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Influence of the size and depth of a circumferential notch on the impact behavior of streetlights. A passive-safety concept.

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Abstract: Impact tests on weakened streetlights were carried out using a high energy pendulum. The weakening mechanism consists of a circumferential notch at the base of the streetlight. The objective is twofold: firstly to reduce the maximum acceleration values during an impact which will lessen the potential injuries of the occupants of the vehicle and secondly to help avoid the installation of protective barriers, necessary when the supporting structure has no mechanical fuse, thus helping the failure with low energy absorption values. The machining of the notch is possible in streetlights already installed in the road, due to the fact that the actual values of the structural stiffness and strength of these structures are much higher than those values typically required by the external loadings (mainly wind actions). These preliminary tests have shown a significant decrease in the two parameters under analysis, maximum acceleration and absorbed energy, when using the circumferential notch. These results suggest it would be beneficial to perform a crash test following EN12767 in order to certify the streetlight.

Keywords: Impact, passive safety, EN12767, crash tests.

1. Introduction

Streetlights, as well as other support structures on the road (e.g. traffic lights) are potential obstacles for a vehicle impact. Understanding their energy absorption behavior is of major importance to determine possible injury levels of the vehicle occupants.

In impacts where the incident velocity is low and where the streetlight stops the vehicle, secondary injuries caused by the uncontrolled path of the vehicle after the impact could be avoided. On the contrary, in impacts where the incident velocity is high (typically in intercity roads), a sudden stop at the streetlight could originate high deceleration values giving rise to potential human injuries. In this latter case, passive safety, understood as low energy absorption values at the streetlights, may be considered to be desirable. The residual vehicle speed would be, of course higher, but no potential harm to pedestrians is expected in these intercity roads.

It must also be taken into account that in some national regulations, see for example [1], using support structures which do not generate deceleration values over a certain threshold in an impact, means that the associated protective barrier is not required to be installed, with the corresponding cost saving. In order to reduce the vehicle incident speed in an efficient way (high energy absorption capability without peak acceleration values), there are specific geometries and structure configurations available (see for example [2], the classical work [3] or the more recent developments with filled structures [4]). Vehicles can also be designed to absorb energy in an efficient way using composite materials [5]. Nevertheless, streetlights are not specifically designed to act as energy absorbers and that is the reason why, in the aforementioned regulations, a protective barrier has to be installed to protect the vehicle from excessive impact loads.

The structural stiffness and strength of most streetlight columns is much higher than those required in the standards dictated by the typical loads definitions (e.g. EN 1991-1-4 "Wind Actions" [6]), giving rise to the presence of dangerous obstacles in the road. One way to reduce the potential injuries to occupants in the event of an impact with a streetlight already installed in the road is to weaken, in some way, the area where the vehicle will make impact. In this study, a circumferential notch was made in the streetlight base. Different radii and depths were used and the impact behavior was studied experimentally.

There are specific standards concerning passive safety of support structures (e.g. EN 12767 [7]) in which the impact test requirements are defined and described in detail. Nevertheless, the cost of such tests, requiring standardized vehicles, high-speed recordings and many additional technical specifications, are quite high for performing a preliminary study like this one.

Therefore, a high-energy pendulum is used first to assess the impact behavior of streetlights. Although the weight and incident velocity chosen is similar to that used in the EN 12767 test (900 kg and 30 km/h), the pendulum (stiff steel block) does not behave in a similar way to a vehicle (designed to deform and absorb energy). Thus, the results and conclusions must only be taken as an initial assessment of the real impact behavior of the streetlight.

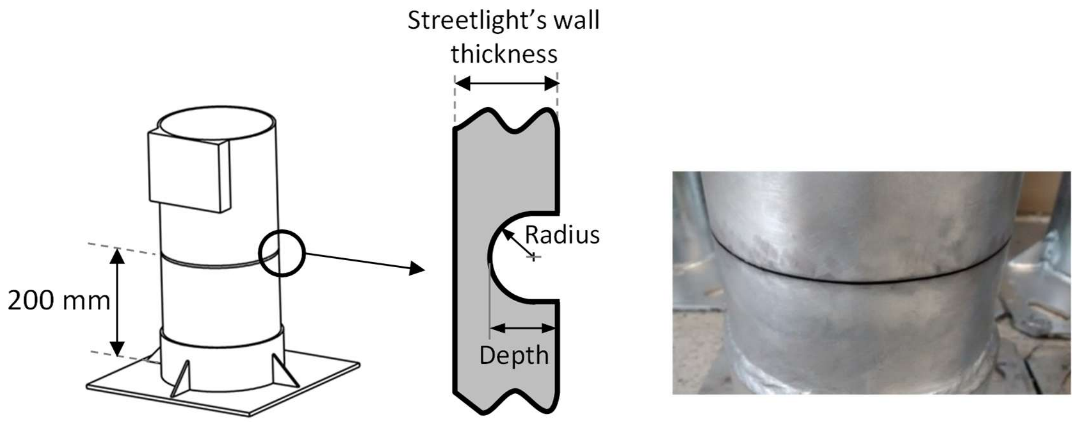
With all previous comments in mind, the objective of the present study is to analyze the influence of a notch on the impact behavior of a streetlight.

