Introduction to Aerospace Structures and Materials

Dr. ir. R.C. (René) Alderliesten

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R.C. Alderliesten

Delft University of Technology
Delft, The Netherlands

Partly funded by the TU Delft Extension School (online-learning.tudelft.nl) as part of the development of a Massive Open Online Course in Introduction to Aerospace Structures and Materials.
ISBN E-Pub: 978-94-6366-077-8
ISBN hardcopy: 978-94-6366-074-7
ISBN PDF: 978-94-6366-075-4

9. Design & certification

9.1 Introduction

With the information presented and discussed in the previous chapters, one may be able to understand the material behaviour in a structure, and one may even be able to calculate based on given load cases the stresses in the various structural components, but that is in itself not sufficient to design, manufacture and operate an aircraft or spacecraft.

Aspects as safety, not easily captured in equations and formulas, must be addressed in certification procedures, to be communicated with airworthiness authorities. Structural design must comply with requirements and specifications, which are often non-negotiable, but sometimes have to be weighted against other criteria or requirements. This chapter describes some of the relevant aspects that relate to material selection, selection of structural design approaches, and certification procedures.

9.2 Safety, regulations and specifications

In chapter 5 the functions of a structure have been explained in general when discussing and defining the airframe, and in detail for the various structural elements. To be able to fulfil their functions, structural elements in aircraft and spacecraft must comply with a number of requirements. Several requirements directly relate to the functions to be fulfilled. For example, if an element should be able to carry a certain amount of load, then a requirement may be that any degradation to the element during service should never lead to strength below the minimum strength to carry that load.

However, there are also a number of requirements that do not directly relate to the functions of that particular element, but they may follow from specifications or requirements of the complete structure to which the element belongs. This section will discuss a number of requirements relevant for aircraft and spacecraft structures.

9.2.1 Safety

Safety is considered an extremely important aspect in aviation. Governmental organisations on national and international level have compiled an extensive set of regulations for all aspects concerning aviation. With each accident or even incident reported in the news, the questions on safety are being raised again; is it safe to fly? Can safety be improved?

These discussions are to some extent interesting, because one of the characteristics of safety is that it is not an aspect easily measured. This is illustrated in Figure 9.1 with a comparison between the number of fatalities of different transportation modes. In general, safety could be associated with the lowest fatality rate. However, to evaluate safety of different transportation modes, or even different flights/missions within only aviation, this fatality rate is considered against a certain parameter. This could be the number of journeys, the number of hours, the distance, or even a combination of these. From the comparison in Figure 9.1 it is evident that safety seems to depend on the way of presentation. In addition to this, there is a psychological aspect contributing to the society's perception on safety. Even if the probability of dying within the air transportation mode is substantially lower than any other mode, and even if the presentation in Figure 9.1 would have resulted in the lowest fatality rate for air transport, then still people may perceive flying as less safe. This is simply related to the fact that with one aviation accident often many fatalities are involved, which receives great attention from the media, while the many car accidents with one or two fatalities per occurrence hardly receive any attention. As a consequence, people are very aware of aviation accidents, but to lesser extent of accidents in other transportation modes.

Deaths per billion journeys	
Bus	4.3
Rail	20
Van	20
Car	40
Foot	40
Water	90
Air	117
Bicycle	170
Motorcycle	1640

Deaths per billion hours	
Bus	11.1
Rail	30
Air	30.8
Water	50
Van	60
Car	130
Foot	220
Bicycle	550
Motorcycle	4840

Deaths per billion kilometres	
Air	0.05
Bus	0.4
Rail	0.6
Van	1.2
Water	2.6
Car	3.1
Bicycle	44.6
Foot	54.2
Motorcycle	108.9

Figure 9.1
Comparison between number of fatalities in different transportation modes relative to respectively journeys, hours and kilometres. (Ford, 2000 and Beck et al., 2007 as listed on Wikipedia – Aviation safety.)

Another drawback of presenting safety by accident rates as illustrated in Figure 9.1 is that this presentation does not distinct between the different routes, operators, distances or type and age of aircraft. Furthermore, the occurrences of accidents in the various transportation modes exhibit large fluctuations, especially in air transportation.

This implies that with the introduction of a new aircraft type into service, a safety level has to be established for that particular aircraft type. But even then, one has to be aware that the operator and the location and routes on which the aircraft is operating may influence the statistics.

