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A NEW HYBRID TESTING PROCEDURE FOR THE LOW CYCLE FATIGUE BEHAVIOR OF STRUCTURAL ELEMENTS AND CONNECTIONS

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Abstract*. The current test recommendations adopted for the assessment of low cycle fatigue of steel building elements and detail are briefly described, and some disadvantage and incompleteness of these procedures are discussed, particularly in what regards the ultimate bearing capacity and the difficulty to represent the cumulative displacement behavior of elements and details in one direction. In order to overcome these problems, a new testing procedure is proposed, whose aim is to take explicitly into account the actual exercise load and its influence on the cyclic behaviour, particularly for the cumulative displacements, and on the effective collapse condition. The proposed cyclic test is a hybrid procedure where the sequence of reversed cycles have an initial force-controlled part, up to the applied vertical load, and a final displacement-controlled part.*

1 INTRODUCTION: TYPES OF CYCLING TESTING

To characterize or to model a structural element or a structural detail for which the expected load condition is characterized by a cyclic loading history with known or unknown amplitude as, for instance, for a structure in seismic area, a *Cyclic Test* is necessary.

Dynamic Tests with shaking machines or shaking tables simulate effectively dynamic loads or seismic events, but they are generally very expensive. *Pseudo-Dynamic Tests*, characterized by the application of variable step-by-step static forces in order to simulate the dynamic behaviour, provide a realistic seismic simulation using an equipment considerably less expensive than the shaking table, but are suitable only for structures that can be easily modelled with a few degrees of freedom (one or two storey frames, etc.) A *Quasi-Static Cyclic Test,* whose apparatus is the most common in research laboratories, is less suitable to simulate seismic load conditions, but it is simple and less expensive.

2 LOW CYCLE FATIGUE TESTING: STATE OF THE ART

In order to assess the state of the art on low cycle fatigue testing of structural elements, a research was done through the Internet, the Scopus search engine (web-based abstract and citation database provided by Elsevier) and through the proceedings of the World Conferences on Earthquake Engineering and other Conferences. The research, limited to the last 20 years, resulted in about 200 articles/papers found, the majority of them from European or North American universities, and a significant number from Japan. Two official procedures seem to be mainly used: the 1986 European ECCS-45 (European Convention For Constructional Steelwork "*Recommended Testing Procedure for Assessing the Behaviour of Structural Steel Elements under Cyclic Loads)* and the six years younger North-American ATC-24 (Applied

Technology Council-24 *"Guidelines For Cyclic Seismic Testing of Components of Steel Structures")*. Moreover some recent papers adopt the new procedures from ANSI, mainly ANSI/AISC 341s1-05 appendix S of November 2005. There is also a more recent testing protocol, FEMA 461 (June 2007) *Interim Testing Protocols for Determining the Seismic Performance Characteristics of Structural and Non-structural Components.* Nevertheless many papers, especially from Japanese authors, don't indicate explicitly an official procedure, but apply loading histories defined in the paper, generally similar to the ECCS or ATC-24 protocols. The majority of the structural elements tested are beam-to-column connections. The other elements tested are heterogeneous, with particular relevance to the testing of composite columns and to the cyclic behavior of braces.

3 GEOMETRY OF SPECIMENS

To achieve an adequate knowledge of the cyclic structural behaviour of a steel structure by means of quasi static testing, the first step is to define the "minimum sub assemblage" that should be tested. For a framed steel structure, the minimum sub-assemblage is a two storey (two bays and two naves) spatial frame, with concrete slabs at each floor level. This specimen contains beams, columns, two, three and four ways beam-to-column joints and can be loaded vertically, to simulate gravity loads, and horizontally, to simulate earthquake loading. It is a complete specimen, but it can be tested only in special circumstances. A first simplification could be the testing of part of the sub-assemblage, a two bays, two storeys plane frame. As the most critical details, whose cyclic behavior should be investigated, are usually the beam-column joints, the next step toward a simplification is to consider a single node of the plane frame, with part of a column and part of a beam. This test setup is simple, it is the less expensive, but it is the less complete. The test configuration can be a horizontal T, with vertical column and horizontal beam, or an inverted T, with horizontal column and vertical beam (Fig. 3.1).

