The Influence of Base Layer Thickness in Flexible Pavements

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Abstract-Flexible pavement design and analysis were carried out in the past with semi-experimental methods, using elastic characteristics of pavement layers. Due to the complex interferences between various layers and their time consumption, the traditional pavement analysis, and design methods were replaced with fast and powerful methods including the Finite Element Method (FEM) and the Discrete Element Method (DEM). FEM requires less computational power and is more appropriate for continuous environments. In this study, flexible pavement consisting of 5 layers (surface, binder, base, subbase, and subgrade) had been analyzed using FEM. The ABAQUS (6.14-2) software had been utilized to investigate the influence of the base layer depth on vertical stresses and displacements. Three different thicknesses were adopted (10, 20, and 30cm) with constant other pavement layer thicknesses. The results of this study showed that the stress levels at the top of the base layer increased by about 37% when the thickness of this layer increased from 10cm to 30cm, while the stress levels at the top of the subbase layer decreased by about 64%. When the base layer increased from 10 to 20, from 20 to 30, and from 10 to 30cm the vertical displacement decreased by 18%, 24%, and 37% respectively.

Keywords-flexible pavement; ABAQUS; base thickness; finite element method

I. INTRODUCTION

Standard flexible pavements with surface of Asphalt Concrete (AC) are used worldwide. The different layers of the flexible pavement structure have various strength and deformation properties, which make difficult to analyze the system layers [1]. Factors such as material properties, geometry of pavement structures, environment, traffic loading and construction practices affect the pavements. Furthermore, vehicle characteristics, load axle, and wheel configuration may cause damage to the pavements [2]. If the induced strains due to the external load are relatively small, stresses and deformations are usually estimated using the theory of elasticity. Semi-analytical and analytical solutions are available to analyze the behavior of elastic layered pavements subjected to surface loads. In solutions concerning the analysis of the pavement layer system under traffic load, the pavement layers are considered homogeneous, isotropic, and linear elastic [2].

Finite Element Method (FEM) is used to simulate several pavement problems that cannot be modelled using the elastic multi-layer theory. ABAQUS is commercial Finite Element (FE) modeling software. The ABAQUS (6.14-2) software package of engineering analysis is used world-wide to simulate the physical response from loading, contact, temperature, impact, and other conditions of the environment of structures and solid organisms [3]. The software can manage the assembly of parts (including flexible pavement layers, i.e. surface, binder, base-course, sub-base, and sub-grade layer) and define the interactions between these layers and the appropriate boundary conditions. Finally, it can find the value of maximum stress and the displacement for all pavement layers.

Several studies of the behavior of flexible floors in recent years have studied three-dimensional (3D) FE models. Authors in [4] employed the discretization of a 3-layer flexible pavement system subject to various loading types using the FE technique. Three layers of the same elastic module have been applied to turn the three layer systems into equivalent, simpler single-layer systems in the analysis. The utility of the 2-dimensional FE ANSYS program analytics has been described in [5], in order to examine the influence of the variation of thickness on crucial parameters of distinct component layers. It was observed that the tensile strain at the base of the asphalt layer and the compressive strain above the subgrade layer decline, when the depth of the asphalt layer increases. The authors also discussed the utility of FEM analysis for the exploration of the bituminous pavement characteristic sensitivity analysis. One aspect of the analysis was to check for the hypothesized trials of the sensitivity of the axis-symmetric horizontal dimension. Mesh refinement study was also conducted on the selected thickenings and material properties of various layers. Authors in [6] studied the effect of increasing axle load and the variation of pavement modulus on the overall pavement life. The results showed that tensile and compressive strain increased when the axle load increased and decreased when the asphalt layer modulus increased. Authors in [7] used ABAQUS to evaluate the stress and vertical displacement on the top of the surface layer in multi-layer flexible pavements under static loading. It was observed that raised thickness of the pavement surface layer led to reduction of the deformation and stress levels.

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II. Finite Element Modeling of Flexible Pavement

One of the most effective techniques used to simulate the response of different structural engineering challenges is the FEM. It has become the most extensively utilized technique in both academic and industrial numerical simulations [8]. Over the last three decades, substantial advancements in computer programs and FE techniques have made many commonly used 3D structural studies more affordable. The current research models and investigates the behavioral reaction of the pavement system using the ABAQUS 6.14-2 package [9]. Solid structural 3D pavement analysis utilizing the linear, general purpose brick element C3D8R has been adopted in the modeling process. Small elements are necessary to capture a tress concentrated at the structural limit [3].

