One is the virtual crack closure technique (VCCT), and the other one is the cohesive zone modelling (CZM) technique. The CZM method was selected largely based on the confidence and experience gained from our previous modelling work on the mode I delamination of double cantilever beam (DCB) fracture test [5]. Two-dimensional and three-dimensional finite element models of the ENF tests were developed for both non-precracked fracture tests and precracked fracture tests. Optimized parameters to be used in the CZM models were achieved by an empirical study, and the modelling results were validated by the test results. Meanwhile, better accuracy from the effective-crack-length based CBBM data reduction scheme was demonstrated.

2 END-NOTCHED FLEXURE TEST

2.1 Specimen Preparation and Testing Fixture

As indicated previously, the composite interlaminar mode II fracture tests were carried out using the end-notched flexure (ENF) tests, following the procedure in the ASTM D7905/D7905M [3]. In accordance with this ASTM standard, the width and the thickness of the specimen should be between 19 to 26 mm and 3.4 to 4.7 mm, respectively. The length of the starter crack should be longer than 45 mm and the uncracked portion of the beam should be longer than 115 mm. Therefore, the unidirectional laminated ENF specimens were made with a nominal thickness of $2h = 4.35$ mm. After the laminates were cured in an autoclave, they were cut to the nominal dimensions of width $w = 21.3$ mm and length $L = 168.3$ mm. The specimens were made of carbon-fiber-reinforced epoxy prepregs (G40-800/5276-1) that were supplied by Cytec. A 13 µm thick PTFE film was pre-implanted at the mid-plane of each tested laminate during layup to create the starter crack. The mechanical properties of the specimens are presented in Table 1.

The test fixture for the three-point bending static ENF tests is illustrated in Figure 1. During the tests, the response curves of the applied force versus the center roller displacement were recorded. Mode II precracking was performed on all the specimens. Both non-precracked (NPC) and precracked (PC) fracture toughness of the coupons were calculated using two different data reduction schemes that will be described in the next section. The NPC toughness is an interlaminar fracture toughness that is generated from the pre-implanted insert, while a PC fracture toughness is the one generated with the delamination from the pre-implanted insert, and it is regarded as the final mode II interlaminar fracture toughness (GIIC) of the unidirectional composite material.

Table 1. Mechanical properties of the unidirectional composite (G40-800/5276-1)

G40-800/5276-1 composite lamina		
Property	***Value***	***Unit***
E_{11}	143	GPa
$E_{22} = E_{33}$	9.1	GPa
$\nu_{12} = \nu_{13} = \nu_{23}$	0.3	-
$G_{12} = G_{13} = G_{23}$	4.83	GPa

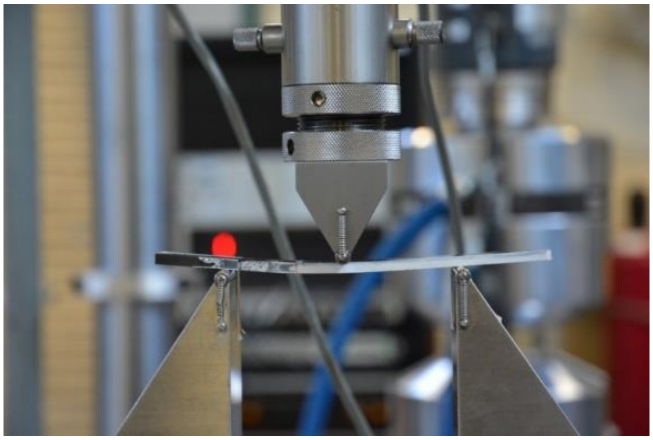

Figure 1. The end-notched flexure (ENF) test fixture

2.2 Comparison of Two Data Reduction Schemes

Strain energy release rate (*G*) is defined as the loss of strain energy in the test specimen per unit width for an infinitesimal increase in delamination length for a delamination growing self-similarly under constant displacement [3]. The data reduction schemes used to calculate the strain energy release rate are based on the classical Irwin-Kies expression [6]:

$$G = \frac{P^2}{2b}\frac{dC}{da} \tag{1}$$

where *P* is applied force, *b* is specimen width, *a* is delamination length, and *C* is specimen compliance.

Two data reduction schemes were compared in this study to calculate the mode II fracture toughness (G_{IIC}): the compliance calibration methods (CCM) and the compliance-based beam method (CBBM).

