ASSESSING THE BEHAVIOUR OF RC BEAMS SUBJECT TO SIGNIFICANT GRAVITY LOADS UNDER CYCLIC LOADS

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ABSTRACT Gravity loads can affect a reinforced concrete structure's response to seismic actions, however, traditional procedures for testing the beam behaviour do not take this effect into consideration.

An experimental campaign was carried out in order to assess the influence of the gravity load on RC beam connection to the column subjected to cyclic loading. The experiments included the imposition of a conventional quasi-static test protocol based on the imposition of a reverse cyclic displacement history and of an alternative cyclic test procedure starting from the gravity load effects. The test results are presented, compared and analysed in this paper.

The imposition of a cyclic test procedure that included the gravity loads effects on the RC beam ends reproduces the demands on the beams' critical zones more realistically than the traditional procedure. The consideration of the vertical load effects in the test procedure led to an accumulation of negative (hogging) deformation. This phenomenon is sustained with the behaviour of a portal frame system under cyclic loads subject to a significant level of the vertical load, leading to the formation of unidirectional plastic hinges.

In addition, the hysteretic behaviour of the RC beam ends tested was simulated numerically using the nonlinear structural analysis software – *OpenSees*. The beam-column model simulates the global element behaviour very well, as there is a reasonable approximation to the hysteretic loops obtained experimentally.

Keywords reinforced concrete, beams' critical zones, seismic response, cyclic test, testing procedure, ductility, nonlinear analysis

Nomenclature

L	specimen length
d	displacement
d_y	displacement at first yield
d_0	reference displacement
Δ	imposed displacement
f_{cm}	mean value of concrete cylinder compressive strength
F_y	horizontal force that yields the reinforcement
F_g	horizontal force corresponding to gravity load effects
M	bending moment
θ	drift
V	shear
ε	strain
σ	stress
δ_b	beam plastic deformation
θ_b	beam plastic rotation
θ_c	column rotation
a	position of the plastic hinge

1. Introduction

The seismic performance of a structure can be defined as its ability to accommodate the earthquake demands, in terms of energy or displacement inputs, and can be evaluated by the extent of damage sustained [1]. A structure with good seismic behaviour should present ductility and resistance in order to be able to dissipate energy. In frame systems, the plastic hinge regions located, in general, in the extremities of the elements, are the main responsible for energy dissipation [2]. Thus, the response of the beam critical zone can be optimized to improve the structure response as a whole.

Unless specific deficiencies are identified in the beam, usually the improvement of the structure seismic behaviour is attained through modifications of the vertical elements (columns and shear walls) [1]. Thus, scientific research efforts have been focused on the study of the hysteretic behaviour and on upgrading techniques of the vertical elements.

In the few research works related to beams, the main deficiencies pointed out for inadequate seismic behaviour are the lack of continuity of bottom bars in the supports and limited deformation capacity of the compression zone. The lack of continuity of bottom bars, eventually, leads to an increase of the lateral deformations [3, 4 and 5]. Although the top slab's reinforcement, within the effective flange width near the supports, may complement the beam top reinforcement and increase the negative bending resistance of the beam, and thus the dissipation capacity of the beam critical region, this reinforcement increase may reduce the beam critical region ductility with premature crushing and reinforcement bucking in the compressed beam side. On the other hand, excessive beam resistance may transfer the plastic hinge from the desired location in the beam end to the supporting column, which may lead to reduced energy dissipation mechanisms.

However, assuming a strong-column–weak-beam seismic conception [6], the plastic hinge should be formed in the beam. This fact justifies the study of the hysteretic behaviour of RC

beams' critical regions and the upgrading of their performance in order to optimize the behaviour of these beam regions.

An experimental study of the seismic behaviour of a structural element may involve: shaking table tests, in which the structure is subjected to simulated ground motion; pseudo-dynamic tests, a hybrid method of testing in which the inertia forces, damping (viscous) forces and seismic input are simulated numerically, and the restoring forces are obtained and measured experimentally from the physical model test; and quasi-static tests, in which equivalent static displacements or forces are imposed on the structural elements to induce an inelastic response of the part of the structure that concentrates the nonlinear behaviour. In this case, the restoring forces obtained can be used to validate and develop numerical models to enable prediction of the seismic behaviour of the structure. The conventional methodology of quasi-static cyclic tests for structural elements is based on the imposition of a reverse cyclic displacement history where the failure is conventionally defined, as follows ECCS [7], ACI [8] or ATC [9] recommendations.