III. Materials and Methods

A. Pavement Model

3D FE was used to model the surface, binder, base course, subbase, and subgrade, all of which may be considered as closed systems of numerous layers. In the present work, a conventional pavement section was considered, consisting of bituminous layers (surface, binder, base), subbase, and subgrade to study the effect of base layer thickness on the flexible pavement layers' performance, starting from 10cm with an increment of 10cm with fixed surface, binder, subbase, and subgrade depth thickness (4, 7.5, 20, and 250 cm respectively), as shown in Table I.

TABLE I. LAYER THICKNESSES

Layer	**Layer name**	**Thickness (cm)**		
		Case 1	**Case 2**	**Case 3**
1	Surface	4	4	4
2	Binder	7.5	7.5	7.5
3	Base course	10	20	30
4	Subbase	20	20	20
5	Subgrade	250	250	250

The pavement geometry has the following dimensions: 500cm in the y- and the x-axes and 300cm in the z-axis. Only a quarter of the sample was used by using the 3D axis-summitry property to reduce effort and time. The pavement geometry with the model can be seen in Figures 1, 2. A standard single axle load of a dual tire of 80kN was considered.

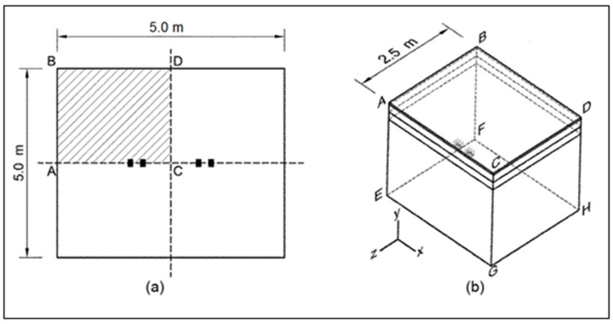

Fig. 1. Geometry model of the flexible pavement: (a) top view, (b) a quarter analytical model.

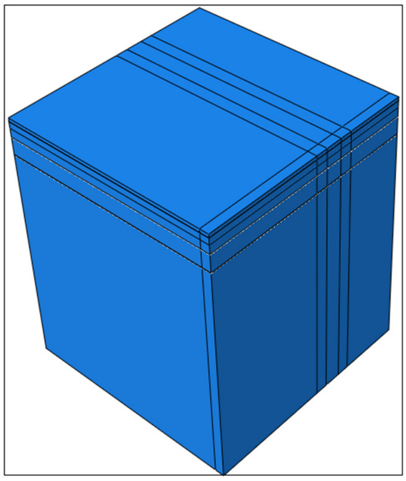

Fig. 2. The 3D multilayer model.

B. Material Properties

The layers' material characterizations listed in Table II were used in the FE program for flexible pavement models.

TABLE II. MATERIAL PROPERTIES FOR ROAD LAYERS [10]

Layer	Modulus of elasticity (E), kpa	Poisson ratio
Surface	2689000	0.35
Binder	2206000	0.35
Base	1655000	0.35
Subbase	110000	0.40
Subgrade	35000	0.499

C. Contact Area and Tire Presure

The print area of the tire can be represented by two semicircles and a rectangle [11]. This shape is converted to a rectangle with an area of $0.5227 \times L^2$. The contact area has dimensions of 0.202m and 0.14m. In research and computing applications, even such a simple model is often applied as a uniformly distributed load over a circular or rectangular area [11].

D. Wheel Load Caracterization

The wheel load is a standard axle loading simplified in a rectangular uniform surface charge treated as a single axis dual tire [11]. The standard has one axle, dual tires, and contact pressure equivalent to the pressure of the tire. The pressure of the tire is 750kPa and the overall load of the axle is 80kN [6]. The load zone established by the vehicle load is illustrated in Figure 3. The width of the print zone is 14cm for each tire, which is the same as the width of uniformly distributed surface loads and the length of the print tire is 20.3cm.