2. Definition and machining of the circumferential notch on the streetlight base

Streetlight columns are weakened by making a circumferential notch along the whole perimeter of their base. This weakening procedure is, of course, directed at streetlights already installed on the road and currently has its patent pending.

The streetlight chosen for the present study is a straight column, made of galvanized steel, with a height of six meters and 3 mm thickness, supplied by JOVIR [8]. The diameter at the bottom part is 135 mm, and 60 mm at the top. Due to the fact that only the local behavior at the notch section was of interest, only the bottom part of the streetlight (at a height of 1.5 m) was tested with the high energy pendulum. A dead mass of 80 kg was fixed to the top part to reproduce the total mass and inertia of the complete streetlight.

Three notch radii and three notch depths were used to weaken the streetlight base. The selected radii were: R=0.5, 1.5 and 4.0 mm. Taking into account that the thickness of the streetlight is 3 mm, the selected depths were: D=1.0, 1.5 and 2.0 mm. The notch was machined along the perimeter, 200 mm above the bottom part of the streetlight. A view of the base of the streetlight, where the circumferential notch was made, is shown in Fig. 1.



a) b) c)

Figure 1. Detail of the notch, a) notch section detail view, b) detail of hollow streetlight's wall, c) picture of a real notch machined at the streetlight base.

Six streetlights were prepared with the combination of radii and depths shown in Table 1. The order shown in Table 1 corresponds to the order in which the streetlights were tested. Test specimens 2, 3 and 5 (in Table 1) have a constant depth (1.5 mm) and three different radii (0.5, 1.5 and 4.0 mm respectively). Test specimens 1, 3 and 4 (in Table 1) have a constant radius (1.5 mm) and three different depths (2.0, 1.5 and 1.0 mm respectively). These parameter combinations, keeping one of them constant, allow the influence on the impact behavior of the variable parameters to be seen more clearly. The reason for choosing these values is linked to the fact that the hollow streetlight's wall thickness is 3 mm. 1.5 mm (one half of the wall thickness) was chosen as a reference value for depth and radius, and then, one value was chosen higher and one lower, both for the thickness and for the depth.

Table 1. Radii and depths of the notches performed at the streetlight bases. Streetlight #6 does not have any notch. Superindex * indicates failure at the notch section.

		Radius (mm)		
		0.5	1.5	4.0
Depth (mm)	1.0	--	4	--
	1.5	2	3*	5*
	2.0	--	1*	--

Note: Number 1-5 indicates the streetlight number.

Due to the fact that the streetlights are manufactured by means of welding a curved steel plate along the longitudinal direction, the geometry of the transversal plane does not have a constant radius value. This means that direct machining along the external perimeter, using a rotatory device, which would give rise to a truly circumferential geometry, cannot be performed. To solve this issue, the machining was completed by sectors, in an area where the external geometry had approximately a constant radius to guarantee a constant depth during the machining process. Depth measurements were taken, after the machining process, to guarantee that a reasonably constant notch depth was achieved.

Other notch geometries, such as sharp V notches, have not been considered in this study. Sharp V notches together with the typical dynamic wind loads, would give rise to quick fatigue crack initiation. In fact, as will be seen later, from the three configurations with the same notch depth (1.5 mm) that with the larger radius (r=4 mm) has been chosen as the most appropriate to minimize the notch stress concentrations.

3. Impact tests

A high energy pendulum was used for the impact tests. A steel block of 900 kg ("impactor" in what follows) was dropped from the adequate height to reach the resting line (see Fig. 2) at a nominal target speed of 30 km/h. The shape of the front part of the impactor is cylindrical. The distance from the resting line to the streetlight contact ("L" in Fig. 2) is 350 mm and the impact height ("H_s" in Fig. 2) is 400 mm, 200 mm above the notch height. The door to access the interior of the streetlight base was placed facing the impactor (originally, this access door was placed on the opposite side, but an unexpected failure of the door welding, at test #2, was observed, see comment on Section 4).

