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Structural Integrity Problems in Dual-Phase High Ductility Steel Bar

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Abstract

In EU regions with intense seismic activity imposing building code improvements like the EC2 and EC8-part3, introduced the use of high performance reinforced steel for example the dual phase B500c steel bar. In particularly earthquake-prone areas, like Greece has been over the past decade, the use of steel B500c is exclusively used in all structures from reinforced concrete. The present study focuses on investigating the mechanical behaviour of the material in the elastic region, through a series of mechanical tensile tests. In the elastic region of most of the steel specimens (15 pre-corroded and 5 non-corroded) a “knee” was observed which appears to be related to the localized detachment of the martensitic cortex from the core of the material. The interesting mechanical behaviour at the interface limit of the martensitic and ferritic-perlitic core on B500c steel bars, was further examined by performing (non destructive) ultrasound testing (C-Scan) and failure analysis using SEM, which led to the confirmation of the structural internal failure.

Keywords: Dual-phase; Steel bar; Martensite; ferriteperlite; Chloride induced corrosion; Structural integrity

Introduction

The main reason that over the last decades the global industry (automotive and aerospace) has adopted the use of dual-phase steels was to ensure high mechanical performance combined with low cost [1]. The severity and the extent of the disaster that was reported after powerful earthquakes (Northbridge in the USA on the year 1994, Kobe in Japan on the year 1995), on construction sites that used reinforced concrete, troubled and taught engineers.

Consequently, the global scientific community took actions to improve the existing regulatory laws affecting the design and construction practices, as well as the materials and the geometry of the structural load–bearing elements. The designing requirements based on the new requirements and principals, obliged the European Union to use dual high performance steel such as the S500s and B500c. The upgraded mechanical performance of the dual-phase steel used in reinforced concrete is achieved through the ideal combination of yield strength Rp and the ductility property (elongation at maximum load Agt) of the material. Similar reformation initiatives concerning the framework that specifies the regulations and the standards of the materials used in construction are taken on by an increasing number of countries.

As it is known, dual-phase steels of reinforced concrete show an outer high strength core (martensitic phase) and a softer core (ferrite-perlite phase), Beyond these two obvious phases, there is a transition zone called bainite phase. The mechanical performance of B500c steel results from the combination of the mechanical properties in each of the individual phases, where the increased strength properties are credited to the presence of the outer martensitic zone whereas the increased ductility in the presence of the ferittoperlitic core.

The need to regulate effectively and reliably similar seismic activity triggered the establishment of demanding codes regarding reinforced concrete constructions and respectively strict standards for the materials used.

The demand for constructions with high mechanical performance in earthquake prone areas of the EU was expressed through EC2, EC8-part3, and is currently mainly served by the use of dual phase B500c steel bar. The mechanical properties of the dual-phase steels present interesting results not only when they are sufficiently protected from corrosion but also from the initial phase of their corrosion.

In coastal locations such as Greece, Turkey, Romania, Italy etc., the climate conditions constitute one of the most aggressive environments for concrete structures due to the severe ambient salinity, high temperature and humidity and also due to the ingress of chlorine through wind-borne salt spray. Chloride induced damage of reinforced steel results in concrete cracking and spalling, destruction of the protective steel barrier and formation of pits as well as notches and cavities on the steel surface. Durability is one of the most important merits of using reinforced concrete; however formation of cracks causes corrosion of the steel bars and initiation of a serious problem, which becomes more severe in harsh environments. Even though the impact of corrosion on the strength of steel reinforced bars is well known the current design practices do not face the problem since they are unable to quantify it and need further review. It has been attempted to quantify corrosion and mass loss of steel with the reduction of its mechanical properties [2-5]. A stable and predictable mechanical reaction of corroded reinforced steel remains to be further explored. The mechanical behavior of dual-phase steel (tempcore) like S500s and B500c, before and after corrosion, is analyzed in the papers [3,5,6].

A macroscopic view, in the interface limits between the borders of the two phases of these steels (the external martensitic skin and the ferritic-perlitic core) would lead to an assumption that the continuity between the phases is predictable and guaranteed, yet from a metallurgic point of view, this does not seem to be true. In reality, in the cases of dual phase steel products, the interface between the core (ferrite–perlite

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zone) and the martensitic skin is often not continuous because these are distinct areas of different types of crystallic structure and there are different types of mechanical behavior on each phase of the material.