The above discussion is based on civil aviation in general and not particularly related to safety of vehicle structures, i.e. structural integrity. Roughly 70% of the accidents is related to human factors rather than structural failures. However, similar considerations may apply. For example, a known factor applied in design of aircraft and spacecraft structures is the so-called safety factor. This factor reduces the load, the number of flights, or another relevant parameter to a level that the probability of failure or accident is reduced to an acceptable level. But what is considered acceptable is not easily measured or defined.

9.2.2 Safety regulations

Structural safety is the joint responsibility of different parties involved. It is not solely the responsibility of the aircraft manufacturer, the operator or the airworthiness authorities. In Figure 9.2 these three parties are presented with their main responsibilities with respect to assuring structural safety. In general, if one of these parties does not comply with its responsibilities, one may assume structural safety to be at risk.

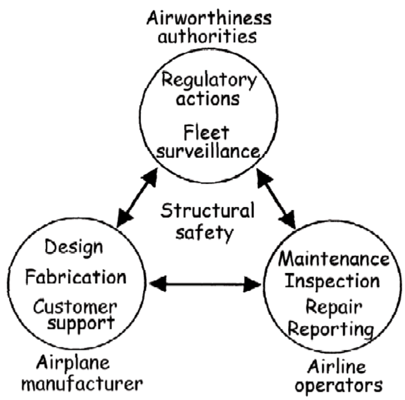

Figure 9.2
Illustration of the three major parties involved in structural safety and their main responsibilities. (Alderliesten, 2011, 9-2.jpg. Own Work.)

9.3 Requirements for aeronautical structures

Depending on the application or structure and its usage, a variety of requirements can be formulated that have to be met. However, concerning the structure, the requirements relate in general to three aspects:

- Strength
- Loads
- Life time

The strength should not be limited solely to the material strength (i.e. σ_{ult}), but should be considered the resistance to failure. This could be failure of the structure with or without the presence of damage.

Although listed second, the aspect of loads and load cases should be considered the most important and most difficult aspect. The strength of a material or structure can assessed relatively easy. One may either perform tests or perform an analysis based on the known mechanical properties of the material.

However, to evaluate whether the integrity of the structure can be maintained throughout all potential usage scenarios, one must know the loads related to these scenarios in advance. This implies that the forces acting upon the structure should be known in advance, which is practically impossible.
Often the loads are predicted based upon experience and measurements on earlier aircraft with similar configuration and usage. With the development of analysis techniques based on computational fluid dynamics, loads can be evaluated based on the aerodynamic shape of the aircraft.

Either way, the determination of relevant loads and load cases relates to the events that can be identified during the operational life of the structure. This means that estimation of loads relates to risks, i.e. the probability that certain events may occur and what risks are considered acceptable or not.

The third aspect concerns the topic of structural integrity and durability. The assessment of structural strength and potential load cases could be considered quasi-static. This maximum loads can be estimated and the structural strength to meet these loads can be achieved.

However, most engineering materials applied in aeronautical structures are affected by the environment when exposed sufficiently long, as discussed in chapter 2. In addition, the repetition of loads throughout the operational life may impose additional degradation of the structure, known as fatigue. This topic is discussed in more detail in chapter 10.
Time, however, can be defined in various units. For example, the life of the aircraft can be defined in years, flight hours, or flights. Depending on the component or structure, different units for time may be considered. For example, the pressurization of the fuselage during the flight relates to each flight. The loads related to the pressurization therefore are recorded against the number of flights. However, the usage of the engines is often expressed in flight hours, because the engine components are loaded continuously during the time the engines are operated.

The accurate recording of usage during operational life is important to evaluate whether the aircraft in reality is loaded more or less severe than the loads and load cases considered during the design and certification of the aircraft. Heavier usage of the aircraft than anticipated in design may impair the structural integrity before the end of life has been reached.

For the operator the recording against the number of flight hours is relatively easy, as it relates directly to the planning of flights, i.e. each flight in general has a specific duration. However, for certain components the number of flights should be known to assess the actual life.