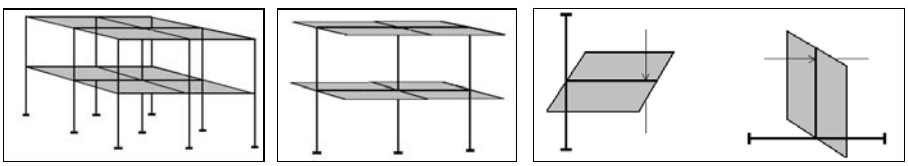


Figure 3.1: Spatial frame, Plane frame sub-assemblage and Testing setup outline for horizontal T and inverted T specimens.

The effects of the gravity loads acting in the real structure, in the usual testing procedures are generally neglected because it is difficult to apply them on the T specimen. The shear force and the bending moment due to gravity loads determines in a real node cyclically loaded a cumulative deformation in one direction. The current experimental recommendations fail to address the unsymmetrical displacement histories experienced by beam-to-column connections, as well as the governing phenomena.

4 ECCS-45 RECOMMENDATIONS

ECCS-45 recommendations were published in 1986, and no update followed that first edition. After the assessment, according to a proper definition, of the yielding loads F_y^+, F_y^- and the yielding displacements e_y^+, e_y^- in opposite directions, the protocol provides groups of three cycles with increasing imposed displacement in the $(2+2n)\, e_y^+ \div (2+2n)\, e_y^-$ interval with $n = 0,1,2,3,....$ up to the end of the test. The unsymmetrical demand on structural elements due to long duration actions which have no reversal in sign (e. g. gravity loads) can be taken into account performing the test with a partial reversal of displacements, that can be of various forms and must be properly justified. There is not any definition of collapse in the ECCS-45 recommendations. Regarding the end of the test, it is only specified that the test may be stopped at any level of displacement, decided with regard to specific code or research requirements. Nevertheless in order to compare the capacity of specimens, the adoption of a conventional collapse definition is needed, but there are different approaches concerning this subject. This fact is considered one of the main disadvantages of the ECCS procedure.

5 ATC-24 RECOMMENDATIONS

The *Applied Technology Council* (ATC) in 1992 published the ATC-24: *"Guidelines for Seismic Testing of Components of Steel Structures"*, specifically for experiments with slow cyclic load application. The recommended loading history to be applied, quite similar to ECCS-45, consists of stepwise increasing displacement cycles symmetric in peak displacements (Figure 5.1). At least six cycles are with a peak displacement less than δ_y (yielding displacement), then there are three groups of three cycles each, with displacement respectively δ_y, $\delta_y+\Delta$ and $\delta_y+2\Delta$. The experiment continues with groups of two cycles with peak displacement $\delta_y+3\Delta$, $\delta_y+4\Delta$ and so on until collapse.

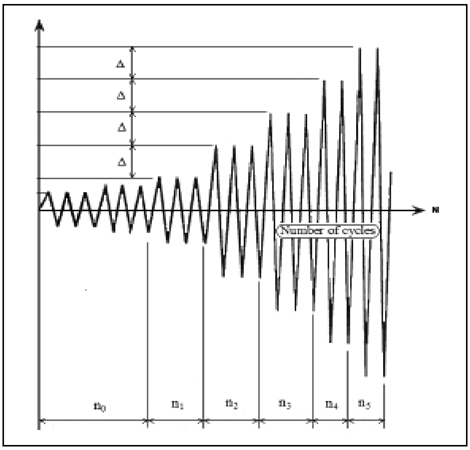


Figure 5.1: ATC-24 loading history

While ECCS-45 indicates only the recommended testing procedure, ATC-24 provides an additional commentary with general considerations justifying the proposed loading histories in term of seismic demand and seismic capacity of components. ATC-24 suggests the inter-storey drift as the most suitable parameter to represent the demand imposed by earthquakes to structural components. As a consequence, the increment Δ in peak deformation between load steps for the specimen should correspond to the deformation at an increase in storey drift equal to the yield displacement of the storey.

In defining failure, ATC-24 presents the same problem as ECCS. There is not a conventional definition of this phenomenon, nevertheless the parameter Q_{min}, required strength before failure, is specifically considered, defined as the minimum force at peak deformation that must be resisted according to a stipulated performance criterion.

