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# Assessment of timber structures using the X-Ray technology

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**Abstract.** The assessment of timber structures is a permanent task to check the normal function of individual structural timber elements. Non-destructive testing methods are preferred but the value of the information is limited due to the performance of the applied assessment method. However, X-ray is a technology which allows a view into the structural member or the connections. The mobile X-ray technology has been used in laboratory tests and practical situations at existing structures and led to excellent results which allowed detailed analyses. The method and its possibilities for non-destructive testing of timber structures will be presented. The results reached show a high potential for an effective assessment of existing structures including connections and structural timber members.

## Introduction

The structural assessment of timber structures is caused by different reasons, such as regular inspections, structural modifications, changes in serviceability or historic preservation. The assessment of timber structures always begins with the visual inspection of the complete building for the analyses of the supporting structure. The following assessment of the single members, connections or specific details will take place only after this step. An advantage in assessing timber structures is that abnormalities are normally relatively easy to detect due to discoloration, cracks or plastic deformations. Especially in combination with the measurement of the moisture content, first specification can already be done. Depending on the abnormalities found, specific testing methods are available and can be used. The test methods can generally be classified into nondestructive, less destructive and destructive test methods. For the detailed survey of the building and assessment, an overview of common methods is given in Table 1. Further explanation can be found in e.g. Aicher [1], Görlacher [2], Kasal & Tannert [3], Köhler et al. [4], Rinn [5], Steiger [6] and Vogel et al. [7].

Non-destructive testing methods are preferred, but the value of the information is limited due to the performance of the applied assessment method. Especially the occurrence of internal damages like cracks, holes, fitting inaccuracy or plastic deformations of mechanical fasteners cannot be detected reliably with these common methods. However the X-ray technology allows a view into the structural member or connections. The application of the X-ray technology on wooden structures was investigated and the results and limitation are presented.

Table 1 Common assessment methods for timber structures

| **Nondestructive testing methods** | **Less destructive testing methods** | **Destructive testing methods** |
|---|---|---|
| Visual inspection | Resistance drilling | Test of glue line quality |
| Survey | Penetration resistance tests | Mechanical testing for strength prediction |
| Moisture content | Withdrawal resistance test | |
| Crack detection and mapping | Drill core specimens | |
| Ultrasonic wave or echo method | Endoscopy | |
| Chemical investigations | | |
| X-Ray | | |

## X-ray technology

**Method.** The X-ray technology is known from the medical use. Nowadays there are also mobile X-ray systems available which are used for the in-situ assessment of structures, as shown in [8], [9], [10], [11], [12], [13]. The adoption of this technology provides the possibility to look inside the member with a high accurate resolution according to the measuring area of 30 by 40 cm for the film used. The X-ray technology is a non-destructive testing method and works quasi contactless. The use of a mobile X-ray technology in combination with the specific digital scanner allows in-situ assessment of existing structures.

The safety requirements for the use of the mobile X-ray system do not limit the practical use on existing timber structures. The mobile X-ray system used works with hard X-ray impulse generator but with a very low dose as against stationary X-ray systems known. Furthermore the exposure transmitter is only active, meaning X-rays are only generated, while ”taking” the picture. This process takes only a few seconds and before and after no X-ray exposure happens. In practical use, the safety zone is specified as follows: 3 meters around the transmitter, 30 meters in measuring direction and 11 meters perpendicular to it. The users carry a personal dosimeter to register any irradiation.

**Theory and Calculation**. X-rays are a form of electromagnetic radiation. The X-rays are absorbed depending on the material respectively their density. The X-ray absorption parameter is defined by the Beer-Lambert law as follows:

$$I = I_0 \cdot e^{-\mu d} \tag{1}$$

Where $I$ is the intensity after radiography in [W/m$^2$], $I_0$ the intensity before radiography in [W/m$^2$], $d$ the thickness in [m] of the material and $\mu$ the X-ray absorption coefficient in [m$^{-1}$]. For wood, the X-ray absorption coefficient is defined as follows:

$$\mu = \mu' \cdot \rho \tag{2}$$

With $\mu'$ as the mass absorption coefficient in [m$^2$/kg] and $\rho$ the density of the material in [kg/m$^3$]. The absorption capacity depends on the density of the material, the atomic mass, atomic number and the depth of the material, [14].