9.4 Structural design philosophies

Throughout the evolution of flight, structural design philosophies have changed based on experience. Unfortunately, this experience relates to incidents and accidents. Initially, the strength of aeronautical structures was evaluated based on quasi-static loads. The estimation of relevant loads was based on experience and engineering judgements. As a consequence, the load estimation was fairly inaccurate.

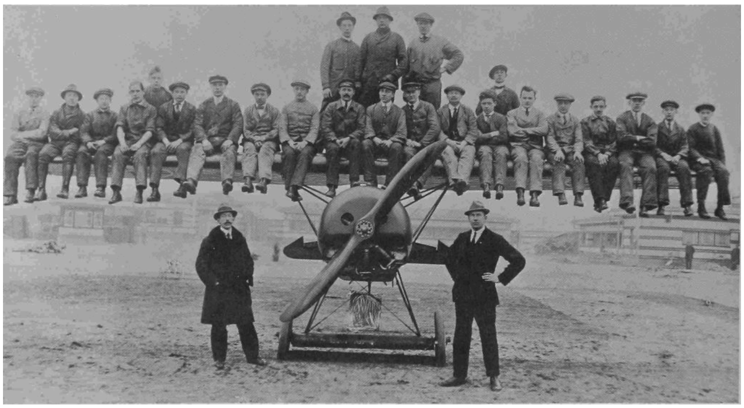

Figure 9.3
Illustration of a typical static strength tests on early aircraft. (Fokker, n.d., Public Domain.)

An excellent illustration of the evaluation and experimental assessment of strength of an aircraft structure is given in Figure 9.3. Here a maximum static load is considered that is represented in the tests by the number of persons on the wing. Interestingly in this case the main load on the wing is related to upward bending, while the people in the experiment apply a downward bending of the wing.

9.4.1 Safe life

The strength assessment example of Figure 9.3 implies the assumption that throughout time the structure will remain as it is, i.e. the structural integrity is not affected by either corrosion, accidental damages, fatigue, etc.
The first design philosophy that assumes that the structural integrity is maintained during operational life and that any degradation or strength reduction due to fatigue or corrosion is often denoted as 'safe life'. It can therefore be defined as:

Safe-life of a structure is the number of flights, landings, or flight hours, during which there is a low probability that the strength will degrade below its design strength.

This design philosophy can also be described as safety by retirement. The aircraft or structure is retired at the end of life before structural degradation may impair the structural integrity. This concept is illustrated in Figure 9.4.
As a consequence of the rapid introduction of new aircraft until the 50s of the previous century, this design principle could be considered sufficiently safe. The aircraft were often replaced before the anticipated end of life was reached. However, due to economic reasons aircraft lives were fully used and occasionally extended, increasing the risk of failure during operational life.

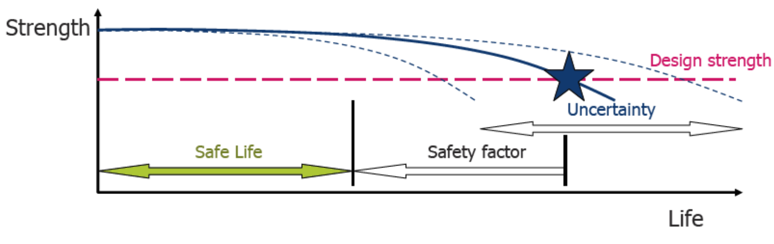

Figure 9.4
Illustration of the Safe life principle; strength reduction is considered beyond end of life. (TU Delft, n.d., 9-4.jpg. Own Work.)

The design philosophy also lead to failure as result of higher loads than anticipated in design and the use of stronger materials with usually poor fatigue properties, crack growth and residual strength. Well known examples are the two Comet aircraft that exploded at cruising altitude in 1954.

9.4.2 Fail safe

Educated by the accidents and incidents, the design philosophy was modified. The structural robustness was increased by adding redundancy to the structure. The design philosophy is referred to as 'fail safe' and can be defined as:

Fail-safe is the attribute of the structure that permits it to retain required residual strength for a period of un-repaired use after failure or partial failure of a principal structural element.

The objective of this design philosophy is that failure of a primary member by fatigue or otherwise does not endanger flight safety. As a consequence, emphasis was put on 'multiple structural member concept'. The redundancy in structural members allowed failure or partial failure of one member, redistributing the load to other intact structural members, preventing complete failure of the structure. This design philosophy can also be described as safety by design.