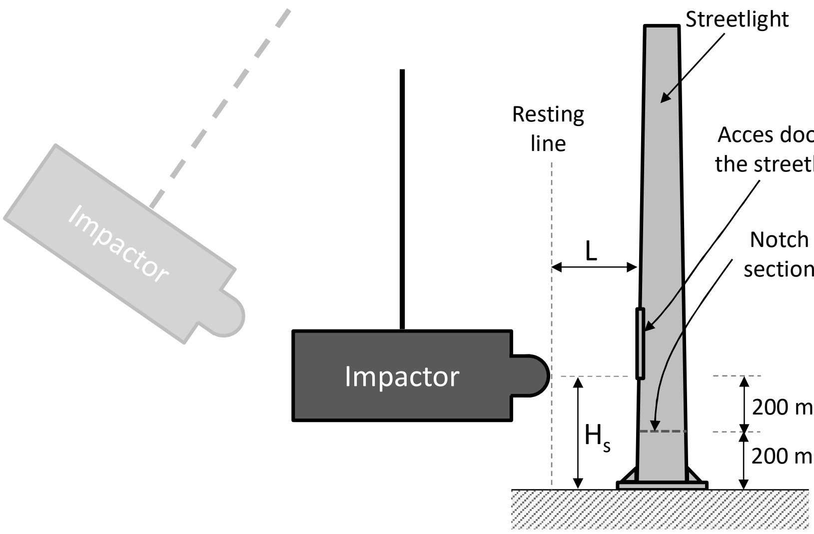


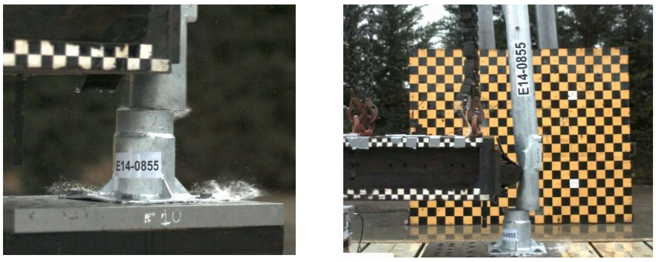
Figure 2. Impact test scheme and definition of distances.

For each test, two high speed cameras (1000 frames per second) were used, one recording a global view of the test and the other one with a detailed view of the notch area. Additionally, the horizontal deceleration vs time curve was recorded using an accelerometer (Endeveco, model 7264B-500T). The tests were carried out at CIDAUT Facilities [9] which has the EN 12767 impact test with accreditation issued by the Spanish accreditation body, ENAC [10]. The streetlight was fixed to a metallic plate (50 mm thick and fixed to the ground) by means of four screws with hexagonal head M.16x35 grade 5.8 (UNE 135122 [11]) and 4 washers M.16 (EN ISO 7091 [12]).

4. Results and discussions

Although it must be remembered that the acceleration profiles measured from a real crash test following EN12767 criteria are not comparable to the acceleration profiles obtained in the present test with a rigid steel block, this type of test (high energy pendulum) is typically performed in advance of the EN12767 test, as a preliminary, cheaper test. Figure 3 shows two pictures (a detail of the notch area and a global view of the test) of the high-speed recordings for each test. In the case of the streetlights failing at the notch section, the pictures correspond to those taken some milliseconds after the complete section failure. In the streetlights not failing at this section, the picture was taken after an approximately similar interval of time (around 12-15 ms after the impact).

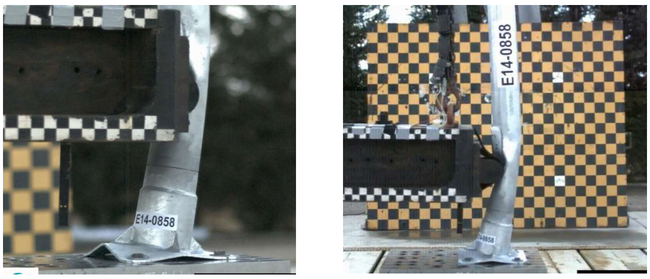
Streetlight-1
Radius=1.5 mm
Depth=2.0 mm
Test number: E14-0855
Notch failure: YES



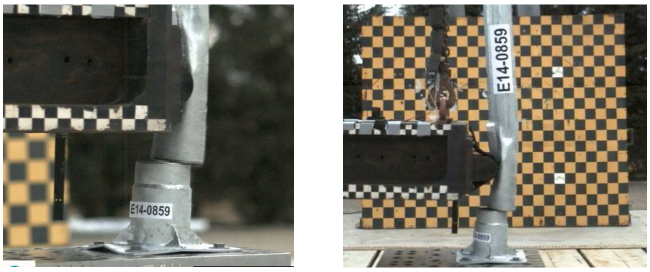
Streetlight-2
Radius=0.5 mm
Depth=1.5 mm
Test number: E14-0856
Notch failure: NO