There are some experimental studies related with the cyclic behaviour of the plastic hinges in RC beams [10, 11, 12, 13, 14, etc]. However, there is a lack of research works related with the plastic hinges hysteretic behaviour of the RC beams in the presence of significant gravity load effects.

In order to address this subject, Proença et al. (2006) [15] presented an experimental test on steel beam-to-column subassemblages, Gião et al. (2009) [16] presented a study on a reinforced concrete beam critical regions and Gião et al. (2012) [17] performed cyclic tests on strengthened reinforced concrete beam critical regions. Walker and Dhakal (2008) [18] used a test procedure starting from 75% of the theoretical flexural strength to study the cyclic performance of reinforced concrete beams with normal ductility detailing.

The aim of the present study is to assess the influence of the gravity load effects on RC beam critical regions subjected to cyclic loading. For this purpose, a cyclic test procedure for RC was implemented to reproduce the demands on a beam critical region more realistically and also consider the asymmetries of the cross-section in terms of geometry and reinforcement. This test procedure involves the imposition of a reverse cyclic displacement history, starting from the gravity load effects and leading to a non-symmetrical loading history where failure takes place when the connection is no longer able to sustain the gravity load, or when the drift exceeds specified limits.

2. Experimental program

2.1. Specimens

The reinforced concrete specimens are T-beams (VR1 and VR2), with a cross-section 250 mm wide by 500 mm high (Fig. 1).

In terms of mechanical characteristics the average cylindrical compressive strength at the time of the VR1 and VR2 tests was f_{cm} = 41.7 MPa and f_{cm}= 44.8 MPa, respectively. The steel yield strength of the longitudinal reinforcing bars was 473 MPa.

The specimen is a cantilever beam that simulates approximately 1/3 of the clear span of a beam connected to columns at both ends. In the test the column is simulated by a rigid concrete block to confine the study to the beam critical region, neglecting the influence of other parameters as the column and beam-column behaviour. The beam reinforcement detailing, the location of twenty-four strain-gauges and seven displacement transducers used in the test program are shown in Fig.1 and Fig.2. Section 1 corresponds to the beam support end.