The strength evaluation implies therefore that various damage scenarios have to be considered for which the static strength evaluation is performed. In this philosophy, each individual structural item or member is adequately designed according to the safe life concept.

Example: Comet aircraft accidents in 1954

The aircraft accidents occurred after only 1286 and 903 flights. Investigation of the accidents revealed that cracks initiated near the automated direction finder (ADF) window linking up via rivets to adjacent windows, see Figure 9.5. The fuselage was designed with high strength aluminium with poor fatigue characteristics (high notch sensitivity) while relatively high stresses were allowed.

For certification, a full scale fatigue tests was performed, which only shows the initiation of fatigue cracks after 16000 flights. Subsequent investigation of the fatigue performance of aluminium alloys revealed that the static pressure tests performed before the fatigue load spectrum was applied induced a favourable response of the full scale test article. The static and fatigue test were combined on one aircraft for economic reasons.

The effect of the high load induced by two times Δp caused local plasticity near windows and notches, with favourable redistribution of stresses. As a consequence, the full scale fatigue test was un-conservative, i.e. the measure life was longer than the actual life of the aircraft.
Repetition of the full scale fatigue test on a Comet aircraft taken out of service without the static pressurization load revealed initiation of fatigue cracks near escape hatches after 3036 flights.

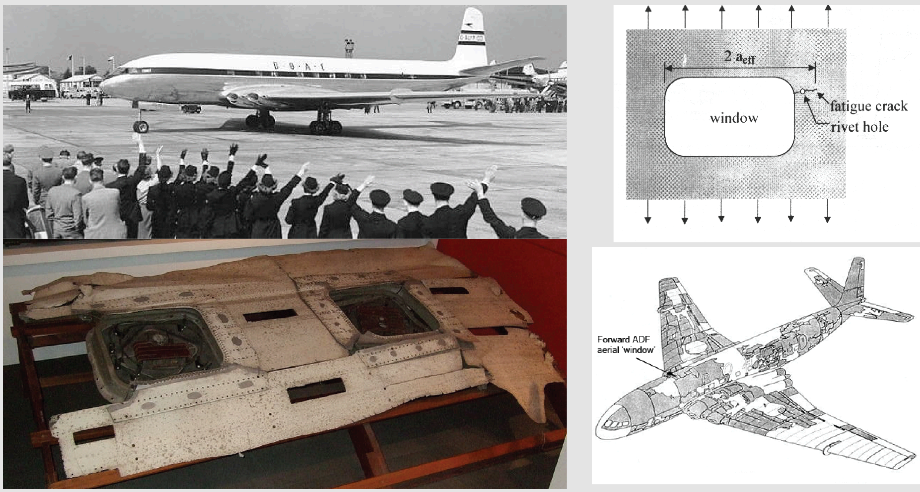

Figure 9.5
Comet aircraft(upper left), illustration of reconstruction of one of the two aircraft (right) and the fuselage section containing the aerial windows. Derivative from top left: British Airways, (1952), Public Domain; top right: Ministry of Transport and Civil Aviation, (1954), Public Domain; bottom left: Krelnik, (2009), CC-BY-SA3.0; bottom right: Ministry of Transport & Civil Aviation (1954), Public Domain.

The main advantages of this design philosophy compared to the safe life philosophy are related to safety and economics. The damage could be detected within a given amount of time before full failure occurred, which implies an increase in safety. In the safe life philosophy a structure or component had to be replaced once reaching end of life indifferent of the integrity of the component. In the fail safe philosophy, a structural member could be kept in service until partial failure occurred or damage was observed.

Although the fail safe design philosophy implied an increase in safety, still incidents and accidents occurred induced by structural failures. Evaluating these failures revealed that not all failure modes were anticipated in the static strength evaluation. In addition, the redundancy in the structure obtained by multiple elements did not consider particle failure of multiple elements.

For example the lug illustrated in Figure 9.6 has been considered for decades as the typical illustration of the fail safe concept. However, once one of the lug elements contains a crack, its stiffness reduces, redistributing the load to the other lug members. As a consequence, all members of the lug start cracking simultaneously. The occurrence of multiple cracks in adjacent components or elements is called Multiple Site Damage (MSD). In case of MSD, the fail safe design philosophy becomes ineffective.