The X-ray radiography depends on the impulse intensity of the X-rays, the distance of the test object to the transmitter as well as to the film plate and also the thickness of the material. The principle of the process is shown in Fig. 1, where the test object is located between the X-ray

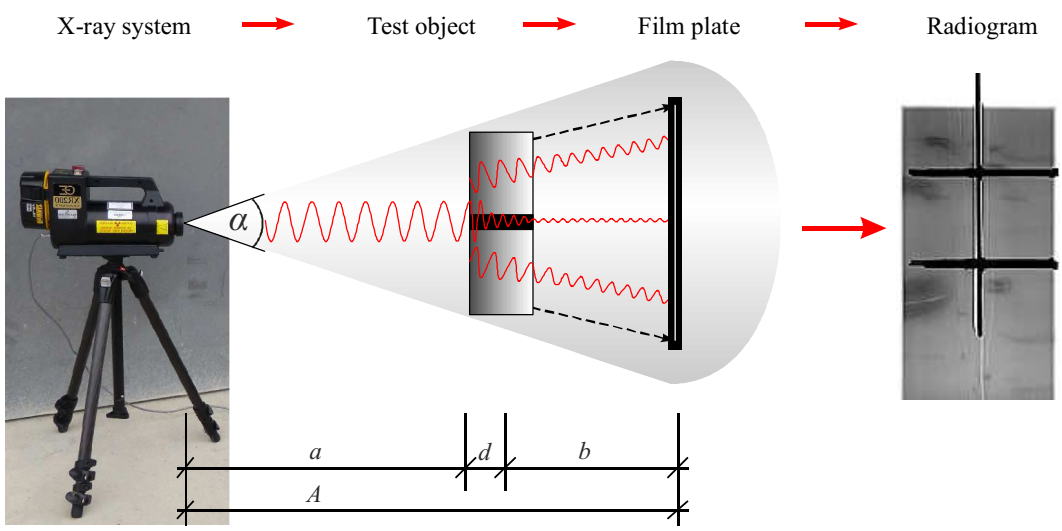


Fig. 1 Principle process of X-ray technology and investigations

transmitter and the film plate. The X-rays transmitted travel through the test object and will be absorbed with different intensities before they hit the film plate. The material specific absorption of the X-rays leads to the so called radiogram which will finally be transferred in a grayscale picture. The volume of the three dimensional test object will be reproduced as a two dimensional picture.

## Applications and limits of the mobile X-ray technology

**Laboratory analyses of the system.** The principle of the X-ray process is similar to taking a picture with a photo camera. The quality of the photo depends on the depth of field, sharpness of movement and focus. These parameters are not comparable for X-ray systems. Here the impulse intensity, the distances of the test specimen between the transmitter and the film plate and the thickness respectively density restrict the results, resolution and accuracy of the method.

According to Eq. (1), the intensity $I$ on the film plate increases linear with the intensity of the transmitter $I_0$. The gray value of one pixel behaves proportional to the intensity and will increase. Fig. 2 shows the radiograms taken with different numbers of impulses from a steel screw tip inserted in wood block as test object. The test object had a constant thickness $d$ of 70 mm. Increasing the thickness increases the absorption of the X-rays, so that for radiograms with comparable quality, the number of impulses has to be increased as well. The effect of the number of impulses was analyzed for two different thicknesses and is shown in Fig. 3.

Furthermore the distance $a$ between the transmitter and the test object and the distance $b$ between the test object and the film plate, see Fig. 1 was verified related to the accuracy and sharpness of the radiograms. The same test object with the steel screw inserted in a wood block with a thickness of 70 mm was used. The increase of the distance $b$ results in a smaller projected area where the object is enlarged compared to the original size, as shown in Fig. 4. On the other hand, the reduction of distance $a$ leads to a clear “burned” spot and unusable radiograms. A minimum distance $a$ of about 1 meter was necessary for the test configuration with a film plate of 30 by 40 cm. The relation between the two distances $a$ and $b$ is summarized in Fig. 5.