Streetlight-3
Radius=1.5 mm
Depth=1.5 mm
Test number: E14-0857
Notch failure: YES

Streetlight-4
Radius=1.5 mm
Depth=1.0 mm
Test number: E14-0858
Notch failure: NO



Streetlight-5
Radius=4.0 mm
Depth=1.5 mm
Test number: E14-0859
Notch failure: YES



Streetlight-6
NO NOTCH
Test number: E14-0860
Notch failure: NO

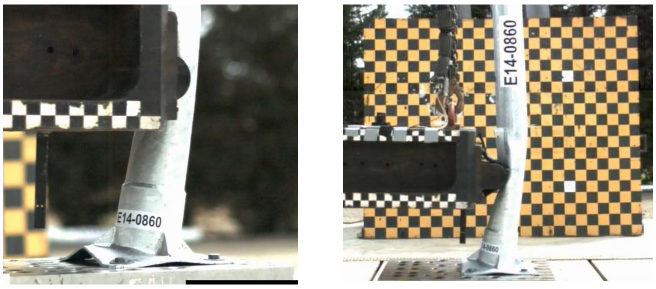


Figure 3. Pictures (detail and global view) of the impact tests.

The first two tests were carried out with the access door on the opposite side of the impact. In test #1, failure was observed to occur at the notch section. In test #2, the local bending induced by the impact at the bottom part of the streetlight, with longitudinal tensile stresses at the door side, gave rise to an unexpected failure at the welding of the door with the streetlight column (which can be seen in the picture of the global view of test #2 and with more detail in Figure 4). The rest of the tests were carried out with the access door on the impact side of the streetlight. No more failures occurred at the welding.

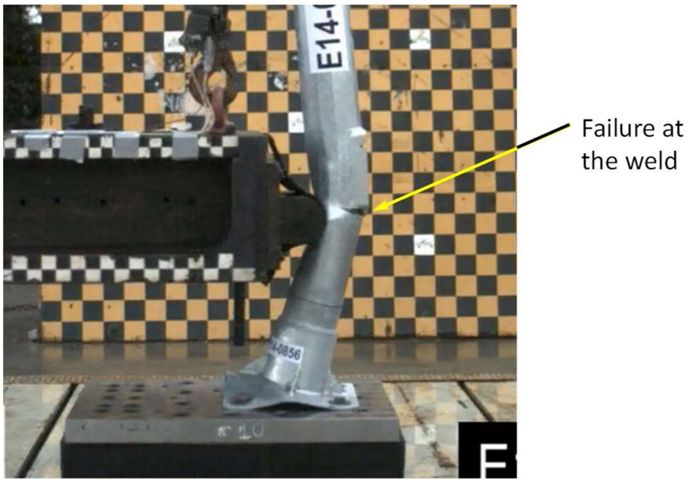


Figure 4. Detail of the unexpected failure at the weld seam of the access door (test #2).

The horizontal decelerations were measured by an accelerometer inside the impactor. The six impact test results (acceleration vs time) are shown in Fig. 5 for the interval 0ms<t<30ms (using the legend: R=radius and D=depth).

