The Iron Roof Trusses of the New Hermitage in St. Petersburg - Structural Survey, Analysis and Assessment of a Masterpiece of Structural Steelwork from the 1840s

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INTRODUCTION

The New Hermitage of St. Petersburg, planned from 1839 and opened in 1852, is the last building erected in the collection of the former imperial palace complex. Commissioned by Tsar Nicholas 1st and designed by the German architecht Leo von Klenze as a museum for the imperial art collection, with its impressive sets of rooms and its pure classical fassades it now forms the core of the exhibition rooms of the State Hermitage Museum of St. Petersburg **(fig.1)** along with the 18th century baroque buildings of the Winter Palace, the little and the big Hermitage **(fig.2)**. The collection and the buildings have recently been recognized as World Heritage Site by UNESCO.

The iron roof trusses of the New Hermitage in St. Petersburg, erected in 1844-45, are for the most part preserved in their original state **(fig.3)**. They are mainly composed of closely aligned trusses without purlins, following the principle of the "cable-trussed girder" similar to the later well-known "Polonceau"-System. This load-bearing system has been systematically recorded and precisely analysed for the first time. The existing method of "Historische Bauforschung" (architectural historical research), itself a branch of construction history, which has become established in Germany over the past few decades, has for this purpose been expanded with engineering-specific components. A structural survey was added to the existing elements of the geometrical survey of construction and the documentation and analysis of the available archive material. This development allows additional information on the function and structural behaviour of components, the origin and manufacture of the material used as well as the planning and assembly process to be recorded.

This in-situ research combined with the analysis of materials forms the basis for further practical as well as academic analysis. This paper presents an overview of the survey and an initial assessment and analysis of the results. In addition to a statical analysis of the current state of the structure, a comparison and assessment of the different types of roof trusses extant in the State Hermitage complex is included. These trusses were designed by three different engineers in under a 10 year period, using the same structure but varying details, prompting a discussion of the quality of the engineering design.

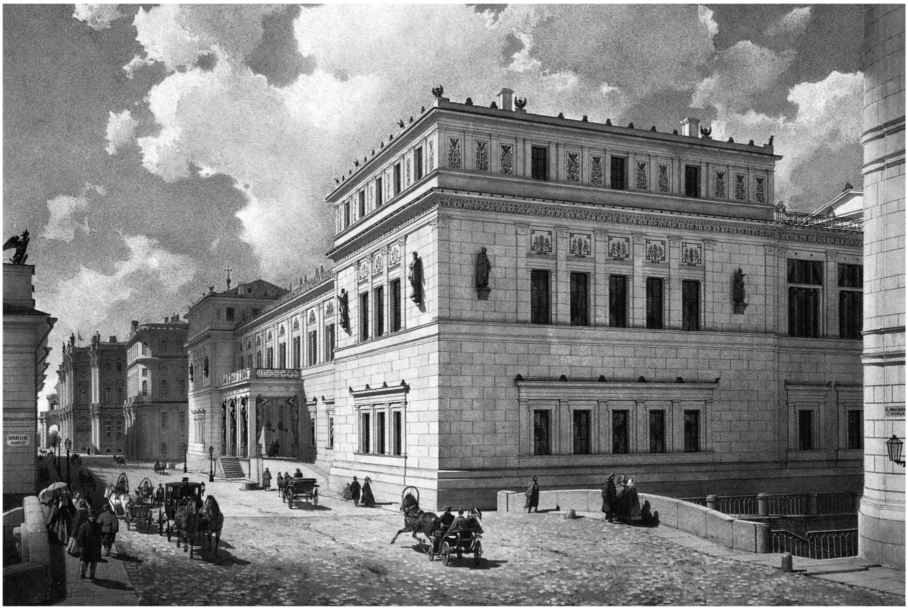

Figure 1. New Hermitage, view from the south-east 1861 (Buttlar 1999)

Figure 2. State Hermitage Museum with New Hermitage (front), Old Hermitage (front right, wing along the bank), Small Hermitage, Winterpalace and Palace Square, view from east 2001