The compliance calibration method (CCM) is one of the classical data reduction schemes to calculate G_{IIC} and is the only data reduction scheme accepted by ASTM D7905/D7905M. The main difficulty of applying the classical data reduction schemes is to identify the crack tip and monitor the crack propagation as mode II fracture of the test specimen often propagates very fast without a clear opening. To overcome this, ASTM D7905/D7905M simplified the CCM approach by using the initial crack length of the specimen instead of the recorded crack length. The CCM approach assumes a cubic relationship between the specimen compliance and the delamination length with the following formulas:

$$C = ma^3 + A \tag{2}$$

$$G_{IIC} = \frac{3P^2a^2m}{2b} \tag{3}$$

where *m* is the slope obtained from the testing data regression analysis and *A* is the intercept constant, which is essentially the compliance of the beam without any crack.

The compliance-based beam method (CBBM) proposed by Moura and Morais [4] is an equivalent crack based data reduction scheme. It avoids the difficulties in monitoring crack propagation throughout the tests and takes the fracture process zone into account in calculating G_{IIC}. In other words, this method doesn't require monitoring the crack propagation during the tests while still considering the effect of the stress concentration near the crack tip and uses an apparent modulus instead of the flexural modulus. The formulas are summarized below [4]:

$$C = \frac{2L^3 + 3a_e^3}{8E_1Bh^3} + \frac{3L}{10G_{13}Bh} \tag{4}$$

$$C_c = C - \frac{3L}{10G_{13}Bh} \tag{5}$$

$$E_{1a} = \frac{3a_0^3 + 2L^3}{8Bh^3C_{0c}} \tag{6}$$

$$a_e = \left(\frac{C_c}{C_{0c}}a_0^3 + \left(\frac{C_c}{C_{0c}} - 1\right)\frac{2L^3}{3}\right)^{\frac{1}{3}} \tag{7}$$

$$G_{IIC} = \frac{9P^2C_{0c}a_e^2}{2B(3a_0^3 + 2L^3)} \tag{8}$$

where C is specimen compliance, B is specimen width, E_1 is flexural modulus, E_{1a} is apparent longitudinal modulus, a_0 is initial (starter) crack length, a_e is effective crack length, C_{0C} is the specimen measured initial compliance. Therefore, besides the specimen geometric configuration, the G_{IIC} can be determined simply by the compliances and the material shear modulus G_{13}.

Using the ENF test results, the G_{IIC} values for both non-precracked (NPC) and precracked (PC) fracture toughness were calculated using these two data reduction schemes, as summarized in Table 2. It is clear that the G_{IIC} values obtained from the CCM method are much more conservative than the ones from the CBBM method for all the coupons.

Table 2. G_{IIC} calculated from the two data reduction schemes

Mode II G_{IIC} (N/m)	NPC		PC	
	CCM	*CBBM*	*CCM*	*CBBM*
Coupon 1	1966.81	2383.62	1651.11	1863.88
Coupon 2	1839.57	2169.24	1636.07	1862.45
Coupon 3	1762.86	2622.47	1507.22	2516.74
Coupon 4	1809.03	2612.45	1503.09	2286.83
Coupon 5	1832.60	2228.93	1386.48	1734.76
Average	1842.17	2403.34	1536.79	2052.93

3 FINITE ELEMENT MODELLING

The cohesive zone modelling (CZM) technique based on the finite element method has been widely used for modelling composite delamination damage, such as the work in [7~9]. Different from the classical linear elastic fracture mechanics approach that brings in stress intensity factor at the crack tip, the CZM method with cohesive elements defines a "cohesive zone" on the crack propagation path that is identified as two cohesive surfaces (implemented by one layer of cohesive elements). The cohesive surface constitutive relationship is governed by a traction-separation cohesive law. The crack failure is then characterized by the complete separation of the cohesive surfaces using a criterion based on fracture energy dissipation. Such a modelling approach has intrinsic advantages to simulate composite delamination failures because it can easily define the crack surfaces and more realistically describe the fracture process without introducing stress singularity. An empirical study was conducted to address the effects of different modelling strategies and parameters on the computational efficiency and the solution accuracy, such as traction-separation law, cohesive element penalty stiffness, cohesive element interfacial strength, and mesh sensitivities.

3.1 CZM Traction-Separation Law

Among many phenomenological cohesive traction- separation laws proposed in the past decades, linear softening models are the easiest ones to be implemented in an FE code, while the selection of the linear softening models is usually based on the class of materials. The embedded cohesive elements experience softening after damage initiates. The area under the curves represents the dissipated fracture energy during crack propagation in the cohesive zone (Figure 2). The cohesive law describes the tractions acting on the cohesive element surfaces in relation to the material separation and thus is called a traction-separation law.