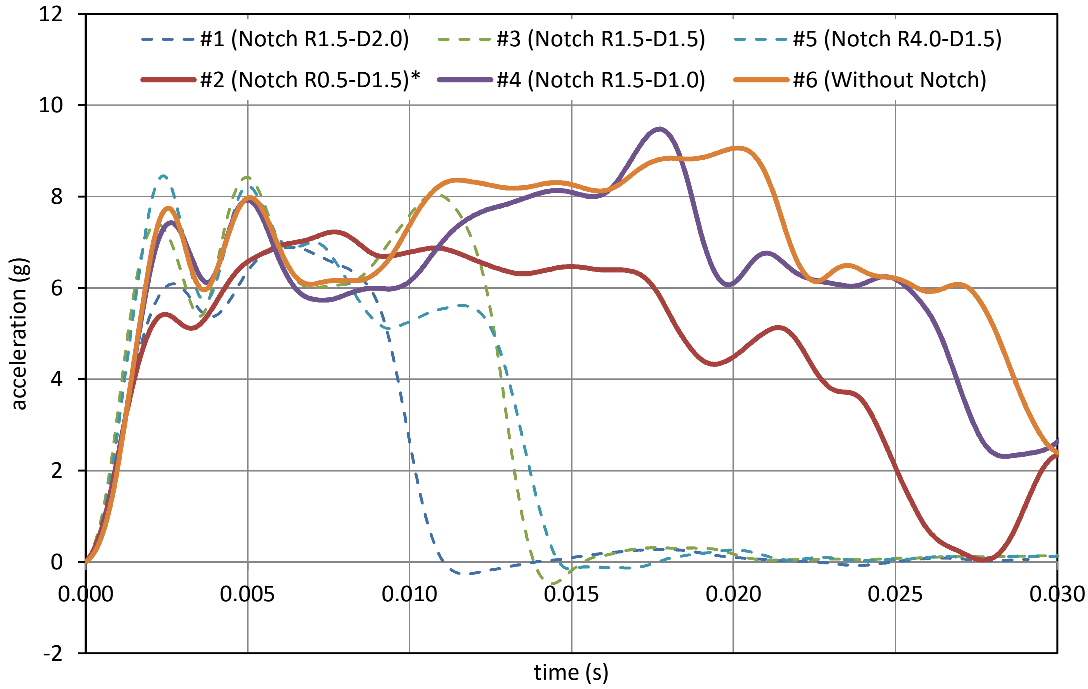


Figure 5. Acceleration during impact tests.

In Fig. 5, streetlights failing at the notch section are plotted with dashed lines, solid lines being used for the streetlights not failing at this section. Two key parameters have been extracted from the acceleration measurements, the maximum acceleration value, as an indicator of potential injuries to the vehicle occupants and the area under the acceleration curve as an indication of the energy absorption capability.

It is clear from plots in Fig. 5 that for streetlights failing at the notch section, the complete failure occurs in the first 15 milliseconds, no decelerations being recorded afterwards. Streetlights not failing at the notch section showed a much higher energy absorption capacity with deceleration values different than zero beyond 30 ms after the impact.

In Table 2, the maximum acceleration and area under the curve are summarized for the six tests.

Streetlights 1, 3 and 5 (which failed at the notch section) have an average value of the maximum acceleration of 7.92 g (with a Standard Deviation of 0.89 g and a Variation Coefficient of 11.3%). Streetlight 2 had, as mentioned previously, an unexpected failure, and therefore it will not be to calculate the average values of parameters in Table 2. It can be clearly seen in Fig. 5 that the curve corresponding to streetlight 2 is different to streetlights 4 and 6 (those not failing at the notch section) with lower maximum acceleration values. The average value for the maximum acceleration from streetlights 4 and 6 (those not failing at the notch section) is 9.27 g (with a Standard Deviation of 0.29 g and a Variation Coefficient of 3.2%), 15% higher than in the weakened specimen tests.

Table 2. Maximum acceleration and area under the impact curves (0<t<0.030s).

	Maximum acceleration (g)	Area (0 < t < 0.030s) (g·s)	Notch Section failure
Streetlight-1	6.89	0.05498	YES
Streetlight-2	7.22	0.14203	NO
Streetlight-3	8.42	0.08447	YES
Streetlight-4	9.48	0.18544	NO
Streetlight-5	8.45	0.08039	YES
Streetlight-6	9.06	0.20354	NO

The average value of the area under the curve for streetlights 1, 3 and 5 is 0.07328 g·s (with a Standard Deviation of 0.01598 g·s and a Variation Coefficient of 21.8%), while for streetlights 4 and 6 it is 0.19449 g·s (with a Standard Deviation of 0.01280 g·s and a Variation Coefficient of 6.6%), 62% higher.

Streetlights with a notch depth of 1.5 mm or higher failed at the notch section, regardless of the notch radius value (with the exception of streetlight 2, which failed by the welding seam). Thus, the weakening of the streetlight could be defined by the following depth (1.5mm) and the highest notch radius value as (r=4.0 mm) in order to minimize the stress concentrations for the static and fatigue load cases.

In Annex A, Finite Element Models are presented to calculate the stress concentration factors associated to the different notch geometries. In Annex B, the static strength and fatigue life are calculated for the final selected notch configuration (depth=1.5 mm and radius=4 mm). Results in Annex B show that the reduced section fulfills the design criteria (static and fatigue life).

5. Final remarks and conclusions

Streetlights are support structures which are not specifically designed to absorb energy in an efficient way during a vehicle impact. From the results obtained, which have to be taken only as a first assessment of the potential behavior of streetlights under impact, the machining of a circumferential notch at the streetlight base reduces both the acceleration peak (by about 15%) and the impact energy which can be absorbed (about 62%).

The excessive structural stiffness and structural strength of those streetlights already installed, allows the machining of the notch without reducing the structural stiffness of the streetlight and without reducing the structural strength below the required limits and as a result giving rise to reductions in the acceleration peaks.

Although crash tests according to EN12767 standards are mandatory for the certification of the support structure, the preliminary results achieved using a high energy pendulum have shown that this notch would effectively reduce the acceleration peak values and the energy absorption.

In countries where regulations require a protective barrier for each one of these roadside support structures, the implementation of this proposal would eliminate the need for the installation of said barriers, with the corresponding cost saving.