Figure 3. Roof trusses over the exibition halls with roof light

IRON STRUCTURES AT THE COMPLEX OF THE STATE HERMITAGE MUSEUM

The part of this monument which is of interest for construction history are the iron structures in the roofs and ceilings which are present in every building. The reason for the highly extensive use of this material, which at the time was seldom used in the construction of this kind of building, was a devastating fire which destroyed a large part of the winter palace in the winter of 1837. In the process of the immediate reconstruction of the imperial palace that followed, the commission responsible ordered the extensive use of iron load-bearing structures, which were thought to be fire-proof. As a result, this decision also affected the design of the still-to-be-built museum buildings. For this reason, the roof-trusses of the New Hermitage are part of an “iron landscape” which in terms of volume, consistency and variety of application in buildings of this type are unique throughout the world and large parts of which are still in original condition. Several load-bearing structures of the Winter Palace are familiar from previous publications (Fedorov, 1990, 1992). The focus of these studies, based on archive material and historical literature, is the history of the construction of the spectacular parallel-chord trusses for ceilings with large spans. The ceiling beams for smaller spans are also mentioned, which consist of thin steel sheets and angle irons and show an elliptical web which are fascinating precursors to modern light-weight construction methods. The work of the engineer Matthew Clark, responsible for the design and production of these structures is recognized in a first biography (Fedorov 1992).

SURVEY OF THE EXISTING STRUCTURES

The predominant type of truss used in the roofs of the New Hermitage **(fig.4)** are adapted according to the span of the roof, which lies between 13.5 and 20 metres, and the height of the roof ridge which lies between 2.5 and 5 metres. The gradient of the roof thus lies between 20° and 25°. The trusses are placed at intervals of approximately 1.2 metres. These trusses also form the main structures in the roofs over the pavilions and are augmented by hip and jack rafters. The skin of the roof is formed by a metal sheet, to which, where it has been replaced in the past years, a second sheet with a layer of insulation in between has been added. Flat strips of iron were riveted or clamped to the rafters to form roof lathing.

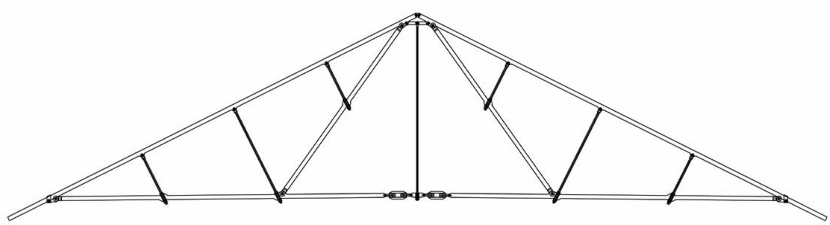

Figure 4. Structure of the roof truss

The upper chord of the trusses form continuous rafters from the eaves to the ridge of the roof**.** The branching bottom chord begins over the crown of the wall and has a rectangular profile throughout. The round profile of the struts form a fork at their upper end which are fastened to the rafters by bolts. The lower end of the struts are threaded and attached to the bottom chord by nuts. The rafters are linked in the ridge of the roof on the symmetrical axi s **(fig.5)**. The bottom chord is fastened using turnbuckles on both sides of a coupling element which is suspended from the ridge. The typical measurement for the rectangular profile is h/b = 75/15 mm and for the rounded profile d = 35 mm, however there can be significant differences due to the fact that these were produced by hand.

Figure 5. Connections: strut with tread and nuts and the branched bottom cord with bolts

The trusses are connected to two stiffening systems along the length of the roof. The first connects the rafters on the flat plain of the roof in several layers between the eaves and the ridge. The second connects the ends of the struts in a continuous band.

As an exception to the regular rows of trusses, one finds interesting examples of a large range of specific solutions particularly in the pavilion roofs. The point of the tented roof of the south-west pavilion contains an impressive spatial puzzle with plug and bolt fastenings, in which the upper chord of the main trusses criss-cross and are joined to the hip-rafters **(fig.6)**. The jack rafters and stiffeners, which are parallel to the roof surfaces, are attached to the hip-rafters with a clamp **(fig.7).** The upper chord of the strengthened truss, which is built over the corner to support the hip-rafters, is further stabilized through strips of iron clamped to it **(fig.8)**.