E. Boundary Conditions

Boundary conditions have a major effect on the prediction of the model response. The lower surfaces against all degrees of freedom are assumed to be entirely fixed for boundary conditions [12]. The edges can move in the vertical (y-) direction for all the geometry models of the pavement. In FE analysis, no movement is considered in the horizontal directions for the four sides of the model. These boundary conditions were chosen in order to simulate the real boundary conditions [13] as shows in Figure 5.

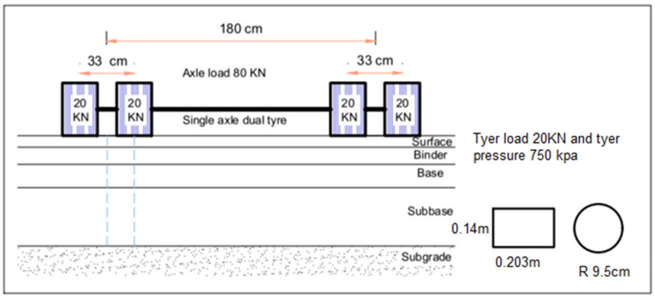

Fig. 3. Standard axle load, critical loads, and loading form.

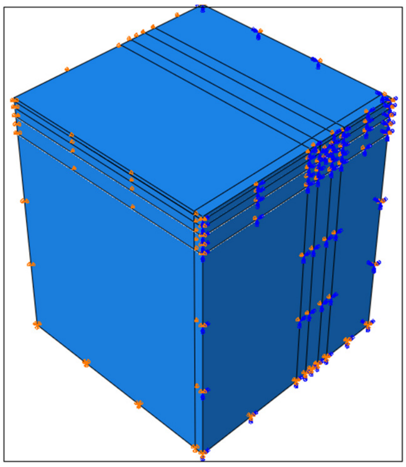

Fig. 4. The boundary conditions of the model.

F. Interaction Modeling Techniques

The Interaction module is employed to simulate the contact surface between the asphalt and the foundation layers [3]. The interaction between the sections of the model with ABAQUS needs to be established in order to define the interaction surfaces.

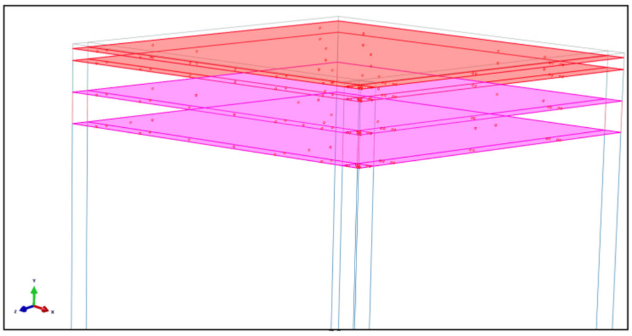

Fig. 5. The interaction layer used in the model.

There are numerous contact formulations and standards in ABAQUS, for the modeling of the interaction between layers. The contact between two flexible or deformable and rigid surfaces is referred to as surface-to-surface contact. The degrees of freedom between the mode areas are utilized in the interaction module constraint and the limitations can be suppressed and repeated to alter the analytical model. The definition of contact is shown in Figure 5. Finally, the ABAQUS interaction module simulates the interaction of several layers of the pavement (surface and binder, binder and base, base and subbase, and subgrade and base) with the tire contact.

G. Mesh Size Distribution in The Model

Figure 6 presents the FE mesh of the model. The average mesh size under the wheel path is about 5cm and the total number of elements is more than 20000. Using a finer mesh near the load when modeling the pavement block as a FE model increases the accuracy of the results [14].

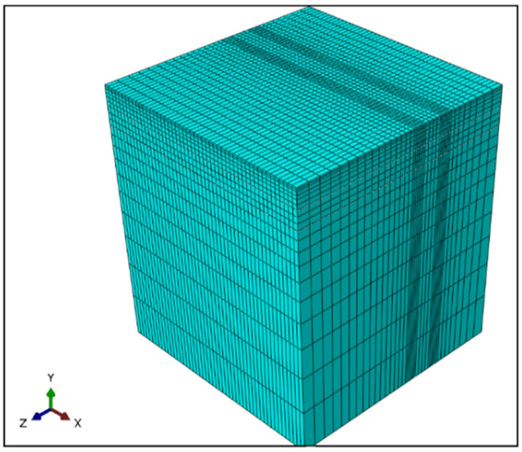

Fig. 6. Mesh size distribution for the 3D dual tire model.