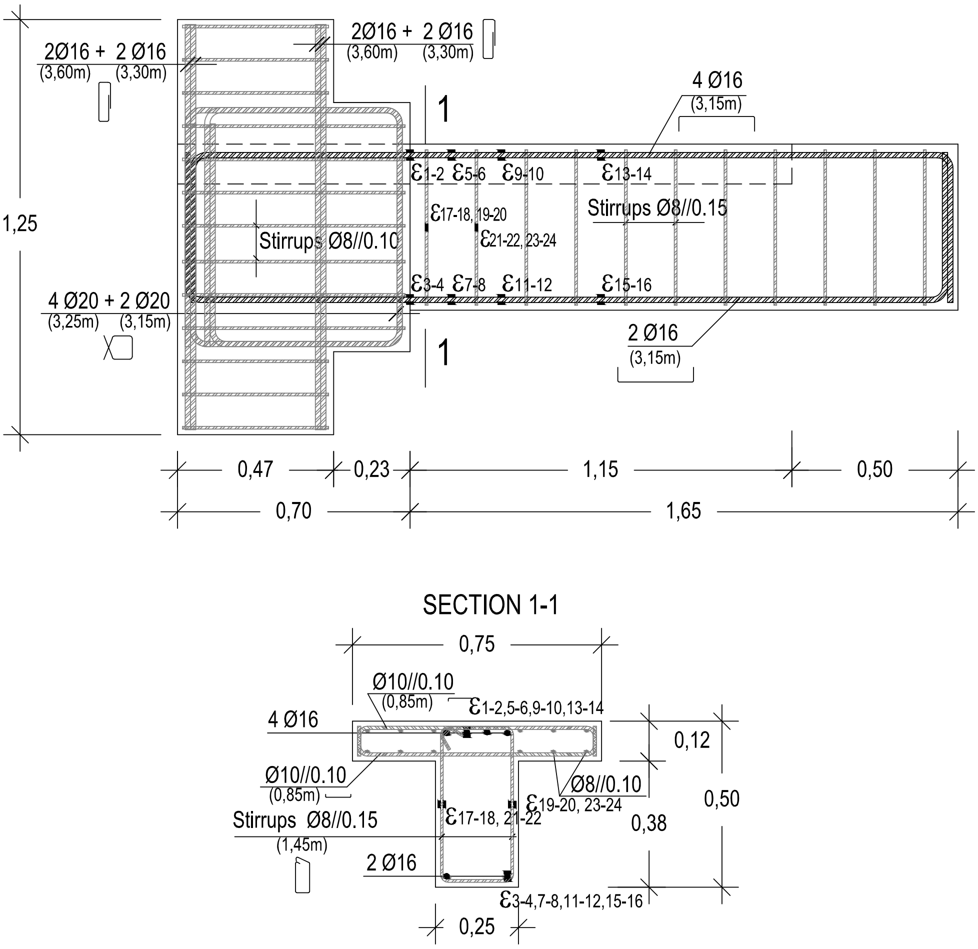


Fig. 1. Geometry, detailing and instrumentation of the specimen

2.2. Test Setup

The experimental campaign was carried out in the Laboratory of Structures of UNL. This laboratory has two reaction walls and a "strong floor". The equipment used in the tests was a mechanical actuator with ±500 kN capacity for horizontal loads up to 400 mm (±200 mm) displacements, a ±500 kN capacity double-action load cell FIMEI CS-24 and 100 mm CDP100 TML displacement transducers. Four 8-channel Spider8 Data loggers from HBM were used for data acquisition - Fig. 2.

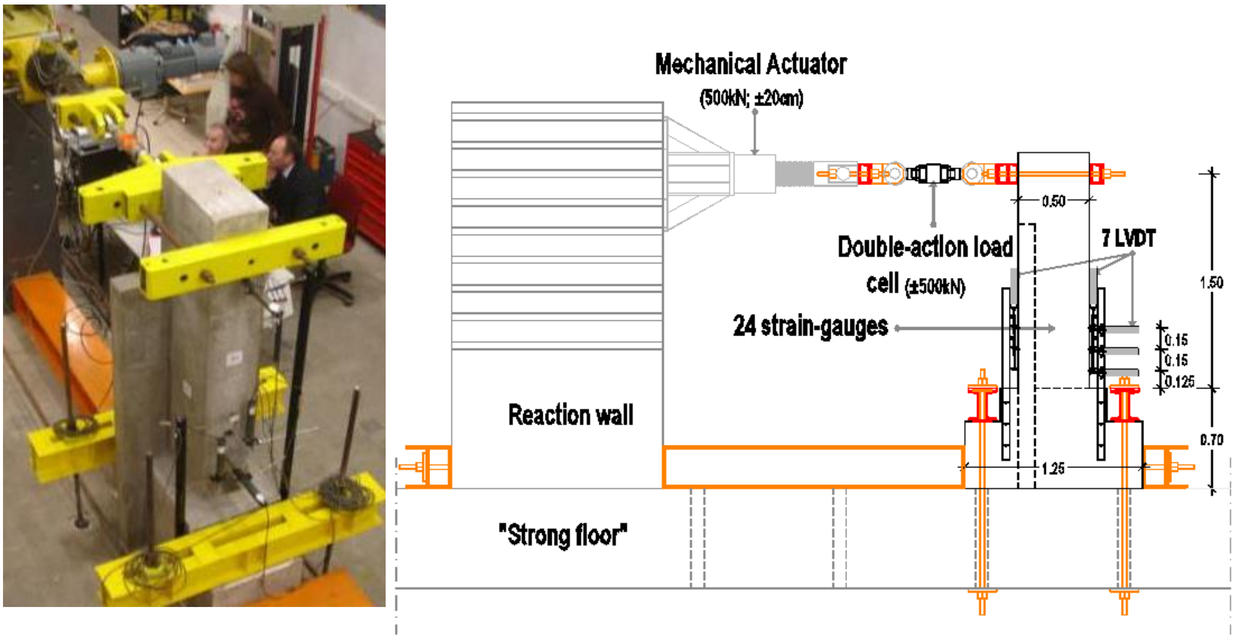


Fig. 2. Test setup

2.3. Loading History

Specimen VR1 was tested according to the ECCS recommendations [7], with the application of a reverse cyclic displacement history with increasing amplitude. The displacement steps were $\pm\Delta = \pm 0.5d_0, \pm 1.0d_0, \pm 2.0d_0, \pm 3.0d_0, \pm 4.0d_0, \pm 5.0d_0$ and $\pm 6.0d_0$, where d_0 is the reference displacement. Three complete cycles were performed for each step - Fig. 3.