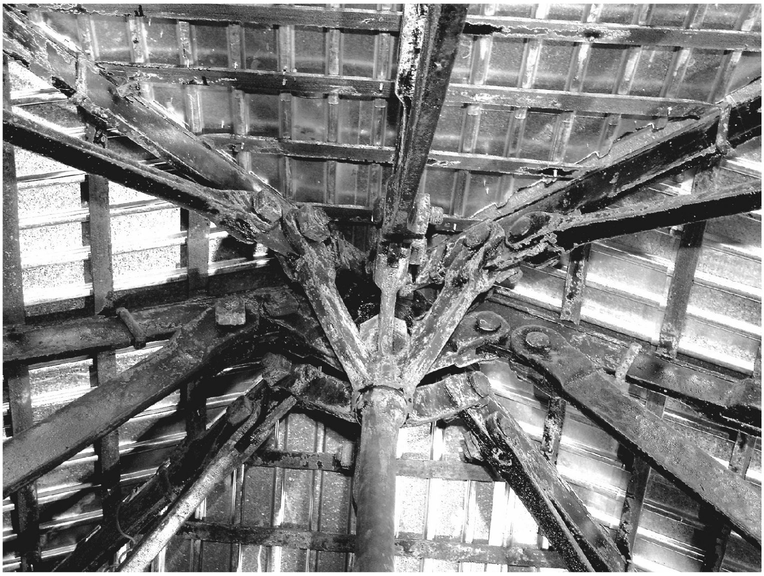

Figure 6. Connection at the top of the south-west pavilon

Figure 7. Clamp connection between jack and hip rafter in the pavilon roof frames

Figure 8. Stabilized upper chord of the support truss in the pavilon roof frames

The design of the trusses can be divided into two groups based on several characteristics. T-sections for rafters and ridge-profiles and screws with square heads are found together, for example in the entire roof-light wing, whereas in other areas of the roof rectangular profiles and screws with cylindrical heads are found. This clearly shows the work of different designers or manufacturers.

EVALUATION OF THE ARCHIVE MATERIAL

The planning and realization of the roof trusses has up to now been attributed to Alexander Fullon, the director of the State Alexandrowski iron works in St Petersburg in the literature of architechtural history (Glinka, Denissov 1991). His designs from 1843-44 contracted by the building commission remain preserved. These include plans for rafters, designs for trusses **(fig.9)** and detailed specific solutions for some roof areas. Archive material on the New Hermitage has been systematically documented for the first time as a result of new work on the arcitectural history of the New Hermitage, whose focus is on the relationship and division of labour between Klenze, the designing architect in Germany, and those responsible in the building commission in St. Petersburg (Fedorov 2004). This material contains a contract from 1844 in which the building commission contracts the St. Petersburg-based company of Emanuel Nobel, father of the creator of the Nobel Prize Trust, for the production of the roof structures for the entire roof-light wing. He adopted the form and components of trusses designed by Fullon, legitimized by documented loading tests, but modified them among others in the ways documented above.

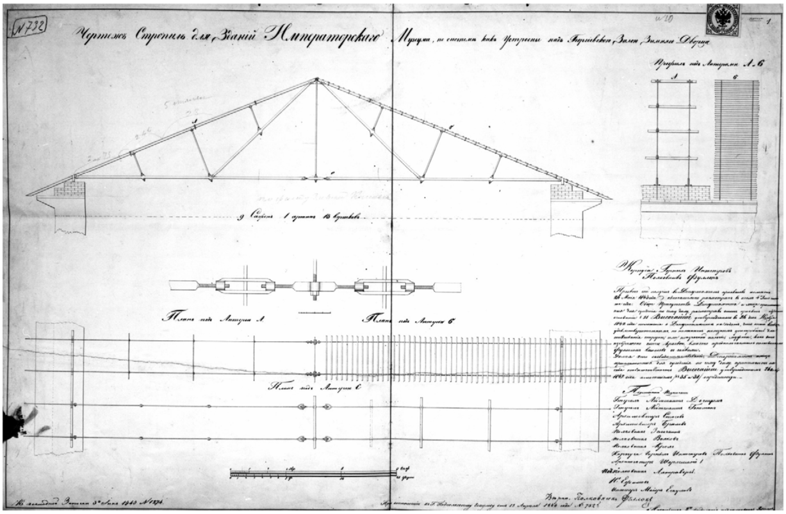

Figure 9. Design for a typical truss by Alexander Fullon 1843. The detailed drawn turnbuckle-connection was added later with coloured ink according to the existing solution (Fedorov)