Finally the thickness of the test object was verified from 70 mm up to 350 mm. Hereby constant parameters for the number of impulse, distances of the test object to transmitter and film plate were used. The radiograms of the test object with the metal screw inserted in the wood block with different thicknesses are shown in Fig. 6. The contrast of the radiogram reduces with the increase of the thickness of the test specimen. The typical structural elements of wood on macro scale level are visible for thicknesses up to 200 mm. For greater thicknesses, only major differences are visible in the radiogram like parts of steel or wood. As summary, the relation between the mean gray value and the thickness is shown in Fig. 7.

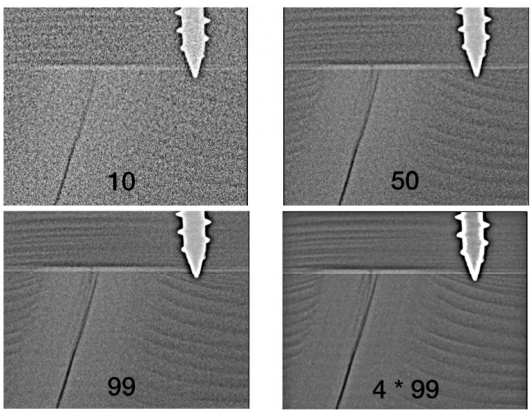


Fig. 2 Radiograms with different number of impulses

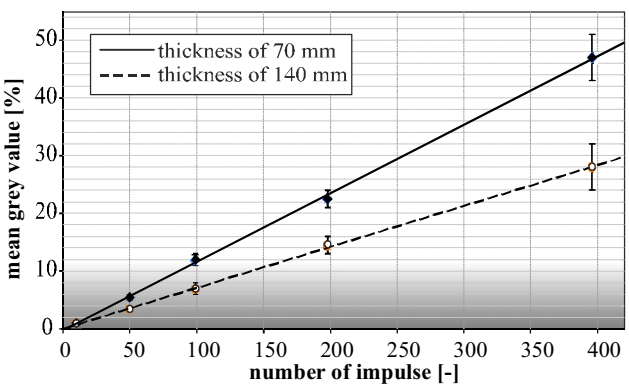


Fig. 3 Effect of number of impulse, the shadowed area marks the not useful configurations

**Assessment of wood and connections.** The first investigations are done in the laboratory with samples of historical wood to wood connections or with mechanical connections. Fig. 8 shows a wood to wood connection with an internal hardwood dowel. Not only the two wood species, European spruce and beech, can be clearly distinguished but also differences within one material like knots and even the annual grow rings are visible. Furthermore the fitting accuracy of such a connection can be checked. In this case gaps are clearly detectable. As a practical application, a historical timber construction in a chateau was investigated. Wooden nails could be detected during the assessment of a multi layered beam construction, as shown in Fig. 9.

The assessment of timber connections with mechanical fasteners is shown in Fig. 10 for a dowelled connection with inner steel plate. The test specimen shown was loaded/unlodaded in certain steps at the laboratory and X-rayed after each load step. For every case, the visual inspection of the outside area (heads of the fasteners) do not indicate any irregularities. But the radiograms show that inside the connection plastic deformations according to the Johansen theory, [15] already occurred, as shown in Fig. 10c)-d). The plastic deformations of the fasteners indicate an overloading and a failure of the connection. The connections have to be repaired in this case.

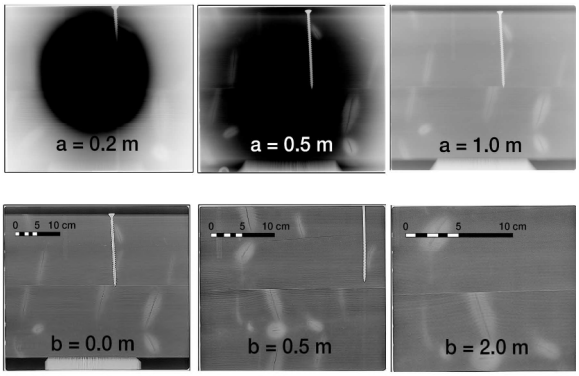


Fig. 4 Radiograms with different distances, top row distance a and bottom row distance b