The FE models built in this study were analyzed using two linear cohesive laws, the most commonly used bilinear law and a trapezoidal law, as schematically shown in Figure 2. It was found that the computational results from the two linear cohesive laws are almost identical. The reason may be attributed to the linear elastic delamination behavior of the laminate coupons in the ENF tests, and the fibre bridging was not observed during the tests.

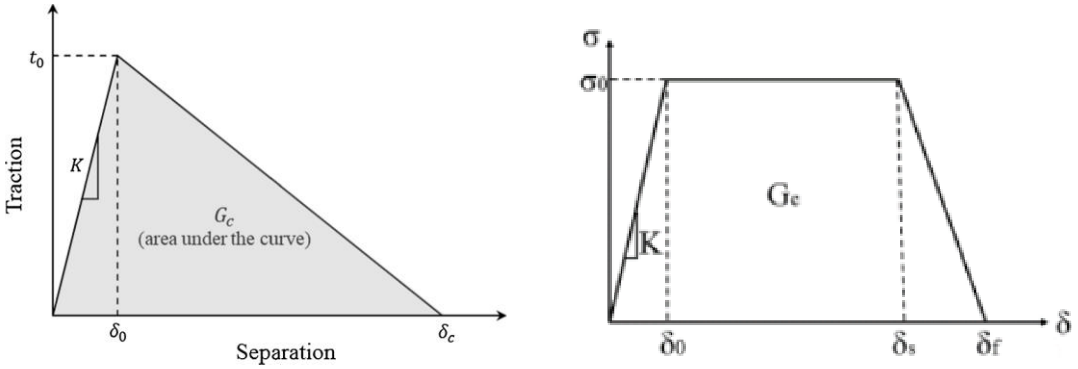

Figure 2. Bilinear and trapezoidal cohesive traction-seperation laws

3.2 FE Model Development for ENF Test

To successfully build an FE model using the CZM technique, the proper input of the three cohesive law related parameters is the key: penalty stiffness (i.e. cohesive surface initial interfacial stiffness represented by the cohesive element modulus, *Ess*), maximum traction (i.e. cohesive element interfacial strength, *Sss*), and steady-state energy release rate (i.e. G_{IIC} in this study). Penalty stiffness and maximum traction were obtained by numerical experiments validated by the testing results and steady-state energy release rate was obtained by experimental tests.

There seems to be a general consensus that an optimum penalty stiffness should be the largest value that does not cause numerical problems, such as the artificial oscillations of the tractions in the cohesive elements [10, 11]. Turon et al. [12] suggested that larger values of penalty stiffness can provide more accurate simulation with less structural stiffness loss and proposed to estimate the penalty stiffness by the following formula:

$$K_0 = \frac{E_3}{t} \tag{9}$$

where K_0 is initial interfacial stiffness, E_3 is elastic modulus in the thickness direction and t is the thickness of the cohesive elements. In the current study, the value of $K_0 = 1.0\times10^{15}$ (N/m^3) was employed in the FE models.

The maximum traction in the cohesive law is identified by the cohesive surface interfacial strength, but it is difficult to be accurately determined from the tests. Based on the authors' experience and trials and errors, 70 MPa was proven a good estimation for the interfacial strength for this study to obtain sufficient solution accuracy. Mode II fracture toughness (G_{IIC}) obtained from the two data reduction schemes were employed to compare the computational results with the experimental data. The optimum cohesive element properties used in the FE models are summarized in Table 3.

Table 3. CZM properties used in the FE models

Cohesive Element Properties		
Property	***Value***	***Unit***
Sss	70	MPa
Ess	1000	GPa
G_{IIC}	2384	N/m

A mesh sensitivity study was carried out through the numerical experiments too. The minimum number of cohesive elements along the cohesive zone length is important for an accurate representation of the cohesive traction distribution ahead of the crack tip. The size of the cohesive elements may also significantly affect both computational convergence and solution accuracy. Referring to the authors' study [5], the minimal cohesive element size along the cohesive zone length = 0.0625 mm for 2D models and 0.1 mm for 3D models were deployed. The thickness of the cohesive elements is also crucial to achieving accurate results. Most of the recent investigations have suggested a value between 0.01 and 0.02 mm for predicting composite delamination propagation. In the current study, for all 2D and 3D models, the thickness of the cohesive elements was set to 0.012 mm.