Acknowledgments

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[17] EN 1993 1-1. Eurocode 3: Design of steel structures. Part 1-1: General rules and rules for buildings. 2005.

ANNEX A: FEM models to evaluate the notch stress concentrations

The presence of the notch creates not only a reduced section, but also a stress concentration. A FEM 2D linear elastic analysis has been performed to evaluate these stress concentrations and the obtained results have been used to evaluate the fatigue life of the weakened section (Annex B).

A parametric model has been created using the commercial software ANSYS 13.0, with the depth and the radius of the notch as the model parameters. The model is 2D linear elastic using the axisymmetric option for the element (PLANE182) with the axis of symmetry at a distance equal to the section radius at the bottom of the streetlight. In Figure A1.a, the global geometry and the mesh used for the calculations are shown, the bottom part being clamped and the top surface with a uniform pressure wit unit value σ_{yy}=1, the symmetry axis is vertical at a distance r=135/2 mm at the left hand side of the planar model.

With the unit pressure loading, the σ_{yy} stress value at the notch tip directly represents the stress concentration factor (k).

To check that no numerical errors are introduced associated to the model discretization, the configuration with depth=radius=1.5 mm, has been compared with the available reference solution given in [13] (page 265, Table 6-1, type 3.b). The comparison takes into account that the reference solution in [13] has the force applied at the center of the reduced thickness (and not at the center of the total thickness), and assumes a 2D Generalized Plane Stress state. The difference between the corresponding numerical model and results in [13] being only of 1.6% which gives confidence on the mesh used for the FEM calculations.

Figures A1.b to A1.f are details of the σ_{yy} stress plots at the notch area.