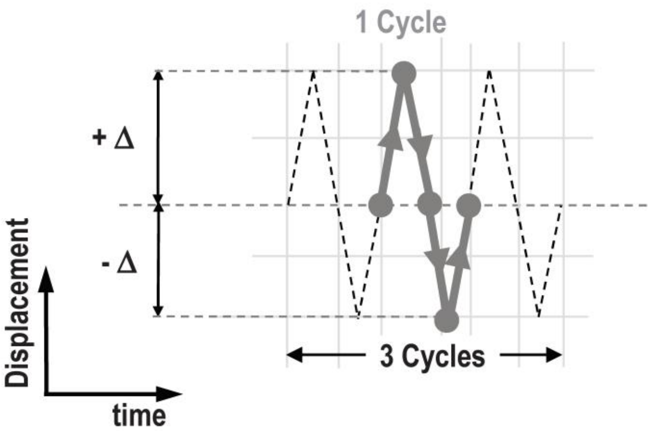


Fig. 3. ECCS typical load step

The displacement at first yield was determined experimentally in the first part of the test; it is the displacement observed when the yielding strain was reached (indicated by the strain-gauges on the longitudinal bars). The displacement at first yield values (d_y) in the beam

connection to the column were 6 mm for positive bending moments and 12 mm for negative bending moments. The procedure was simplified by setting a reference displacement (d_0) as the lower value obtained, i.e., 6 mm.

As stated above, in this study a quasi-static test procedure, that simulates the gravity load on the beam with an asymmetrical cross-section geometry and reinforcement, was implemented in specimen VR2. The proposed procedure imposes a reverse cyclic displacement history with increasing amplitude (wherein three complete cycles are performed for each amplitude step), starting from the gravity load effects.

A cycle is composed of sequential stages with each cycle starting from the position where the pre-established value of the idealized gravity load is restored (in Fig. 4 it is stage 0). The performance of a cycle consists of the following stages (illustrated in Fig.4):

- **(i)** Imposition of a required displacement +Δ;
- **(ii)** *Force-controlled unloading* until the value of the gravity load is re-established;
- **(iii)** Imposition of a *displacement-controlled unloading* -Δ;
- **(iv)** *Force-controlled loading* until the value of the gravity load is re-established.

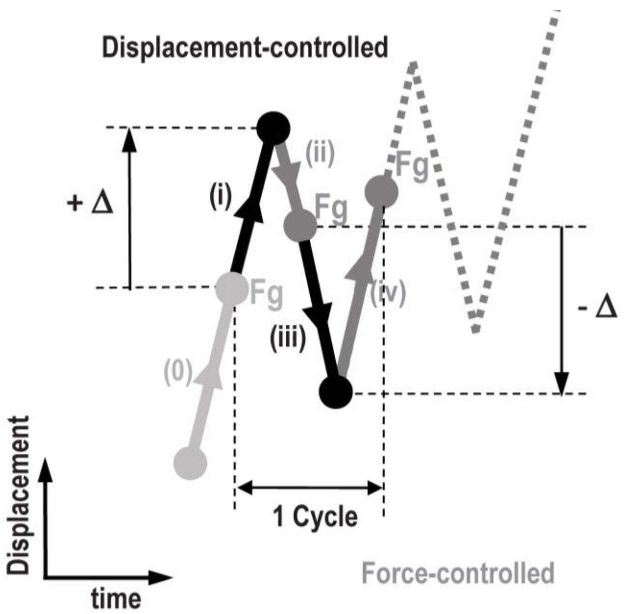


Fig. 4. Typical load cycle in the proposed test procedure

During the test, the restoration of the gravity load corresponds to larger displacements and leads to different starting points for each displacement cycle. In this way, the displacement history is not necessarily symmetrical.