6 AISC-341-05 AND FEMA-461 RECOMMENDATIONS

In AISC (American Institute of Steel Construction) *"Seismic Provisions for Structural Steel Buildings",* the recommendations for testing procedures are contained in Appendix S *"Qualifying Cyclic Tests of Beam-to-Column and Link-to-Column Connections"*. They are expressly for special (SMF) and intermediate moment frames (IMF), and for eccentrically braced frames (EBF). The latter 2005 edition supersedes the previous editions of 2002 and 1997. The recommendations are based on the results of the

1997 FEMA-SAC project, established by FEMA (Federal Emergency Management Agency) in order to update the seismic design provisions, after the 1994 Northridge. The testing protocol is considered mainly a qualification oriented procedure. For beam-to-column connections the inter-storey drift angle θ *(inter-storey displacement divided by the storey height)* is directly assumed as the control parameter and defined in values imposed to the test specimen as specified below:

Θ (rad)	0.00375	0.005	0.0075	0.01	0.015	0.02	0.03	0.04	0.05
n of cycles	6	6	6	4	2	2	2	2	2

Loading continues then at increments of $\theta = 0.01$ *radian,* with two cycles of loading at each step. As this experimental tests are qualifying tests, there are specified requirements for strength and inter-storey drift angle θ. As an example, for SMF *the connection shall be capable of sustaining an inter-storey drift angle of at least 0.04 radian (paragraph 9.2a.)* Moreover, the test specimen must sustain the required values for at least one complete loading cycle.

FEMA 461 (June 2007) *Interim Testing Protocols for Determining the Seismic Performance Characteristics of Structural and Non-structural Components* – limiting our interest only to Quasi-Static tests carried out with displacement control – looks as a further recent upgrading of previous protocols, with more detailed and explicative considerations on the recommended loading histories.

The loading history consists of groups of two cycles with step-wise increasing deformation amplitudes, between a targeted smallest deformation amplitude Δo (a recommended value for Δo, in terms of story drift index, δ/h, is around 0.0015, when no data exists regarding what amplitude of deformation is likely to initiate damage) and the targeted maximum deformation amplitude Δm of the loading history. This is an estimated value of the imposed deformation at which the most severe damage level is expected to initiate. A recommended value for this amplitude, lacking other evidence, in terms of story drift index, δ/h, is 0.03. The number *n* of steps (or increments) in the loading history, is generally 10 or larger. For more details see FEMA 461.

7 PROPOSED INNOVATIVE CYCLIC PROCEDURE

The protocols described encompass only displacement controlled conditions, and fail to describe the unsymmetrical displacement histories experienced by real beam-to-column connections when subjected to earthquake motion. The new testing procedure, proposed in order to obviate these limitations, was extensively applied, up to now, only in an experimental campaign performed on steel racks, whose results are described in references [1], [2]. To simulate an experimental condition similar to the real behaviour of the node in the structure, a load corresponding to the shear force should be positioned at a proper distance L_s from the node, in order to produce both the same shear force and the same node rotation determined in reality by the gravity loads. The distance L_s is obtained by equalizing the rotation of the node of the specimen and the rotation of the node in the portal frame configuration.

7.1 Vertical load: L_s parameter

Let us consider a beam with length *L*, subjected to a uniform linear load *p,* connected to two columns by joints with rotational stiffness respectively K_1 and K_2. The elastic rotations and the bending moments are respectively θ_1 and $M_1 = pL^2/12$ on the left edge and θ_2 and $M_2 =- pL^2/12$ at the connection on the right. Hence from the equilibrium equation on each joint, introducing the beam stiffness $K_b = EI/L$ and solving with respect to the node rotations, we obtain:

$$\theta_1 = \frac{pL^2}{12}\frac{(6K_b + K_2)}{(4K_b + K_1)(4K_b + K_2) - 4K_b^2} \quad ; \quad \theta_2 = -\frac{pL^2}{12}\frac{(6K_b + K_1)}{(4K_b + K_1)(4K_b + K_2) - 4K_b^2}$$

To represent the situation of a T specimen subjected to a discrete load *F* on its extremity, let us have a cantilever of length *Ls* with a rotational elastic stiffness K_S at its connection. It is:

$F = K_S\ \theta_S/L_S$ where F represents the force applied on the cantilever at a distance L_S, which causes a rotation θ_S in the joint of the beam. The stiffness of the joints in the real structure is generally the same: $K_1 = K_2 = K$, and the shear force at each connection of the beam with a distributed load p, is $F = pL/2$; comparing the node rotation θ_1 of the beam in the frame configuration to the rotation θ_S of the beam in the inverted T cantilever configuration an imposing that $K_S = K$, i. e. the T specimen and the real structure have the same joint stiffness, we obtain:

$L_s = \dfrac{L}{6}\dfrac{K}{(2K_b + K)}$; substituting again the beam stiffness $K_b = \dfrac{EI}{L}$ we can write:

$L_s = \dfrac{L}{6}\dfrac{KL}{(2EI + KL)}$ and inverting this relation $L = 3L_S + \sqrt{9L_S^2 + 12\dfrac{EI}{K}L_S}$

For a distributed load, L_S ranges from $L_S = 0$ for a supported beam ($K = 0$), to the limit value $L_S = L/6$ for a perfectly rigid joint $(K = \infty)$.

The values of L_S are generally small: considering the joint stiffness with respect to the beam stiffness, for values from $K = K_b$, to $K = 6K_b$, L_S is from about $5\%\ L$ to $12.5\%\ L$. This result can be a limit to the application of the new procedure, due to the characteristics of the experimental setup.

7.2 Loading history of the proposed innovative procedure

The procedure is referred to cyclic tests, performed after two monotonic tests which identify yielding forces (F_y^+ ; F_y^-) and yielding displacements (d_y^+ ; d_y^-) in the two opposite directions of loading. These tests are generally necessary, because this new procedure is particularly suitable for elements and details with unsymmetrical behavior. The cyclic test is composed by a sequence of reversed cycles (repeated when in the post-elastic range) in which each cycle has an initial force-controlled part and a final displacement-controlled part. Gravitational load effects are expressed through F_g, which can be expressed as a fraction of the yielding force F_y. In what follows, the gravity force is considered to be positive.

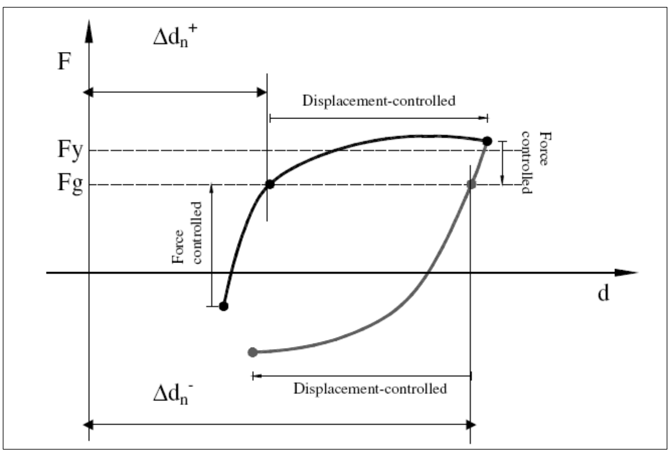


Figure 7.1: The two phases of the proposed new procedure

A typical positive cycle is composed of two parts (Figure 7.1):

- Application of the force correspondent to vertical (gravitational) load effects F_g on the beam-to-column connection (force-controlled part of the cycle), at distance L_s. The values of F_g can be assumed for example as 25%, 50%, 66% or 75% of the yield force F_y.

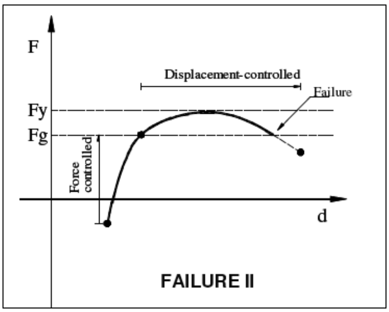
- Starting from the displacement at the end of the force-controlled part of the cycle Δd_n^+ the displacement controlled part of the cycle is imposed. The displacement amplitude applied is a multiple of the yielding displacement.