Dual-phase (DP) steels which are produced by the intercritical heat treatment of low carbon steels possess a composite microstructure consisting of martensite dispersed in a softer phase known as ferrite [7]. The mechanism of failure of DP-steels reportedly occurs in a ductile manner by void nucleation, growth, and finally coalescence [7]. The fracture mechanics approach, which is based on a well-founded mathematical background, fails to address this aspect of failure due to several reasons. Thus, Al-Abbasi and Nemes [7], report that: The most important reason is that the basic philosophy in the conventional fracture mechanics, which uses global fracture parameters such as the J-integral, works only in some limited cases, and often the assumption of the existence of a macroscopic flaw in the material does not correspond to the real material at hand and thus does not account for the characteristics of the material.

This paper will deal with faults that occur at the interface of martensitic and ferritic-perlitic core samples, of the dual-phase steel Φ10 B500c, before and after corrosion.

Microstructure DP-Steel B500c

A low carbon DP-steel bar the type B500c consisting of exterior martensite zone and interior ferrite–perlite core is used in this work. The above material was received in the form of a steel bar of diameter 10 mm. According to ELOT 1421-1 standard (ELOT 1421, 2004) the chemical composition of B500c steel in maximum by weight permissible values are: C=0.24, S=0.055, P=0.055, N=0.014, Cu=0.85 and the equivalent carbon content Ceq=0.52. According to the same standard, the requirements for the material are: Yield strength ≥ 500 (MPa), 1.15 ≤ Rm/Rp ≤ 1.35, and the elongation at maximum load ≥ 7.5%. The heat treatment procedure of B500c steel bar (Quenching with tempering, etc) can be found in paper [6].

Figure 1 shows representative optical micrographs of a DP-steel B500c produced in this work, that were etched revealing the martensitic skin, the transition zone and the ferritic-perlitic core, upon immersion in a nital solution 2%. The martensitic percentage of the Φ10, B500c rebar was calculated at 24%. In the microstructures shown in figure 1, the bright grains are the ferrite phase and the dark ones are the martensite.

Fracture Mechanism of Dual Phase Steel

Although the view that the coexistence between the phases of the martensite and the core (interface limits) appears to be sustained and cohesive this is not however from a metallurgic point of view the case. Reality lies in the fact that the interface is not coherent in the boundaries between the ferritic-perlitic zone as it is a region of different crystal types with subsequently different mechanical properties.

It is well known that many researchers have reported the ductile failure mode of dual phase steels with major reports by Rashid [8], Rashid and Cprek [9], Gladman [10], and Balliger [11] who attributed the failure to void formations resulting from the fracture of martensitic elements and the detachment from the interface of the martensitic and ferritic-perlitic zone.

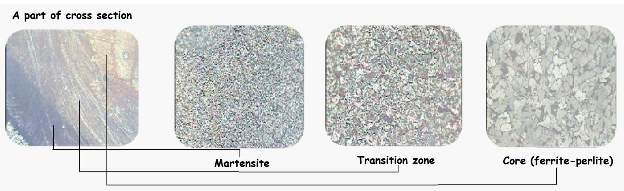

Figure 1: Phases of steel in a cross section after being etched with Nital.

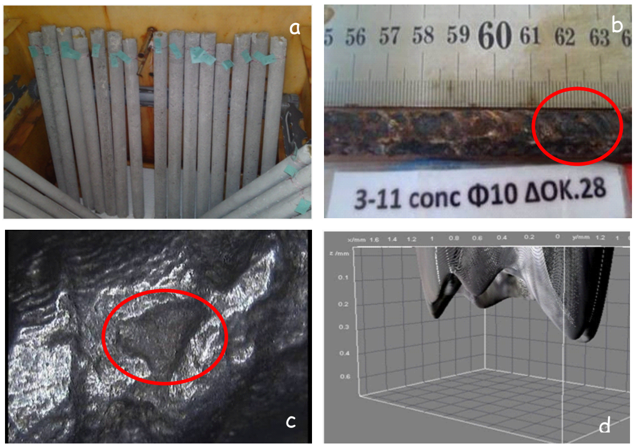

Figure 2: Accelerated corrosion chamber (a) and pit corrosion inspection (b), (c), (d).