Failure occurs when the connection is either unable to resist the gravity loading or a maximum specified beam drift is attained.

For the implementation of this test procedure a LabView [19] code was developed for force and displacement control.

The implementation of the proposed procedure in specimen VR2 test led to the following load sequence: application of a pre-established load (F_g = 90 kN - corresponding to 50% of the horizontal force that leads the top reinforcement to yielding F_y) equivalent to the gravity load effects on the beam's fixed end, followed by the imposition of a reverse cyclic displacement history with increasing amplitude, with displacement steps of $\pm\Delta = \pm 1.0d_0$, $\pm 2.0d_0$, $\pm 3.0d_0$, $\pm 4.0d_0$, $\pm 5.0d_0$, $\pm 6.0d_0$ and $\pm 7.0d_0$; 3 cycles were performed at each step.

The value of the displacement at first yield for negative moments, obtained experimentally, was 12 mm. As in the previous procedure, the base displacement value (d_0) was set as 6 mm.

As stated above, it should be noted that the displacement history is not symmetrical because the starting point for each imposed displacement $\pm\Delta$ is reached not by displacement control but by load control to restore gravity load effects (F_g).

The loading and displacement history for the experimental cyclic test of Specimen VR1 (according ECCS recommendations) and Specimen VR2 (with the cyclic procedure including gravity load effects) are presented in Figure 5 and 6.