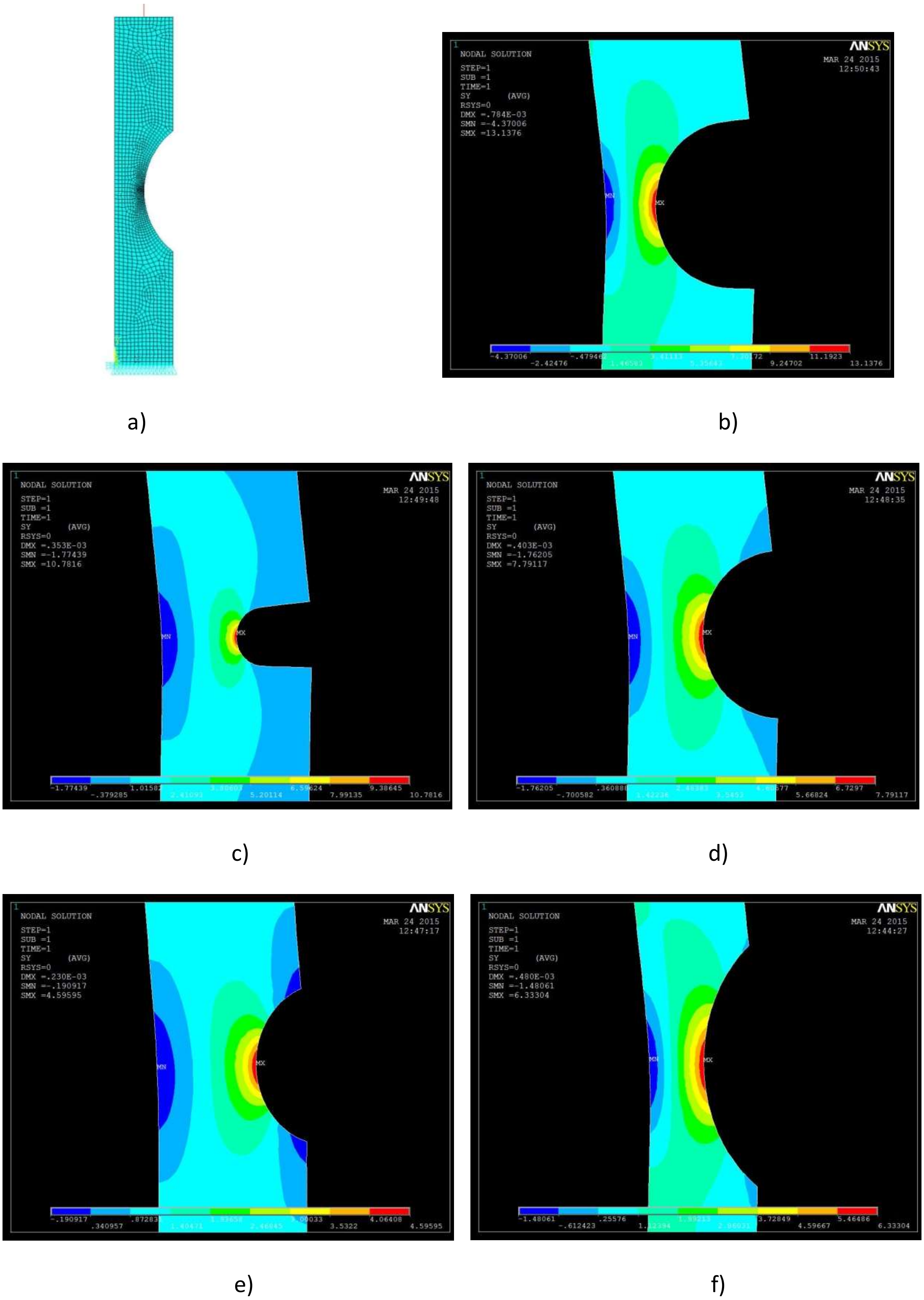

Figure A1. a) Geometry and FEM mesh, b-f) σ_{yy} stress plots corresponding to the notch geometries [r=radius / d=depth], b) [r=1.5/d=2], c) [r=0.5/d=1.5], d) [r=1.5/d=1.5], e) [r=1.5/d=1], f) [r=4/d=1.5].

Table A1. Stress (σ_{yy}) concentration factors (k) for the different notch configurations.

Plot	A1.b	A1.c	A1.d	A1.e	A1.f
Depth (mm)	2.0	1.5	1.5	1.0	1.5
Radius (mm)	1.5	0.5	1.5	1.5	4.0
Stress concentration k	13.13	10.78	7.79	4.59	6.33

ANNEX B: Residual static strength and fatigue life due to the notch.

The circumferential notch obviously reduces the mechanical performance of the streetlight. In this Annex the static strength and fatigue life reduction has been addressed. The calculations have been carried out using the following Standards:

EN 40-3-1 (Lighting columns. Part 3-1: Design and verification. Specification for characteristic loads) [14].

EN 40-3-3 (Lighting columns. Part 3-3: Design and verification. Verification by calculation) [15].

The loads used for the calculations are the wind loads, which are calculated using EN 1991-1-4 (Eurocode 1: Actions on structures. Part 1-4: General actions. Wind actions) [16]. For the verifications (due to the fact that the streetlight is made of steel), it is also used the standard EN 1993 1-1 (Eurocode 3: Design of steel structures. Part 1-1: General rules and rules for buildings) [17].

Static strength.

The standard EN 40-3-3 [15] calculates the bending strength associated to the wind loads and the corresponding bending moment associated to a particular wind condition. A reference wind speed of 100 km/h and a default terrain category equal to II has been used for the calculations. The calculations are particular for the geometry of the streetlight used for the study (3 mm thickness, 6 meters height, 135 mm diameter at the bottom and 60 mm diameter at the top). The reduced section used to do the calculations is the final notch configuration used in the tests (depth=1.5 mm and radius=4.0 mm).

The calculated bending strength $M_{ux} = M_{uy} = M_{up}$ (EN 40-3-3, part 5.6.2.1) for the reduced section is equal to:

$$M_{ux} = M_{uy} = M_{up} = \frac{f_y \phi_1 Z_p}{10^3 \gamma_m} = 7160\ Nm \qquad \text{(B.1)}$$

where f_y=275 MPa is the characteristic strength of the material, ϕ_1=1 is obtained from figure 2 of the standard EN 40-3-3 [15], Z_p=4R^2t=27337 mm^3 is the plastic modulus of the section (calculated using the reduced thickness of the notch section, 1.5 mm) and γ_m=1.05 is obtained for Table 2 of the standard.

The bending strength for the original 3mm thickness wall section is 14320 Nm (Z_p is linear with the thickness), thus, the presence of the notch with a depth of 1.5 mm, reduces a 50% the bending strength.

The bending moment M corresponding to the reference wind speed is calculated multiplying the resultant wind force $F_1 = A_1 c q(z)$ (EN 40-3-1 [14], part 4.1.3) by the distance d measured between the center of the wind pressure distribution and the notch section. For the streetlight under study, A_1=0.585 m^2 is the projection of the area of the streetlight in a plane perpendicular to the wind direction, c=0.98 is the shape factor associated to the circular cross-section of the streetlight, $q(z)$=897.6 N/m^2 is the design wind pressure calculated (following the indications of the standard) at the center the streetlight, assuming a reference wind speed of 100 km/h (and a default terrain category equal to II), and d=2.615 m, as explained before.

$$M = F_1 \cdot d = \left(A_1 c q(z)\right) \cdot d = 1242\ Nm \qquad \text{(B.2)}$$

The static reserve factor M/M_{up}=0.17 is very low for the weakened section and, consequently, the presence of the notch does not significantly affects the static strength of the streetlight.