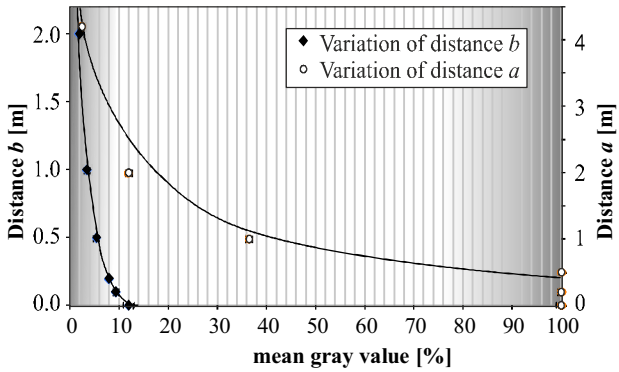


Fig. 5 Effect of distances of impulse, the shadowed area marks the not useful configurations

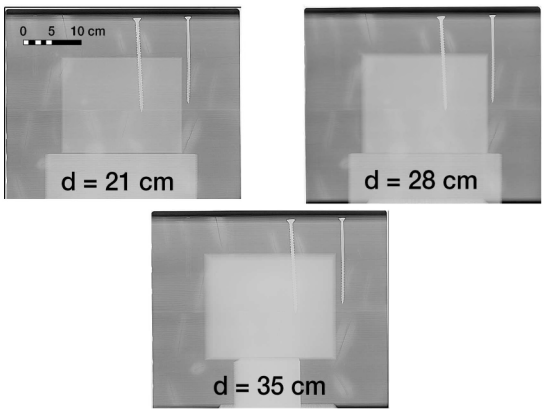


Fig. 6 Radiograms with different thicknesses of the test object

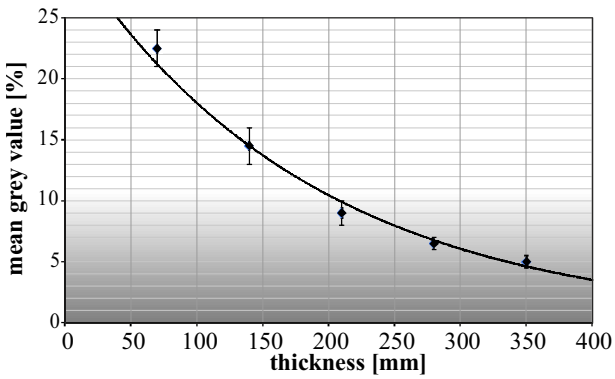


Fig. 7 Effect of thickness, the shadowed area marks the not useful configurations