IV. RESULTS AND DISCUSSION

Stresses and displacements generated in pavement layers and interfaces due to the effect of wheel loads are some of the most primary considered elements in the design of flexible pavements. The obtained results of stresses and their vertical distribution from the FE model analysis adopted in this research are presented in Figures 7-12.

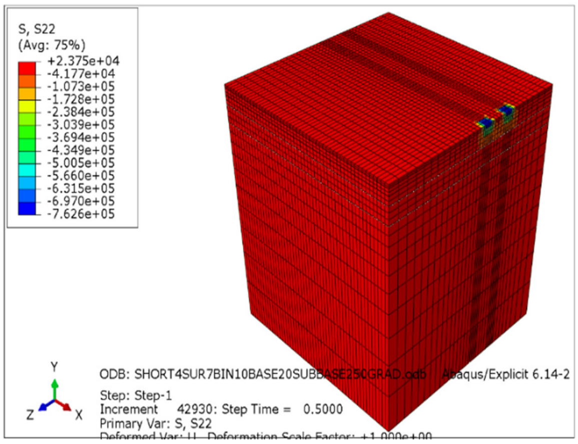

Fig. 7. Horizontal stress (σxx) distribution within pavement layers, case 1.

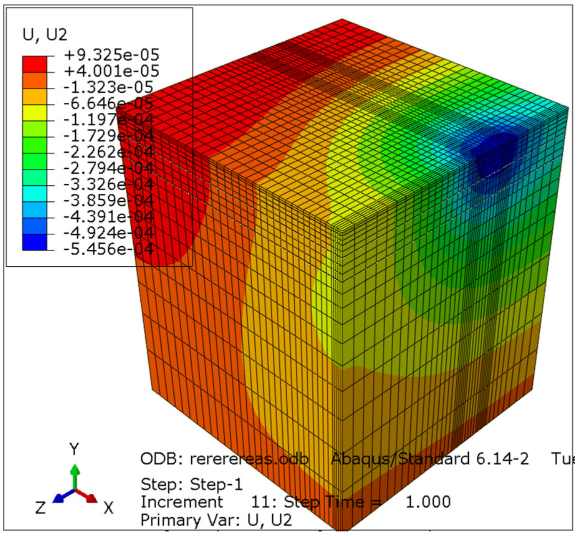

Fig. 8. Vertical displacement distribution within pavement layers, case 1.

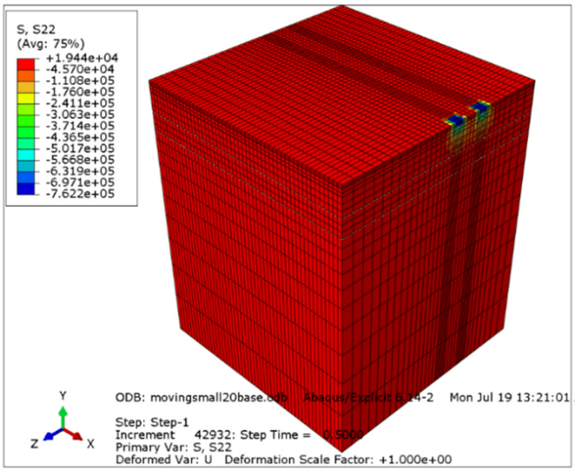

Fig. 9. Horizontal stress (σxx) distribution within pavement layers, case 2.

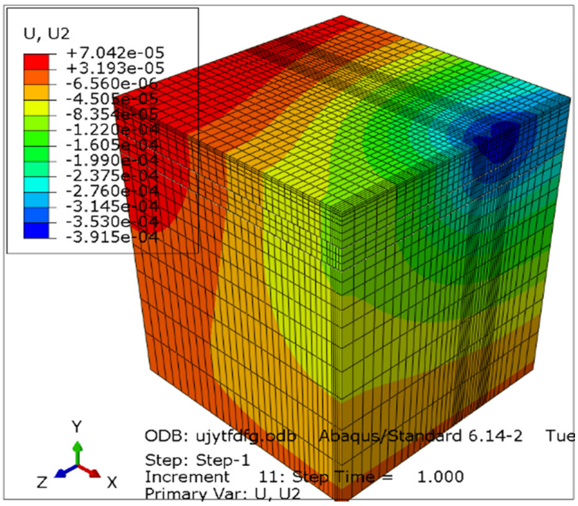

Fig. 10. Vertical displacement distribution within pavement layers, case 2.