A comparison of the existing trusses, manufactured in the Alexandrowski works, with the designs of Fullon from 1843 shows the latter clearly to be drafts and not the blueprints for manufacture. Both structural and detail changes were made in the execution. For example, the longitudinal-main-truss in the south-east pavilion have a greater span, an extra truss was added widthways and the lower chord is lifted as opposed to the hanging design **(fig.10)**. The ends of bars were more shaped at the joints and sometimes other fastening methods were used **(fig.11)**. Even the turnbuckles were manufactured in a different way (fig.9). The bands for the spatial stiffening system is missing in all the plans for the rafters and cross sections.

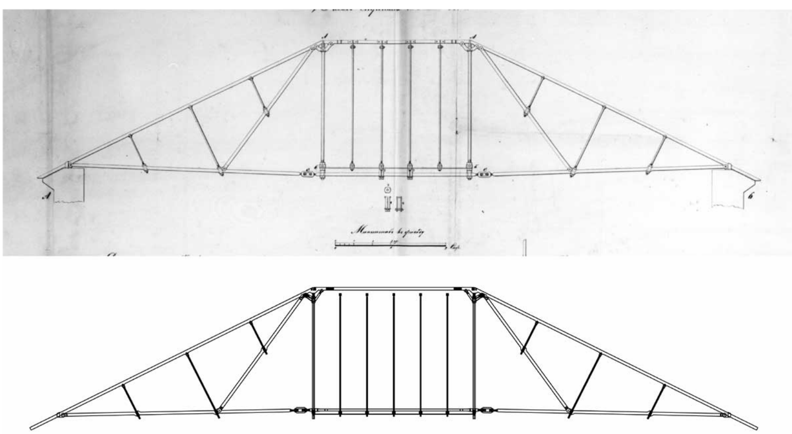

Figure 10. Longitudinal-main-truss of the south-east pavilon: the design and the existing structure (1843 - 2002)

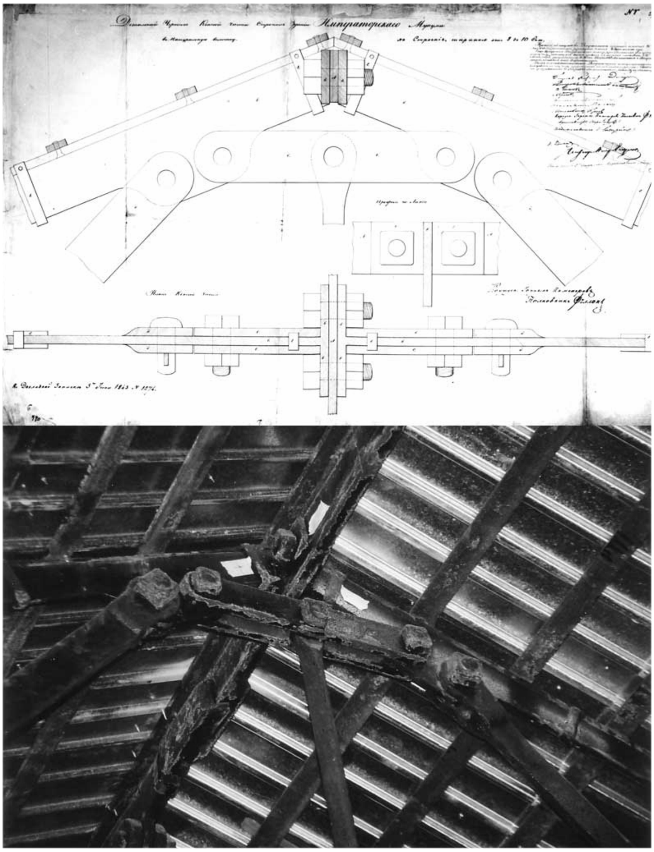

Figure 11. Connection of the rafters at the ridge: partially planned with splint pins, but realized with bolts (1843 - 2002)

STRUCTURAL SURVEY

All of the components of the truss system were systematically and closely examined in the structural survey. A large range of resulting categories were recorded including deformations, evidence of corrosion, damage **(fig.12)** and repairs as well as the functionality of components and joints. Added to this were manufacturing-specific findings such as the lack of homogeneity of materials used, for example, at the joints between semi-finished profiles and fittings such as at the offset of an eyelet forged to a rafter **(fig.13)**. Clues are given to the origin and dating of the semi-finished profiles by their stamps. The stamp, for example, of a certain A. Demidov is found in almost every area of the roof, one of the most influential businessmen of the time **(fig.14)**. The oldest of the semi-finished profiles are, according to their stamps, from 1836, the newest from 1843. This means that the majority of the semi-finished profiles were manufactured long before being finished in the Alexandrowski or Nobel works.