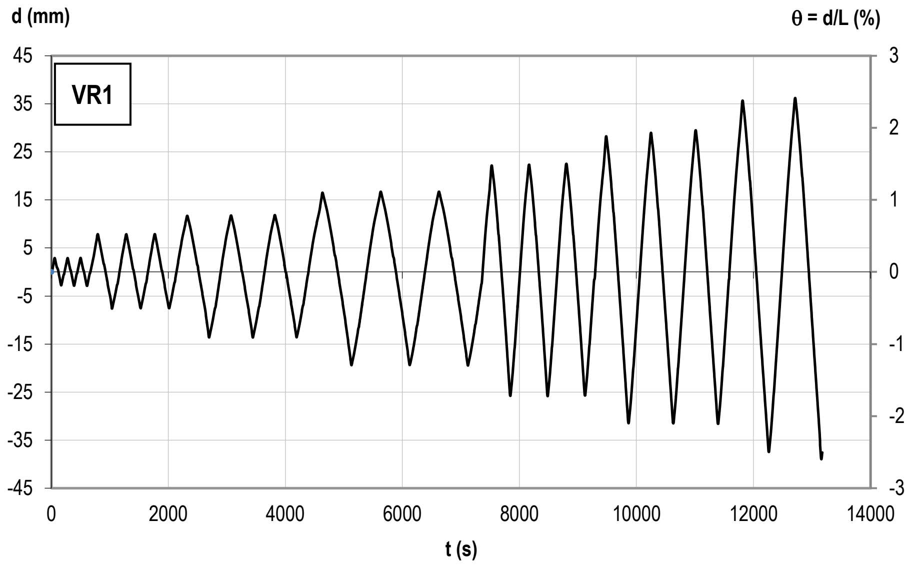


Fig. 5. Displacement history of ECCS cyclic test - Specimen VR1

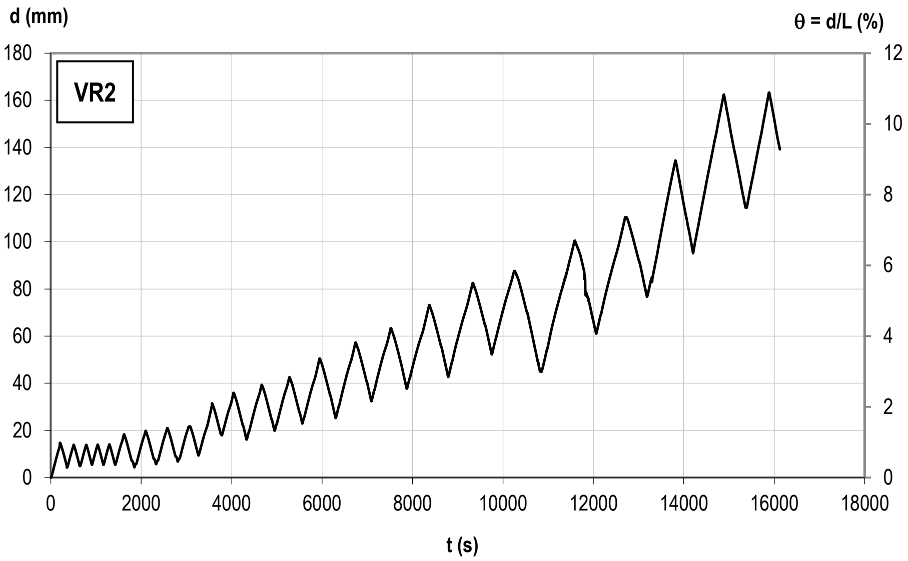


Fig. 6. Displacement history of the cyclic test including gravity load effects - Specimen VR2

3. Experimental results

3.1. Specimen VR1

The first relevant observation of test of specimen VR1 is that, given an unsymmetrical T-shaped section with unsymmetrical reinforcement, where the top-reinforcement within the width of the web was totally mobilized, the behaviour was characterized by a non-symmetric force-displacement hysteretic diagram (Fig. 7). The beam has less resistance in the positive

moment direction (sagging), corresponding to the strength of the bottom reinforcement. Another difference from symmetrical behaviour is the fact that the stage in the reverse reloading cycle, which corresponds to the loading in the positive moment direction, the tension forces induced in the bottom reinforcement were not sufficient to close the cracks previously formed on the top of the cross-section. Consequently a low stiffness without "pinching" was observed. The rather strong "pinching" effect took place in the reloading in the negative moment direction (hogging).

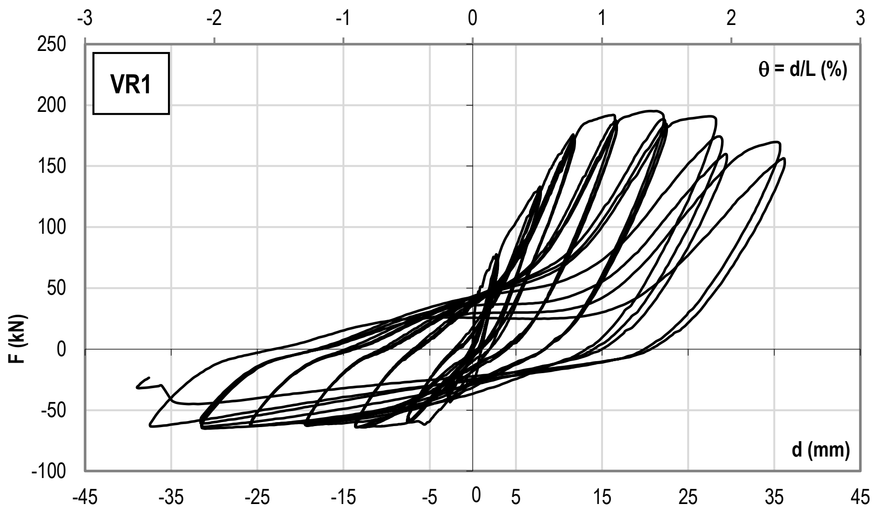
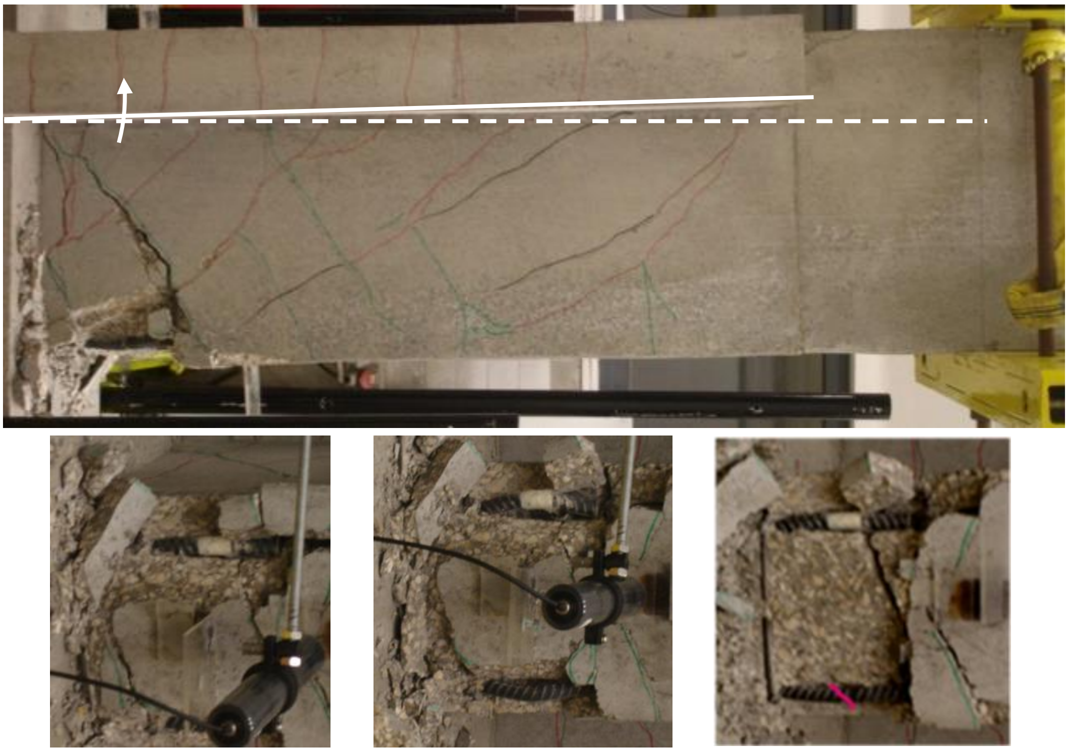