Steinbrunner et al. [12], conducted a micro mechanical study so as to investigate the process of failure in dual phase steels and observed three mechanisms of void formation, namely, the detachment of interfaces, the fracture of martensite and the individual withdrawal of the martensite.

Kang and Kwon [13], studied the fracture behavior of steel structure (in medium carbon steels) and observed that the ferrite-martensite interface decohesion was the predominant mode of void nucleation and growth, where martensite structure was the lath type.

Nam and Bae [14], showed that the overwhelming findings of the reports show that most of the voids that lead to fracture, were formed in the core – martensite interface, despite the initially cracked martensite.

Ahmed et al. [15], mention 3 ways of void formation in grains: Martensite cracking, detachment of the ferrite-martensite interface and detachment of the interface. They associate the failure mode with the percentage of martensite content in the cross section and report that for a medium to low percentage of martensite Vm content, the void formation results from the detachment of the ferrite-martensite interface, while the other two mechanisms appear in higher rates of martensite (Vm more than 32%).

Experimental Procedure and Results

From 20 reinforced steel B500c specimens, with a 10 mm diameter and 510 mm length each, 15 were prepared in cylindrical shape with peripheral concrete with cover at 10mm and compressive strength of 20 MPa, class C16/20 with cement type IV/B-(WP) 32,5 N.

Laboratory accelerated salt spray corrosion tests, were conducted at 35 ± 1.1-1.7°C temperature using sodium chloride solution with concentration of 5% by mass in distilled water, according to ASTM-B117 standard [16]. The pH value of the sprayed solution after its liquidation ranged between 6,5-7,2 and the corrosion procedure was carried out at a cycle time of 3 hours resulting in 8 wet-dry cycles per day.

In figure 2a, the placement of specimens in the chamber is

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presented. The initial mass of each specimen was measured using a precision scale (± 0.01gr), before the encapsulation in concrete, as well as after the corrosion process and the removal of the concrete cover, where cleaning procedure was performed according to ASTM-G1 standard [17].

Figure 2b and 2c present corroded steel bar upon the removal of the concrete coverage and show the surface of this bar after cleaning the corrosion products. In figure 2c it is worth observing the creation of intense pits due to chloride attack which appear from the very first phase of corrosion and in image 2(d) its 3D depiction (pit depth 0,35 mm) produced with the use of Image J analyses.

Mechanical tensile tests were conducted in B500c bars, according to the ISO 15630-1 standard [18] in a servo hydraulic MTS-100kN test system which is equipped with an automatic controller with a cross head speed of 2 mm/min at room temperature.

In figures 3 and 4 indicative stress strain diagrams of tensile test in B500c steel bars are presented before and after corrosion exposure. In the majority of stress strain diagrams a "knee" was observed in the elastic region, both in non corroded and corroded bars. Figure 3a and 3b depict a tensile test of a non corroded steel bar and figure 4a and 4b of a corroded steel bar (sample 27).

By examining a series of stress-strain diagrams in which "knee" occurred in the elastic region of Φ10 steel specimens in both non corroded and corroded embedded steels the following findings were revealed:

• In non-corroded specimens "knee" occurs in regions at a stress up to 420 MPa.

• In embedded specimens that have been subjected to laboratory salt spray corrosion with a mass loss rate of 0,46%, the "knee" occurs in regions between 350 MPa and 400 MPa.

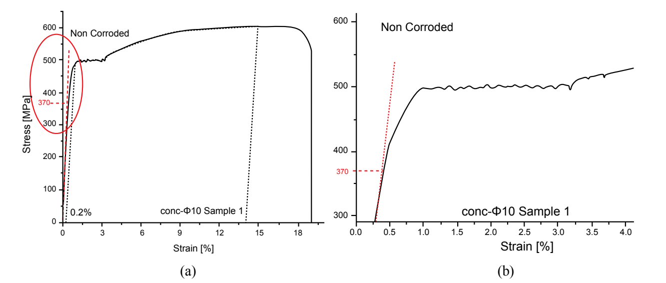

Figure 3: Indicated stress-strain diagram of non corroded steel bar.