The FE models were built and solved using ABAQUS with 2D plane strain elements CPE4R and 2D cohesive elements COH2D4 for 2D models, 3D incompatible elements C3D8I and 3D cohesive elements COH3D8 for 3D models. The 2D FE model and the 3D mesh are shown in Figure 3.

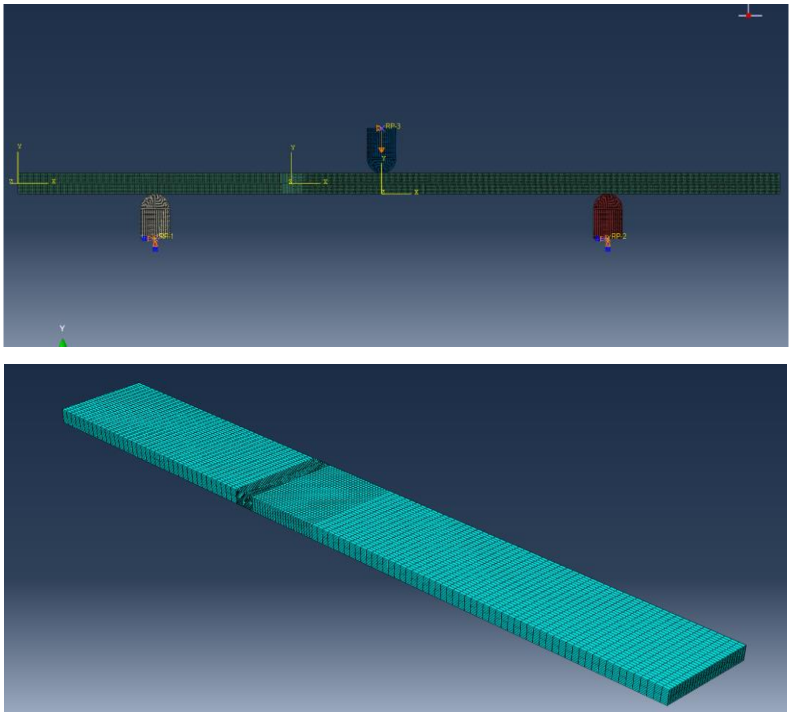

Figure 3. 2D and 3D FE models for the ENF tests

4 RESULTS AND CONCLUSIONS

Computational results and conclusions are only briefly presented herein to provide a concise summary of the study, while more details and discussions may be available in a related NRC Lab Technical Report.

First of all, it is shown from this study that there is a significant difference to obtain the mode II fracture toughness (G_{IIC}) between the two data reduction schemes. It is indicated that the CCM provides a quite conservative approach, while the CBBM is much more accurate and thus suitable to be used for predictive modelling of the composite failure behavior. The von-Mises stress and the longitudinal stress results at the crack tip region are shown in Figures 4 and 5. The state of damage at the delamination front with the Abaqus damage variable (SDEG) at the maximum loading displacement is shown in Figure 6. A comparison of the load-displacement curves from both tests and analyses is shown in Figure 7, from which the effectiveness of the modelling approach can be validated.