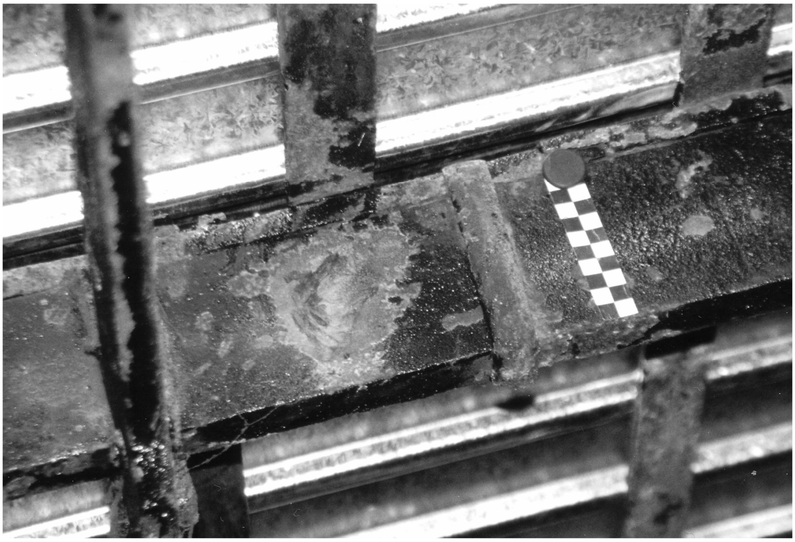

Figure 12. South-east pavilion: damage dated from the World War II

Figure 13. Forged eye of a rafter with an offset (Nobel 1844)

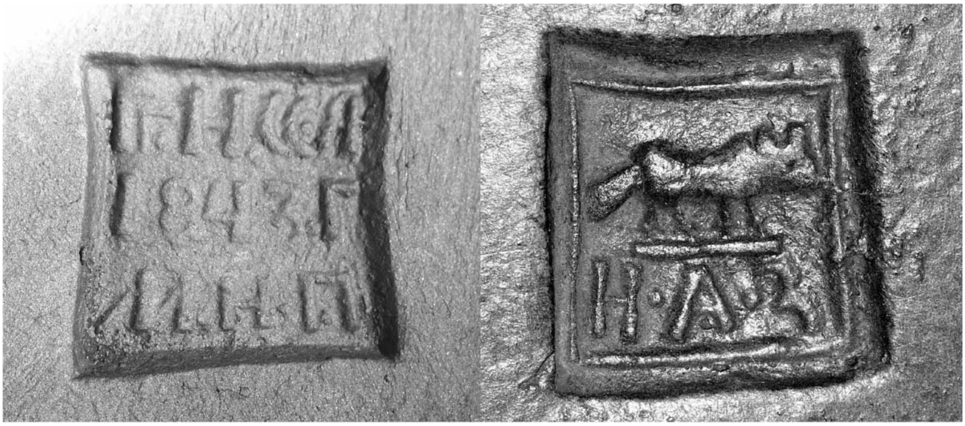

Figure 14. Stamp with dating year and label of the Demidov smelting works

MATERIAL PROPERTIES

All elements of the load-bearing structures are made of wrought iron. Based on the traces on their surfaces, recorded in the structural survey, some of the semi-finished profiles were forged, others, particularly the rounded cross-sections, were milled. The material samples subjected to tensile tests showed the characteristic layered breaking structure of puddel iron. The resulting measurements often varied widely even within a sample and indicates anisotropy dependent on where the specimen was taken from the component, either longitudinally or transversally to the axis. The material used in construction is ductile, with a failure strain of about 15%. The following results were derived for the structural survey: an yield strength of 170 N/mm^2, a tensile strength of 300 N/mm^2 and the modulus of elasticity of 160 000 N/mm^2.