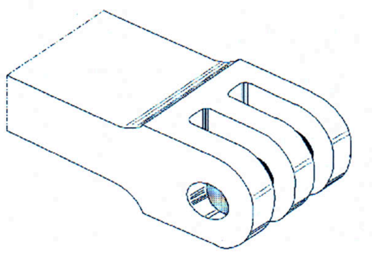

Figure 9.6
Typical illustration of fail safe redundancy in a lug. (TU Delft, n.d. 9-6.jpg. Own Work.)

9.4.3 Damage Tolerance and durability

Since 1978 the aviation requirements (FAR/JAR) adopt the damage tolerance philosophy. This philosophy can be defined as:

The ability of the structure to sustain anticipated loads in the presence of fatigue, corrosion or accidental damage until such damage is detected through inspections or malfunctions and is repaired.

The damage tolerance design philosophy is not considered a replacement of the safe life and fail safe philosophy, but rather an advanced concept that combines these two into a new philosophy.

The main advantages of the philosophy are twofold. First, it is assumed that defects, flaws and imperfections are present in the structure directly after manufacturing. These flaws and defects may increase during operational life inducing degradation of the load bearing capability of the structure.

Second, the damage (fatigue corrosion, impact) may be present in the structure and even grow until detected during prescribed inspections and subsequently repairs. This repair assumes that the structure is restored to its original strength.

The damage tolerance design philosophy can also be described as safety by inspection. The determination and execution of regular inspections forms an inherent part of the aircraft design.

Example: Aloha airlines accident in 1988

In 1988 a Boeing 737 operated by Aloha airlines lost a large portion of the upper fuselage during flight. Fortunately, all passengers were tied to the chairs with their belts limiting fatalities to one flight attendant.
The investigation of the accident revealed that the riveted lap joints were susceptible to corrosion and contained multiple cracks (MSD). The operators were informed by the aircraft manufacturer about the susceptibility to fatigue and corrosion, especially for warm, humid and maritime air environment near Hawaii, but the operator did not perform sufficient inspections.

This example could be taken as an example that even the damage tolerance philosophy does not guarantee flight safety. Although part of design, inspection and repair have to be performed in order to limit structural failures.

Figure 9.7
Photos of the damage to the fuselage of the Aloha airlines aircraft. Derivative of NTSB, (1989), Public Domain.

The damage tolerance design philosophy as currently applied to aeronautical structures is closely tied to the durability concept. Durability can be defined as:

The ability of the structure to sustain degradation from sources as fatigue, corrosion, accidental damage and environmental deterioration to the extent that they can be controlled by economically acceptable maintenance and inspection programs.

The combination of the damage tolerance concept and the effect of environment on structural integrity implies that the damage scenarios considered in the strength evaluation should account for the superposition of cases, i.e. fatigue in metals together with corrosion, fatigue delamination in composites together with reduced resistance due to moisture absorption.

9.5 Design approach

The approach applied in designing aeronautical structures is to identify all critical structural locations for which detailed evaluation must be provided. For each of these locations it must be determined whether inspection is possible or not. This approach is illustrated in Figure 9.8. Currently, only the landing gears and attachments are certified according to the safe life design philosophy, because these components are considered practically impossible to inspect with inspection intervals sufficiently long to comply with durability requirements.

The strength justification of the structural elements is to great extent based on experimental substantiation. In fact, the requirements specify that it must be shown with sufficient tests (supported by analysis) that the probability of failure is negligible.

Figure 9.9 illustrates that the aircraft manufacturer performs many generic tests that are not specifically for an aircraft, but applicable to any of the aircraft it considers developing. The data from these tests form the basis for the strength evaluation. Throughout the development of the aircraft, more detailed and complex tests are performed to evaluate and justify the behaviour of the actual structures. Near the end of the development, component tests and full scale fatigue tests can provide the basis for certification.