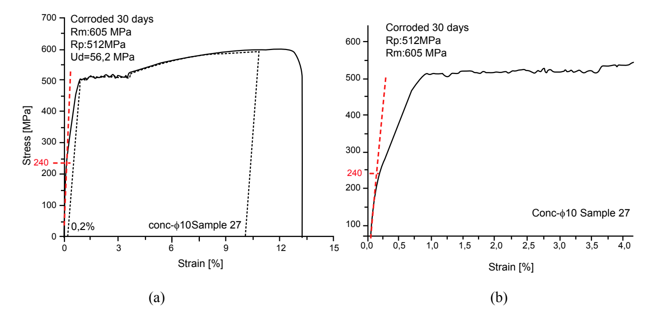

Figure 4: Indicated stress-strain diagram of a corroded steel bar.

Sample	Rp (MPa)	Rm (MPa)	Rm/Rp	U (MPa)	Ag (%)	Corrosion Exposure (Days)	Mass Loss (%)
Mean value of non corroded specimens	539,5	627	1,16	80,85	13,83	0	0
16	528	620	1,17	70,8	12,15	15	0,47
17	523	612	1,17	56,32	9,91	15	0,56
18	527	615	1,17	51,7	7,8	15	0,46
19	528	620	1,17	80,16	13,82	15	0,46
20	552	634	1,15	71,2	11,87	15	0,34
Average	531,6	620,2	1,17	66,04	11,11	-	0,46
21	536	616	1,15	50,66	8,8	30	1,75
22	534	617	1,16	50,03	9,65	30	2,03
23	525	608	1,16	64,0	11,07	30	2,51
24	532	615	1,15	50,28	8,84	30	1,59
25	513	606	1,18	56,68	10,3	30	2,1
26	517	608	1,18	72,62	12,7	30	1,47
27	512	605	1,18	56,2	9,98	30	2,23
28	527	608	1,15	59,31	10,2	30	2,77
29	534	611	1,14	60,29	10,53	30	2,11
30	518	607	1,17	61,59	11,57	30	1,72
Average	524,8	610,1	1,16	58,17	10,36	-	2,03

Table 1: Presents the mechanical properties and the mass loss of steel specimens.

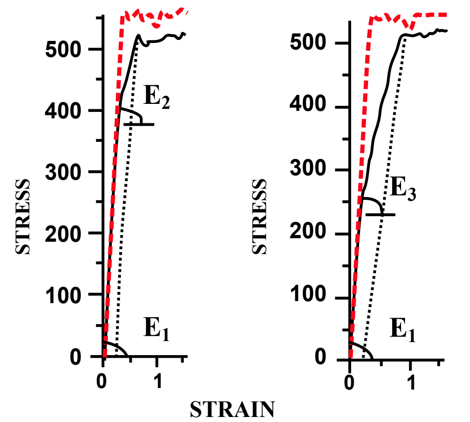

Figure 5: "knee" occurs in different positions in non corroded and corroded specimen.

• In embedded specimens subjected to laboratory salt spray corrosion with average mass loss of 2%, the "knee" occurs in regions below 350 MPa (Table 1).

Figure 5 illustrates the gradual deteriorating response of the material and the degree of its corrosion. The initial Young's modulus E1, appears to take each time different values E2 and E3 in respect with the gradually imposed loads on the corroded material. As a result the respective value of yield stress point corresponds to an increased strain.

Summarizing, the response of the material in the elastic region (before and after corrosion), it can be concluded that the strain corresponding to the yield value appears more and more increased with the degree of corrosion.

The occurence of "knee" in the elastic region of the reference specimens, led to further tests. For this reason, after perfoming tensile test in non corroded (reference) rod B500c Φ10, until the necking initialization on the material, (cross sections of 10mm each were cut succesively along the bar's length. After numbering the samples as shown in figure 6 and figure 7a, they were then tested with the non-destructive method of ultrasound C-Scan (Figure 7b). Ultrasound examination was performed so as to detect and evaluate any internal discontinuities in the structure of the bar. The examination showed that the samples with numbers 1,2,3,4,5,6,9,10,11,12 showed a structural defect in the interface of martensitic and feritoperlitic cortex as shown in figure 8.