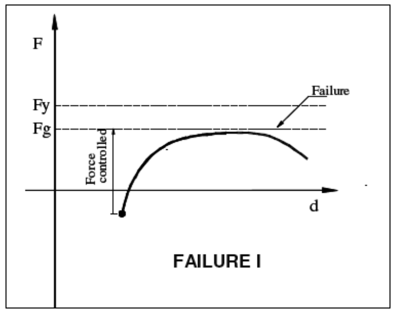
Also the following negative cycle is composed by two different parts:

- Force-controlled unloading until the attainment of the force F_g associated with the presence of the vertical (gravity) loads alone.

- Starting from the displacement Δd_n^- reached at the end of the force-controlled part of the cycle, the displacement-controlled part of the cycle is imposed to the specimen, until the intended displacement amplitude is reached.

The positive and negative cyclic displacements (in the post-elastic range) are derived from the following relation: $[(2 + n)d_y^+ + \Delta d_n^+] \div [(2 + n)d_y^- + \Delta d_n^-]$; with $(n = 0,1,2,3..)$





Figures 7.2 – 7.3: Type I and Type II failure I.

7.3 Failure for the proposed procedure

Failure is identified when in any of the positive or negative cycles one of the following situations occurs:

When the specimen fails to develop the force correspondent to the gravitational loads F_g in the force-controlled part of the positive cycle (Figure 7.2)

II. When the restoring force decreases to values below those corresponding to the gravitational loads F_g in the displacement-controlled part of the positive cycle (Figure 7.3).

7.4 Comments on the application of vertical loads

When L_s is small, depending on the experimental setup characteristics, it might not be possible to apply the hybrid procedure. If the parameter L_S is not too small and the test set up is adequate, the simplest procedure to obviate the small value of L_S, is to apply the gravity load F_g at the distance L_S and then performing the testing procedure with the variable force applied to a suitable distance, considering that the origin of the load-displacement diagram now corresponds to a fully pre-loaded an pre-deformed condition. The test begins now with the displacement controlled part, and is similar to the one proposed by ECCS-45 testing procedures, with a shifted origin.

7.5 Seismic bearing capacity representation

The effectiveness of the new testing procedure in representing the seismic bearing capacity of a structural element, can be suggested also by the following qualitative considerations.

For an elastic–perfectly plastic Single-Degree-of-Freedom element, subjected to an impulsive force large enough to cause a plastic excursion, the displacement behavior can be represented by the line OABCD in Figure 7.4. The energy absorbed by the element, is in part dissipated by the plastic deformation (AB), then the element oscillates between the positions A and B, with decreasing amplitude in time, due to the damping of the system. Neglecting this dynamic effect, it is possible to consider the cycle represented in Figure 7.4 as the result of two consecutive opposite impulsive forces, spaced in time, as in Figure 7.5. The second impulsive force determines the force-displacement relation of line CDEOA, with final damped oscillations between points A and E.

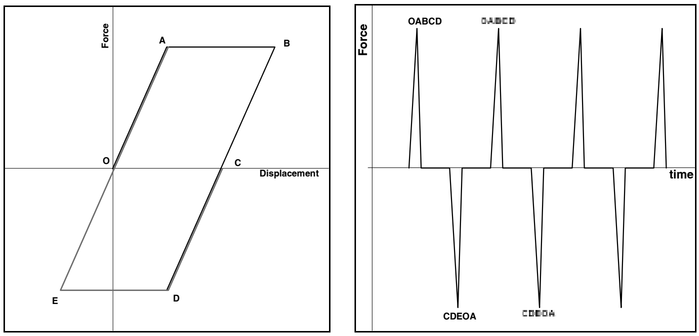


Figure 7.4 - 7.5: Time spaced opposite impulsive forces

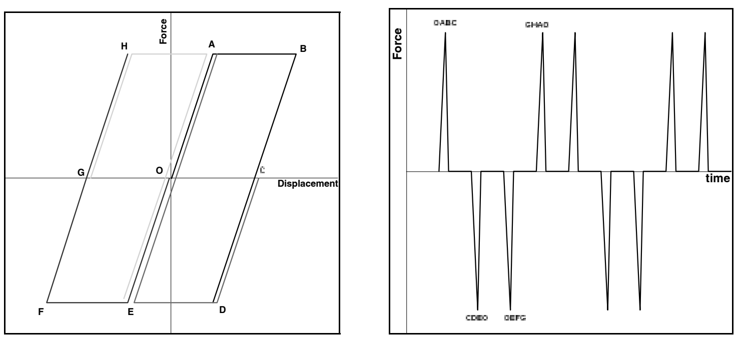


Figure 7.6 – 7.7: Equal displacement cycle obtained by four time spaced impulsive forces

From this point of view, an usual quasi-static testing cycle, performed between two opposite values of the displacement, as points C and G in figure 7.6, can be considered as the result of four consecutive impulsive forces, spaced in time, inverting their sign at every two impulses (Figure 7.7). The increasing plastic cycles, imposed in traditional quasi-static tests, can be obtained from the effect of groups of four increasing impulsive loads, spaced in time, with the same sign properties.