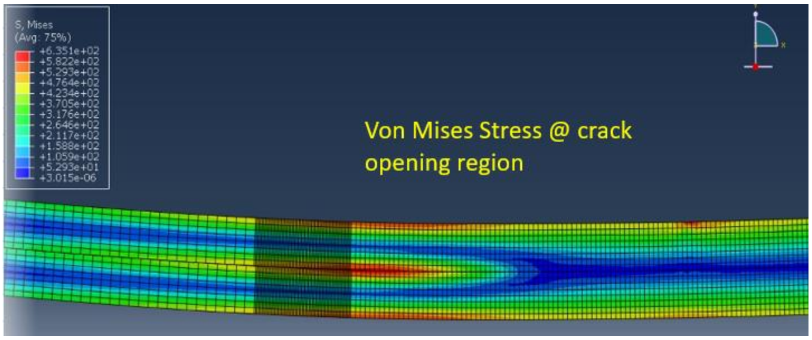

Figure 4. The von-Mises stress at the crack tip region

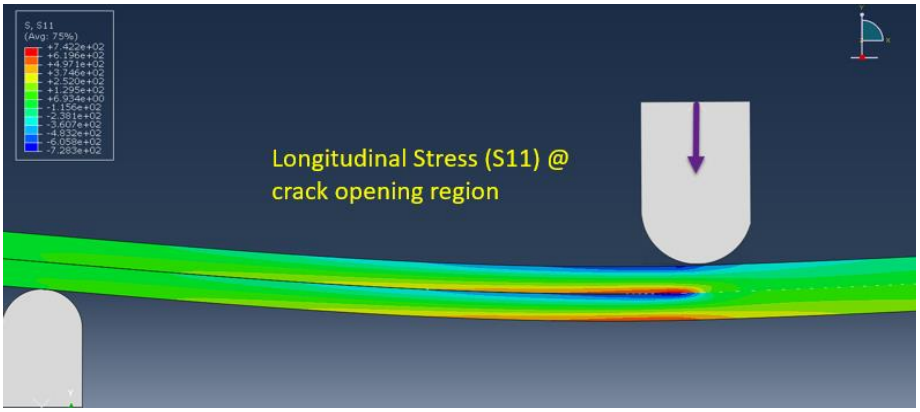

Figure 5. The longitudinal stress at the crack tip region

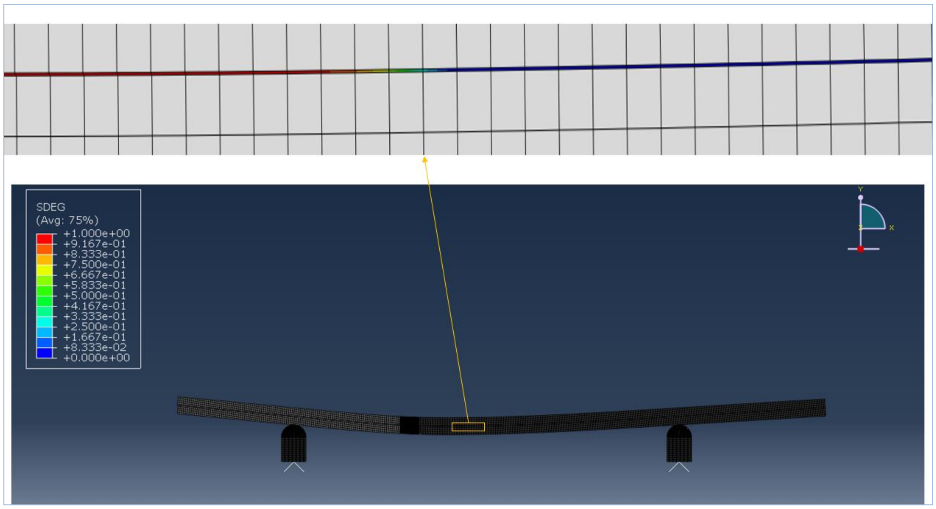

Figure 6. Damage of cohesive elements at delamination crack front

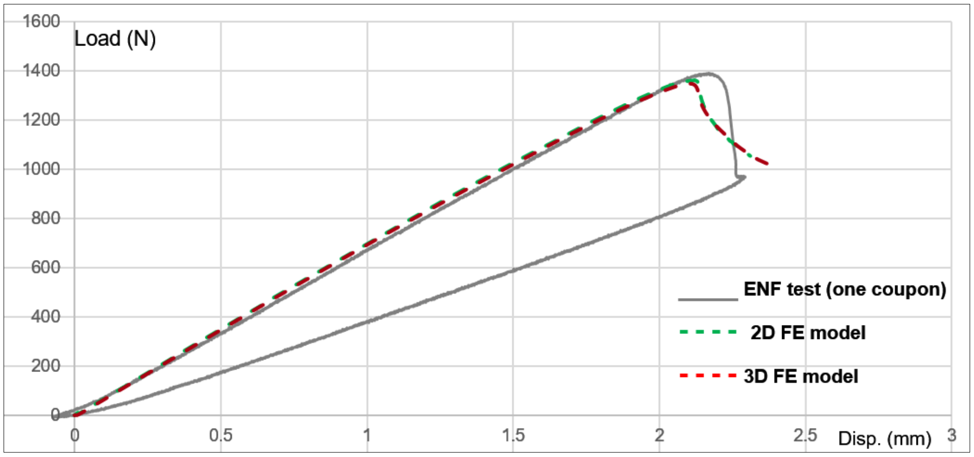

Figure 7. A comparison between FE results and ENF test data

In conclusion, the finite element modelling and simulation using the CZM technique for the ENF tests were conducted. To obtain efficient and robust solutions, an extensive parametric study was carried out to explore the effects of cohesive element initial stiffness, interfacial strength, and mesh densities, as well as the data reduction schemes. This study indicates that a reliable modelling strategy has been achieved for the effective prediction of mode II delamination damage behavior of composite laminates.

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