However, the occurrence of "knee" in the elastic region along with the results (qualitative nature) of ultrasound process, raised serious "hinds" regarding the non consistent bonding of the martensitic cortex and the core which led to further investigation. So as to eliminate the possibility of structural defect in ferritic perlitic core of B500c, three mechanical tests were performed in non corroded specimen which had previously been lathed till they reached a 4mm diameter a point at which only the core remained. Figure 9, depicts a lathed specimen

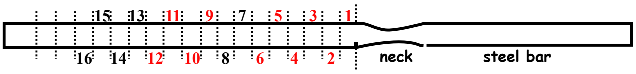

Figure 6: Sample mapping.

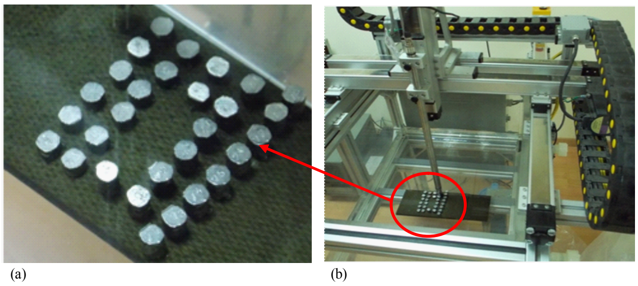

Figure 7: Ultrasound inspection of samples.

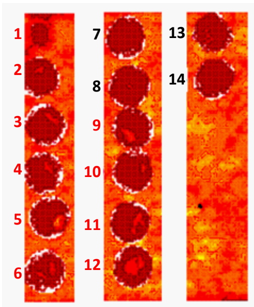

Figure 8: Ultrasonic C-scan results.

Figure 9: Lathed specimen till core remains.

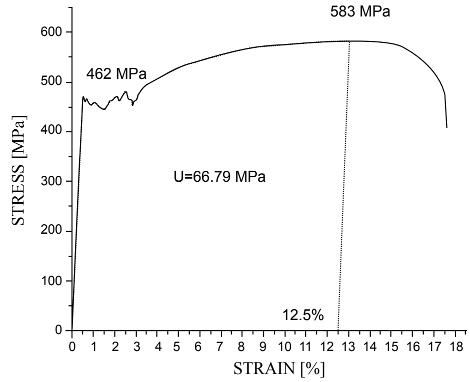

Figure 10: Stress-strain diagram of lathed specimen.

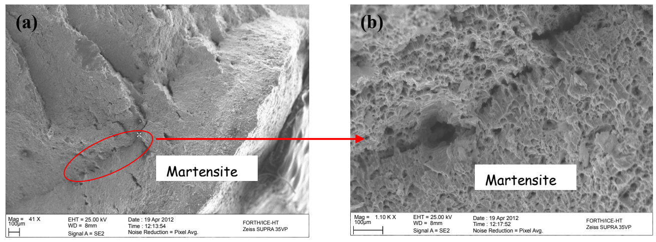

Figure 11: The detachment of the corroded martensitic skin can satisfactorily explain the formation of the "knee" in the elastic region. Focus on the boundary between the martensite and the core of the cross section.

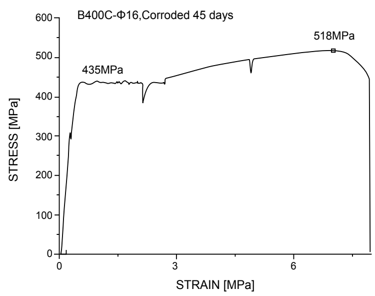

Figure 12: Indicative diagram of a pre-corroded dual-phase B400c (σ-ε) steel where the regions with fast relaxation in the elastoplastic region can be noted.

and figure 10 presents its respective stress-strain diagram after a tensile test. In none of the three diagrams of the lathed specimens, did a "knee" occur in the elastic region.

Excluding structural defect in the core of the material, the interest was focused on the examination of the fracture surface on the interface of the martensitic skin and the core,using Scanning Electron Micrographs analyses. Figures 11a and 11b clearly show a localized detachement in the interface of the martensite and the internal core of the precorroded material. In figure 11, the crack is located in a distance of approximately 700 μm from the external surface of the steel bar which coincides with the average thickness of the martensitic cortex in dual-phase steel B500c with a nominal 10mm diameter.