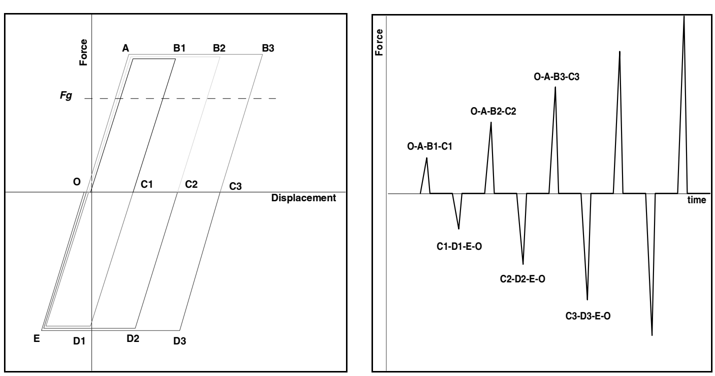


Figure 7.8 - 7.9: Force-displacement cycles from time spaced increasing impulsive forces

As a seismic load can be seen as the application of a series of alternate impulsive forces, the seismic carrying capacity of a structural element may be better represented by a the quasi-static simulation of the effect of a group of alternate increasing impulsive forces spaced in time, as respectively in figures 7.8 and 7.9, than with equal amplitude increasing cycles.

The first impulse in plastic range can be considered to cause a total displacement of $2\ e_y$ (point B1) transferring the total energy $1.5\ F_y\ e_y$. The second impulse is equal to the previous one, but in the opposite direction, so the maximum displacement corresponds to point E. The third impulse can be set to cause a total displacement of $3e_y$ (point B2) transferring the total energy $2.5\ F_y\ e_y$, followed by an opposite similar impulse, reaching again point E. Subsequent couples of opposite impulses will cause total displacements of $4e_y$, $5e_y$, and so on, transferring the energy $3.5\ F_y\ e_y$, $4.5\ F_y\ e_y$. Of course the cycles can be repeated.

The result is a global behavior of the specimen with cumulated displacement in one direction. The loading cycles obtained (Figure 7.8) are similar to the new proposed testing procedure with no permanent loading, with displacement accumulation in one direction. Applying the new procedure, in the first cycle the force is applied with displacement control from point O up to the required displacement in point B1, then with force control the specimen is unloaded until point C1. The reverse load is applied with displacement control from C1 up to point E, imposing a displacement equal to OB1, and with force control the specimen is unloaded to point O. The subsequent cycle is performed with the same steps but a larger displacement, corresponding to point B2, and so on. To take into account the presence of permanent vertical loading, signifies only to limit the force control loading and unloading to the considered load F_g. Moreover it can be observed that, even if an impulsive force is applied before the completion of the effect of the previous one, that is during the elastic oscillation after the plastic displacement, the global aspect of the cycles obtained is similar, with different cumulative displacement in one direction.

8 CONCLUSION

This new procedure gives a significant improvement to the commonly adopted recommendations for low cycle fatigue testing. It has hybrid characteristics, as it is in part a force control procedure and in part a displacement control procedure for every inelastic cycle.

The global performance of the specimen is clearly defined with explicit reference to its requested carrying capacity F_g in usual service conditions, therefore in this sense the new experimental tests may be considered “complete”: the performance of the specimen subjected to transversal reversal loads is investigated as far as it can resist the design gravity (dead and live) loads. The failure to resist these loads represents the collapse of the specimen. Accepting this point of view, the proposed new testing procedure could be the basis for new Low Cycle Fatigue testing recommendations, or for a new edition of ECCS recommendations, which takes into account the experiences accumulated in the last 25 years on this item.

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