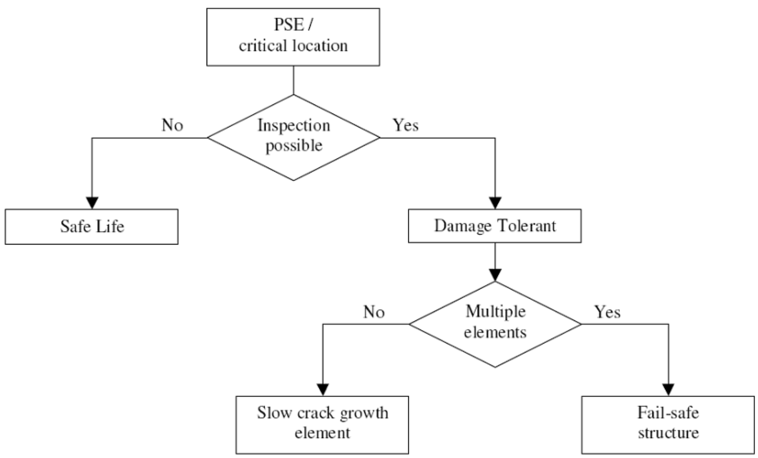

Figure 9.8
Schematic presentation of the design approach. (Alderliesten, 2011, 9-8.jpg. Own Work.)

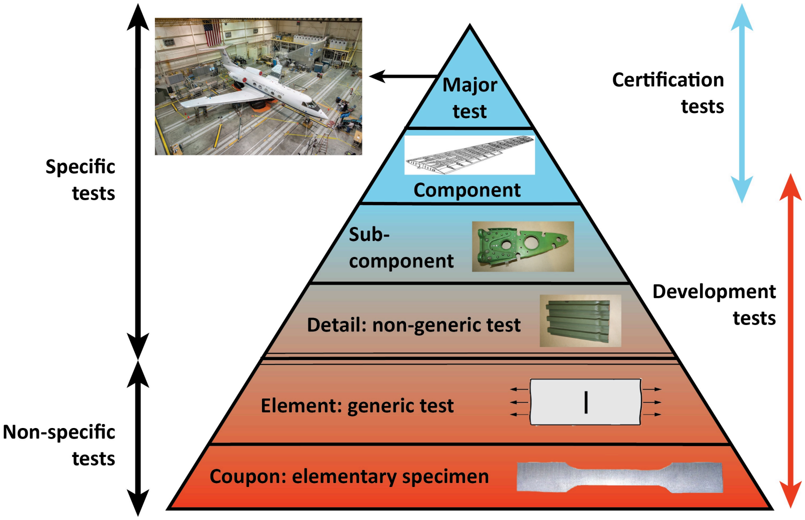

Figure 9.9

Illustration of the experimental pyramid.Derivative from top row: Ulbrich- NASA, (2014), Public Domain; second row: DTom, (2007), Public Domain, third row: Saunders-Smits, (2018), 9-9-c.jpeg, Own Work; fourth row: Saunders-Smits, (2018), 9-9-d.jpeg, Own Work; fifth row: Yapparina, (2014), CC-BY-SA3.0; Bottom row: Wizard191, (2010), CC-BY-SA3.0.

Introduction to Aerospace Structures and Materials

Dr.ir. R.C. (René) Alderliesten

This book provides an introduction to the discipline of aerospace structures and materials. It is the first book to date that includes all relevant aspects of this discipline within a single monologue. These aspects range from materials, manufacturing and processing techniques, to structures, design principles and structural performance, including aspects like durability and safety. With the purpose of introducing students into the basics of the entire discipline, the book presents the subjects broadly and loosely connected, adopting either a formal description or an informal walk around type of presentation. A key lessons conveyed within this book is the interplay between the exact science and engineering topics, like solid material physics and structural analysis, and the soft topics that are not easily captured by equations and formulas. Safety, manufacturability, availability and costing are some of these topics that are presented in this book to explain decisions and design solutions within this discipline.

Dr.ir. R.C. (René) Alderliesten
TU Delft | Faculty of Aerospace Engeneering

Dr. Alderliesten obtained his MSc and PhD degree both at TU Delft, and holds since 2012 the position of associated professor within the department of Aerospace Structures and Materials at the faculty of Aerospace Engineering, TU Delft. His expertise is fatigue and damage tolerance of metals, composites and hybrid materials, with the emphasis on proper understanding the physics of damage growth. Dr. Alderliesten introduces Aerospace Structures & Materials in the first semester of the BSc curriculum, while teaching Fatigue of Structures & Materials in the first semester of the MSc both at TU Delft and at the University di Bologna.

ISBN 978-94-6366-075-4
DOI https://doi.org/10.5074/t.2018.003

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