Taking these results into account, it can be suggested that the mechanical performance of the particular series of steel specimens was not reliable.

In addition the results of other tensile tests like B400c, Φ16 (with a nominal 16mm diameter), also appear local irregularities close to the yield stress point and in the elastoplastic area as is indicated in figure 12. The B400c, Φ16 steel is also dual phase with a percentage of martensite in the cross section up to 27.50%.

Conclusively it appears that mechanisms like debonding and decohesion may initiate in several locations and in some of them lead to a complete detachment of the two metallurgical phases (Figure 11).

Discussion

Despite the consideration that for a full investigation of this topic an examination of the reference material-before the imposition of any charge or before its corrosion-with SEM remains to be made, it can be noted with an account of the so far results that: The response of the material of steel in the elastic region, that is the creation of "knee", may be resulting from the way it is produced.

The gradual decline of the recorded stress in which the "knee" occurs, appears to be associated with the degree of corrosion of the material. This phenomenon may be attributed to the corrosive agent that is responsible both for the gradual "softening" of the martensitic zone and for the development of pitting corrosion on the surface which increases with regard to the degree of corrosion. The synergy of these two functions seems to be acting as a factor for further degradation of the material.

The previous reports concerning the failure mechanisms of two-phase steels confirm the failure mode of dual phase reinforced steel Φ10, B500c (from the SEM) in the present tensile test, since the percentage of martensite in this steel was measured to be below 32% (steel of medium and low content of martensite). By performing SEM analysis it can be verified that the failure occurs mainly due to the detachment of the interface between the ferrite and martensite phase.

From the stress-strain diagrams of the samples which exhibited "knee" it appears that the yield point of the steel corresponds to strains within a range of 0.5% and 0.9%. The corroded specimens showing "knee" at low stress, present larger strains at their yield point compared to the non-corroded ones (Figure 5).

Admittedly, the mechanical properties and performance of steel and concrete play a significant role in the way structures from reinforced concrete are designed. In this sense, the steel is calculated (obtained) with a maximum deformation of 0,2% in its initial state of yield point and respectively the concrete with a maximum deformation of 0,35% before the fracture. Given that a reliable estimate of any construction of reinforced concrete is subject to meeting these constraints, a question of credibility is raised at least for the "batch" of steel tested in this study.

In the paper Apostolopoulos et al. [19], a similar pattern of detachment of the martensitic cortex at a Φ8, B500c steel rebar was recorded, which also presented a martensite percentage lower than 32%.

Following the findings of the present study, a further investigation of the structure of the original reference material as well as an extension of this investigation to larger cross sections remains to be made. This train of thought is based on the findings from the experimental study Apostolopoulos [20], in which it is illustrated that the percentage of the martensitic zone is increasing when there is an increase of the cross section of the steel bar. In this case, it seems interesting to explore the elastic region of a dual phase B500c steel, with a martensite rate larger than 32% before and after various degrees of corrosion. This is because, by increasing the degree of corrosion, (among other things) the decrease of the active surface can be noted, a fact which is interrelated with the decrease of the martensitic cortex rate.

Nowadays, within the countries of the European Union with intense seismic activity, the use of dual-phase steel (especially tempcore B500c) is widely used on reinforced concrete constructions from steel reinforced concrete. Although the use of dual phase steel is perceived from an engineering point of view as a cohesive material with a fairly powerful interface between the metallurgic phases it appears that certain phenomena occurring in the interface between the martensitic skin and the ferritic-perlitic core, present interesting characteristics in their mechanical behavior.

Conclusions

The following conclusions can be drawn from the present study:

- The dual phase reinforced concrete Φ10, B500c steel bars subjected to tensile test presented "knee" in the elastic region.
- The "knee" point in the elastic region of the tensile test performed in dual phase B500c steel appears to be gradually decreasing in correlation with the rate of corrosion.
- In dual phase Φ10, B500c steel bars with martensite content in the cross section below 32%, the failure is obviously interrelated with the detachment of the martensite cortex from the core.
- The structure of the Φ10 B500c between the core (ferrite–perlite zone) and the martensitic cortex is not continuous since these are distinct regions with different grains and different mechanical behavior of each metallurgic phase.

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