The reference wind speed necessary for the bending moment at the notch section to reach the maximum allowable value of 7160 Nm, would be equal to 240 km/h.

<u>Fatigue life</u>

The Standard EN 40-3-3 [15] does not address a fatigue life calculation procedure for streetlights with a height below 9 meters. Some indications are given in Annex A of the standard [15], but these verifications are specifically given for welded details and streetlights higher than 9 m. The location of the notch is far enough from any weld seam, thus the fatigue life of the welded details can be considered not to be affected by the presence of the notch.

As mentioned at the end of the "Results and discussion" section, among those streetlights failing at the notch section, that with the highest radius (r=4 mm) has been chosen to minimize the notch stress concentrations. The three notch configurations with the same notch depth (1.5 mm) have shown similar impact characteristics, but low values of the notch radius give rise to higher stress concentrations. The notch with depth 1.5 mm and radius 4 mm has shown (FEM linear elastic analysis in Annexe A) to have a stress concentration of k=6.33 (same depth=1.5 mm and lower notch radius, give rise to higher stress concentration values, k=7.79 for r=1.5 mm and k=10.78 for r=0.5 mm).

For design purposes, and for wrought steels with a static strength σ_R<1400 MPa (which is our case: S275, σ_R=340 MPa), it is widely accepted the use of a simplified SN curve (see Fig. B1) with a logarithmic scale in the *x*-axis, having 0.9 σ_R = 306 MPa at N=10^3 and 0.5·σ_R = 170 MPa at N=10^6 as the fatigue limit.

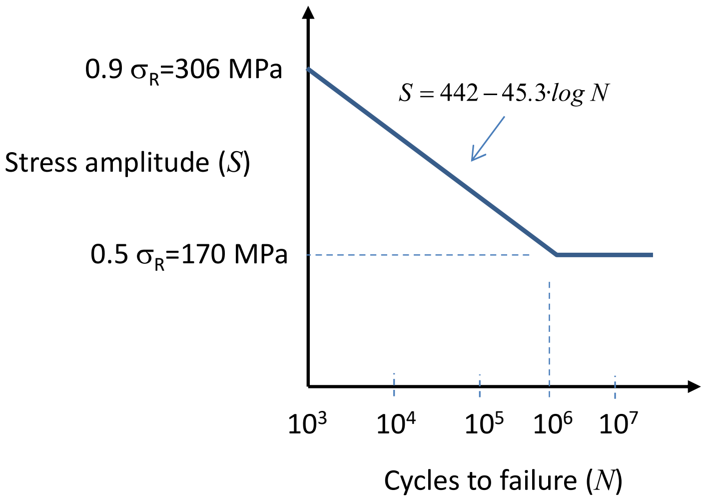

Figure B1. Simplified SN curve for fatigue life calculation at the notch section.

In the absence of a particular load spectrum for these types of streetlights, we will assume a continuously alternating wind, between 0 and v_{ref} (km/h). The maximum stress amplitude being evaluated at the notch section for the reference wind speed v_{ref} using the nominal stress value given by the Strength of Materials equation ($\sigma_{yy}=N/A-M/W$), amplified by the notch stress concentration factor (k):

$$\left|\sigma_{yy}^{max}\right| = k\left(\frac{N}{A} - \frac{M}{W}\right) \qquad (B.3)$$

Where N is the axial force (due to the weight of the streetlight), A is the cross-sectional area of the reduced section of the streetlight, M is the bending moment at the notch section due to wind load (B.2), and W is the elastic section modulus at the reduced notch section.

Table B1 shows the fatigue life calculations (N, cycles to failure), based on the simplified SN curve (Fig. B1) and different reference wind speeds (v_{ref}) giving rise to different maximum σ_{yy} values (B.3).

Table B1. Fatigue life calculations for the reduced notch section.

v_{ref} (km/h)	Max σ_{yy} (B.3) (MPa)	N (cycles to failure)
60	142	∞
70	194	$2.9 \cdot 10^5$
80	254	$1.4 \cdot 10^4$

In order to illustrate the calculated fatigue failure, based on the hypothesis of a continuously wind speed change (from 0 to v_{ref}) during the whole life, 25 years, of the streetlight, the number of changes per day associated, for example, to the v_{ref} =70 km/h would be 32 changes per day (daily, during 25 years), which looks pretty unrealistic to occur. In the case of v_{ref} =80 km/h (a much lesser probable average value for the reference wind speed), 1.5 changes per day, would be necessary, being also a quite unrealistic scenario.

Thus, the selected notch geometry (depth =1.5 mm and radius=4 mm), does not seem reduce the fatigue life below a realistic threshold value. Of course, detailed fatigue life calculations should be performed for any other streetlight configuration (height).