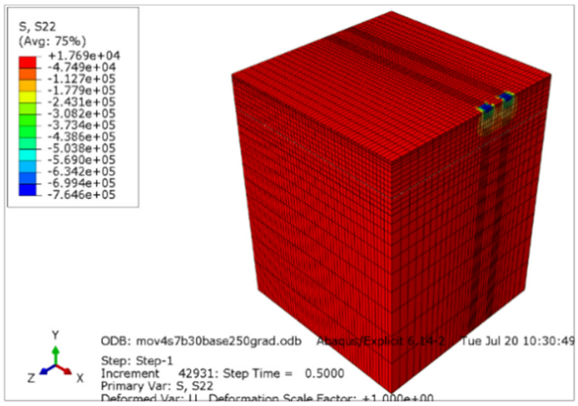

Fig. 11. Horizontal stress (σxx) distribution within pavement layers, case 3.

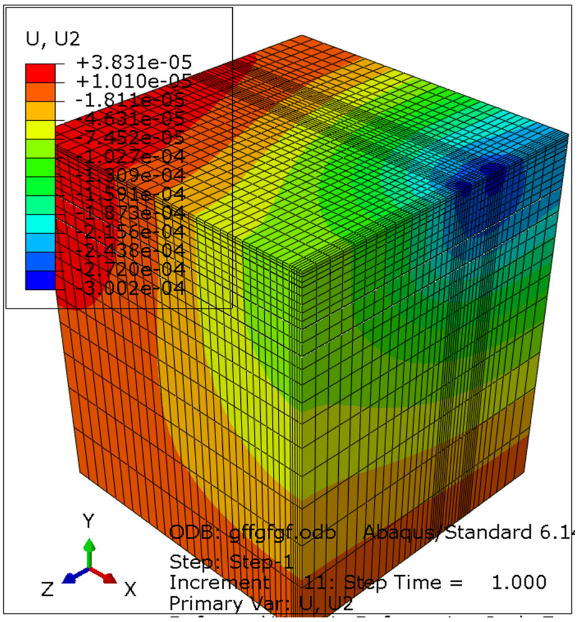

Fig. 12. Vertical displacement distribution within pavement layers, case 3.

The distribution of vertical stresses (σ22) in the pavement system is shown in Table III. In case 1, a maximum vertical stress of 750kPa is concentrated on the top of the surface layer under the tire print. It is reduced to 579.91kPa at the top of the binder layer, which is about 77.7% of the applied pressure. At the top of the base layer, the stress is reduced to a value of 195.63kPa (about 26% of the applied tire pressure). It decreases to 40.547kPa and 20.071kPa (about 5% and 2.5% of the applied tire pressure) on the top of the subbase and the subgrade layer respectively.

In case 2, the vertical stress is reduced to 600.33kPa, 240.39kPa, 22.39kPa, and 13.14kPa at the top of the binder, base, subbase, and subgrade layers (about 80%, 32%, 2.9% and 1.6% of the applied pressure respectively).

In case 3, the vertical stress is reduced to 606.03kPa, 268.87kPa, 14.075kPa, and 9.4576kPa at the top of the binder, base, subbase, and subgrade layers (about 81%, 38%, 1.7% and 1.1% of the applied pressure respectively).

TABLE III. STRESS LEVELS BETWEEN THE INTERFACED LAYERS

Layer name	Vertical Stress (σ22), kPa		
	Case 1	Case 2	Case 3
Top of binder	579.91	600.33	606.03
Top of base	195.63	240.39	268.87
Top of subbase	40.547	22.39	14.075
Top of subgrade	20.071	13.14	9.4576

The results of this study show that the stress levels at the top of the base layer increased by about 37% when the thickness of this layer increased from 10cm to 30cm, while the stress levels at the top of the subbase layer decreased by about 64%. By increasing the thickness of the base layer, the stress level was reduced, as shown in Figure 13. Also, the vertical stresses at shallow depths under the tire print slightly vary when the thickness of the base layer increases, but the difference is negligible at large horizontal distance and depth.