STATICAL ANALYSIS

The statical analyses were largely based on the analysis of variants in modelling resulting from the different possible interpretations of the effects of joints and "adjustment systems" (turnbuckles, threads and nuts at the end of struts). The investigations into parametres were carried out on plains as well as into three dimensional model calculations. The latter was particularly necessary for the structures in the pavilions which were greatly branched due to the stiffening systems. The results of the model variants examined were assessed and adjusted according to the condition of the existing trusses.

The assessment of the behaviour of the supports in the roofs of the New Hermitage differs according to the manufacturer. The condition of the trusses manufactured by Nobel proved to be notably better than the others. The T-profile used by Nobel in the relevant upper chord or respective rafter remained below the material's set limit even under the combined load of snow and wind pressure. The rectangular rafters from the Alexandrowski works demonstrated buckling problems. While they lay above the limit in the stress verification, they lay significantly below the tensile strength. The final assessment, however, has to take into account the relevance of the planned load-bearing ability as well as the stabilizing effects of the neighbouring construction components such as the roof lathing, which the calculations for the statical model are unable, or with great difficulty, to take into account. In the end, the condition of the existing trusses is decisive. They show no signs of failure such as noticeable deformation in the areas of critical rafters. The examination of the effects of the turnbuckles shows that no planned prestress was intended with its use. Turnbuckles were solely intended to be used to compensate for differences in manufacture. The damaged elements of the truss systems, recorded in the structural survey, were also examined, such as the damaged section of rafter shown in Figure 13.

WHAT IS "THE QUALITY OF THE ENGINEERING DESIGN"?

The existence of trusses with the same structure, constructed at almost the same time but with different profiles naturally invites comparison. The truss type planned by Matthew Clark in 1838 can be added to the trusses constructed for the New Hermitage by Fullon and Nobel in 1844-45 for this comparison, an example of which is still in place over the Field Marshall's Hall in the Winter Palace. The structure of this truss, which was presented as a model for the trusses of the New Hermitage in the draft designs, is nearer to a Polonceau truss than the other two, as here the short struts also have an effect. The bottom chord, however, also runs rigid to the suspension rod in the middle in this truss. Three trusses with comparable structures and functionality were developed within eight years by different engineers. One can see an example of their individual differences in all three trusses in the different ways in which the stiffening struts are connected to the rafters - Clark and Fullon **(fig.15)**, Nobel (fig.13).

The question of "the quality of engineering design" requires a set of criteria as comprehensive as possible for comparison based on a suitable definition of the concept of "quality". As a first step the following main criteria were defined by which to compare the three types of trusses, and then subcategorised: bearing behaviour, design and function of the details, reliability, efficiency and economy. Percentage weightings were introduced for each to allow for a formal, number-based evaluation. This method gave the highest values to the Nobel truss, followed by that of Clark and then of Fullon. Although this type of evaluation is necessarily subjective, due to the (in some cases very) different amounts of data they are based on, it focuses the attention in particular on the complexity and the ability of evaluating existing trusses.

CONCLUSION

The documentation and interpretation of the design and manufacturing process of the wonders of engineering within the buildings of the State Hermitage of St. Petersburg began over the last few years with the work on the roof trusses. The systematic and exact recording of the existing trusses just as the systematic recording and evaluation of the historical source material delivered the data set on which it was based. The trusses of the New Hermitage demonstrate the features of early construction in iron, such as the large range of joints. Along with bolt joints typical of the period, and innovative adjustment elements, one finds plug and clamp joints which remind one of solutions passed down from construction in wood. To put these into the context of developments in early European structural steelwork, comparison is possible with examples of the truss systems of the Walhalla near Regensburg (1938) or those of the Neues Museum in Berlin (1845).

Figure 15. Connection of the stiffening struts by Clark 1838 (left) and Fullon 1844 (right)

What is particularly interesting about these early steel constructions is the personal styles of evident in the work of their designers. Due to a lack of standard solutions available later, a continual search for suitable solutions and experimentation was necessary. This process of the development of a language of construction for the then new construction material is to be the object of an upcomming project of „Archäologie des Konstruierens“ (the archaeology of engineering design). The diverse load-bearing structures found in the Hermitage complex are to be the starting point for a complex inter-disciplinary examination.

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