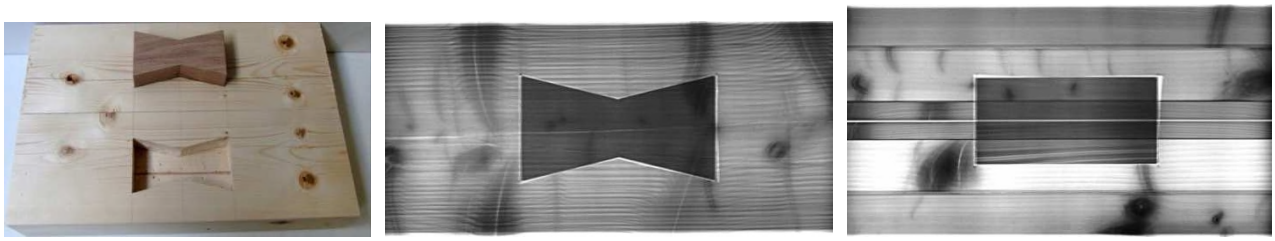

Fig. 8 Wood to wood connection with hardwood dowel

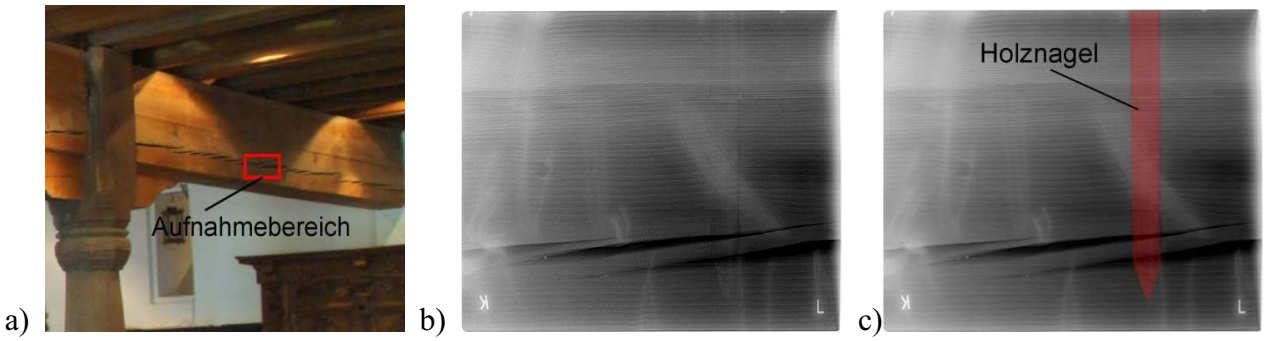


Fig. 9 Historical wood nail in multi layered wooden member, a) position of X-ray shot, b) original radiogram, c) wooden nail marked in radiogram

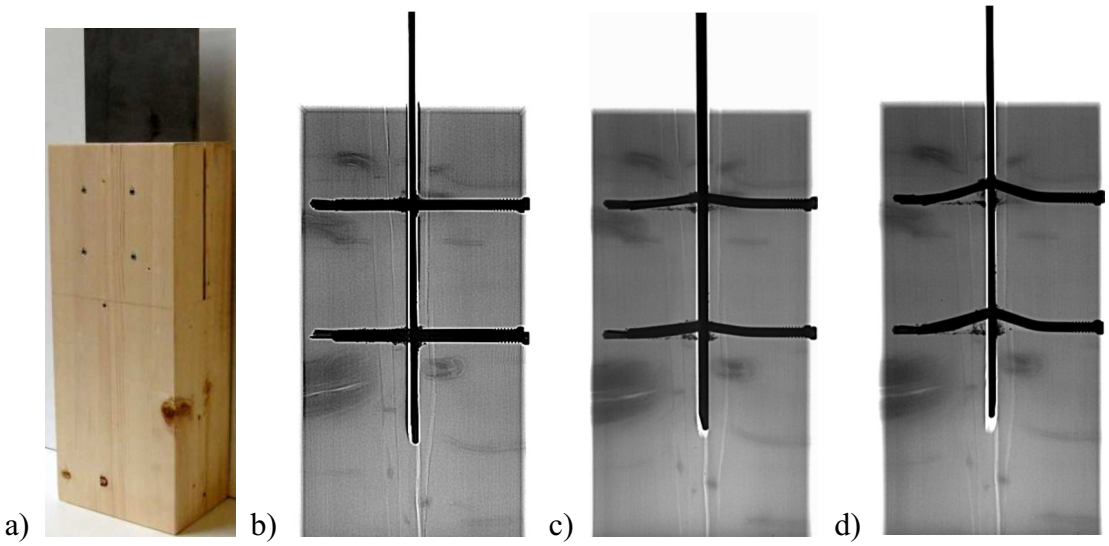


Fig. 10 Connection with mechanical fasteners, a) Test specimen, b) unloaded connection, c) and d) connection with plastic deformations

**Assessment of restored glue lines and fungal/insect decay**. Glulam is a common used engineered wood product for large span timber constructions. The assessment of these structures is a permanent task in order to ensure the integrity and performance. In some cases, the glue lines or cracks have to be restructured or supports and high stressed areas have to be reinforced. The assessment of restructured glue lines was therefore investigated with the mobile X-ray system within a research project. A glulam member with two restructured cracks was X-rayed in different directions to check the restoration. In the first radiogram, taken in a direction perpendicular to the glue-line planes and shown in Fig. 11b), a clear failure at the outside of the beam can be seen. But the allocation to one of the glue-lines or even the evaluation if there are more failures in the same direction is not possible. Fig. 11c) shows the final radiogram inclined to the glue-line plane. Here, the two restructured glue-lines can be separated from each other and the failure spots and injection holes are clearly visible for each glue-line. In this case, both glue-lines show the failure at the same position. Furthermore, the assessment of this member also shows voids and bubbles along the glue-line plane as well as in the injection holes. Depending of the size of these defects, the structural capacity of the beam and the strength of the restructured glue-line can be influenced. In a practical application, also voids and bubbles within a glued-in rod connection could be detected.