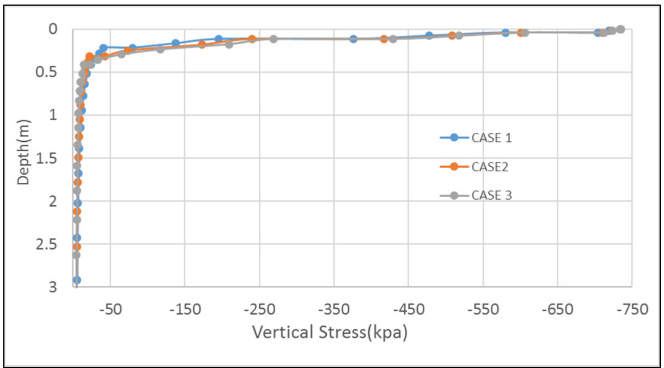

Fig. 13. Vertical stress vs depth.

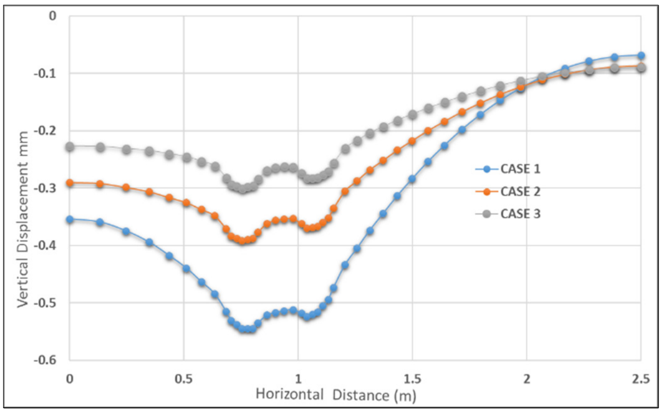

Fig. 14. Vertical displacement on the top of the surface layer.

Figure 14 displays the vertical displacement on the top of the surface layer under the center of the inner wheel with horizontal distance for all cases. When the base layer is increased from 10 to 20cm, 20 to 30cm, and 10 to 30cm the vertical displacement decreases by 18%, 24%, and 37% respectively. The calculated results from this study are in accordance with those in [15], in which the authors used the ABAQUS to simulate flexible pavements and study the effect of increased base layer thickness on the response of the pavement. The results showed that when the base layer thickness changed from 10 to 30cm, the deformation on the surface layer reduced by 41%. Authors in [16] studied the effect of the variation of the thickness of the base layer. It was observed that the number of rutting cycles increased by 4.48% with the change in the thickness of the base layer from 30cm to 45cm. However, the same increase was only 2.47% when the change in thickness was from 45cm to 60cm. Authors in [17] used the ABAQUS program to study the effect of four thicknesses of the base layer, namely 5, 8, 10, and 12cm to the elastic and elasto-plastic behavior. The result in the elastic behavior when the thickness of the asphalt changed from 5 to 12cm was that the deflection on the top of the layer reduced from 4.1 to 1.2mm.

V. CONCLUSION

The following are the main conclusions based on the results of this study:

- The percentage of the deformation decreases by 37%, 18%, and 24% when the thickness increases from 10 to 30cm, from 10 to 20cm, and from 20 to 30cm respectively, so the base layer plays the main role in reducing the deformation on the surface layer in the pavement structure.
- The vertical stress on the top of the base layer is 195, 240, and 268kPa for base layer thickness of 10, 20, and 30cm respectively. It decreases to 40.54, 22.39, and 14.07kPa on the top of the subbase layer corresponding to approximately 20%, 9%, and 5% of the applied stress on the top of the base layer. When the thickness of the base layer increases, the stresses in the layers below the base layer decrease, and thus the stresses above the sub layer decrease.
- It is clear from the study that the vertical stress decreases with the increase in the vertical depth of the all layers. Therefore, the upper layers must be of high quality.
- If the flexible paving layers are too thin, the overall structure of the pavement may disintegrate before the designed life time.
- ABAQUS gives high accuracy in the analysis of multi-layer flexible pavements in addition to the reduction of effort, time, and costs in comparison with the laboratory tests.

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