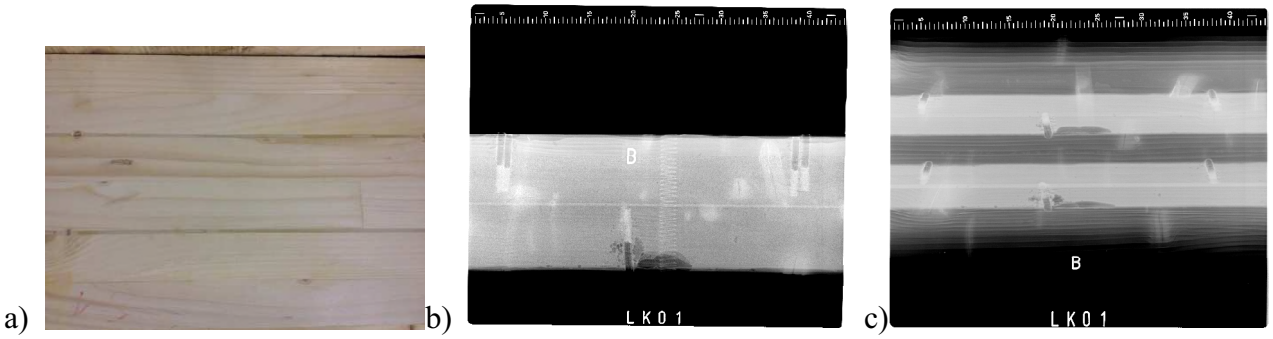


Fig. 11 Gulam member with two restructured cracks, a) test specimen, b) X-ray direction perpendicular to the glue-line (top view),
c) X-ray direction inclined to glue-line

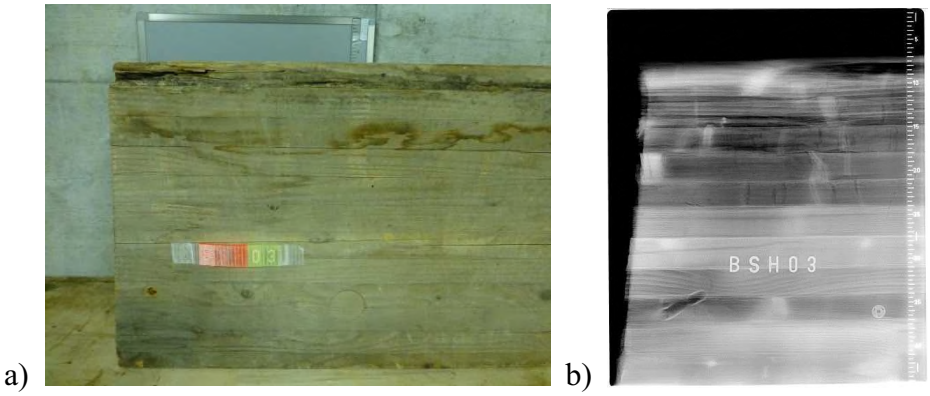


Fig. 12 Fungal decay in X-ray, a) test specimen, b) radiogram

In general fungal or insect decay can be observed within the visual inspection. But in some cases structural elements are covered or only viewable from one side, so that the mobile X-ray system can be used for detailed analyses or specification of assumptions. Fig. 12 shows as example of a glulam member with fungal decay in the top layers. The typical cubic failure structure is visible in the radiogram observed and allows estimating the dimension of the decay.

## Discussion and conclusion

The X-ray system has been used in laboratory tests and practical situations at existing structures and led to excellent results which allowed detailed analyses going further as common non-destructive assessment methods. It was shown that the mobile X-ray technology offers a high potential for an effective assessment of existing structures including connections and structural timber members. Deformations of mechanical fasteners like the formation of plastic hinges due to overloading are visible as well as the macroscopic structure of wood, knots or different wood species. Also glued connections like finger joints or restructured glue-lines were checked for quality and/or damages. Voids or bubbles but also cracks due to overloading could clearly be detected.

The practical examples presented, give an overview of the ability and the limits of this method and show that the mobile X-ray system is a novel successful non-destructive testing method of timber structures. With increase of the differences of the density of the investigated materials, the contrast is getting more and more intensive. However, reliable analyses of the resulting radiograms should be done by people who have experiences with the system and are professionals in timber structures in order to be able to identify irregularities from inaccuracies even in less contrast radiograms.

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