Fig. 7. Force-displacement hysteretic diagram of Specimen VR1

The failure mode observed in Specimen VR1 was caused by the rupture of a longitudinal bottom bar, preceded by spalling of the concrete cover and the buckling of the bar. The specimen after failure is shown in Figure 8. It should be noted that this type of test leads to failure for positive moments (sagging) with an accumulation of positive deformation (quite questionable for a beam loaded with gravity load). Failure occurred in the second positive $6d_y^+$ (36 mm) displacement cycle, and the maximum negative displacement observed corresponded to $3d_y^-$ (-36 mm) cycle (Fig. 7).



Spalling of the concrete cover **Buckling of the longitudinal bottom bar** **Rupture of one longitudinal bottom bar**

Fig. 8. Failure mode of Specimen VR1

3.2. Specimen VR2

The test of specimen VR2 led to an accumulation of negative deflection (hogging), while for positive moments the longitudinal bottom reinforcement remained on the elastic range until the end of the test (Fig. 9).

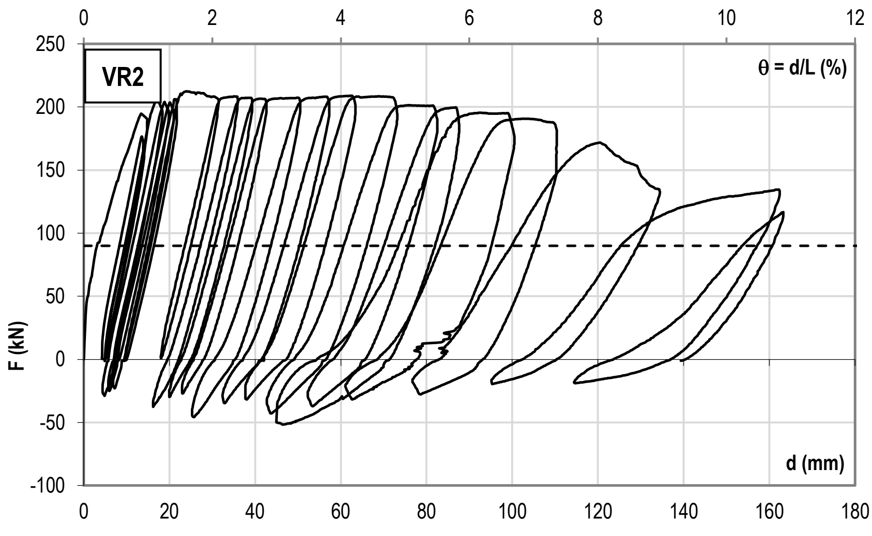
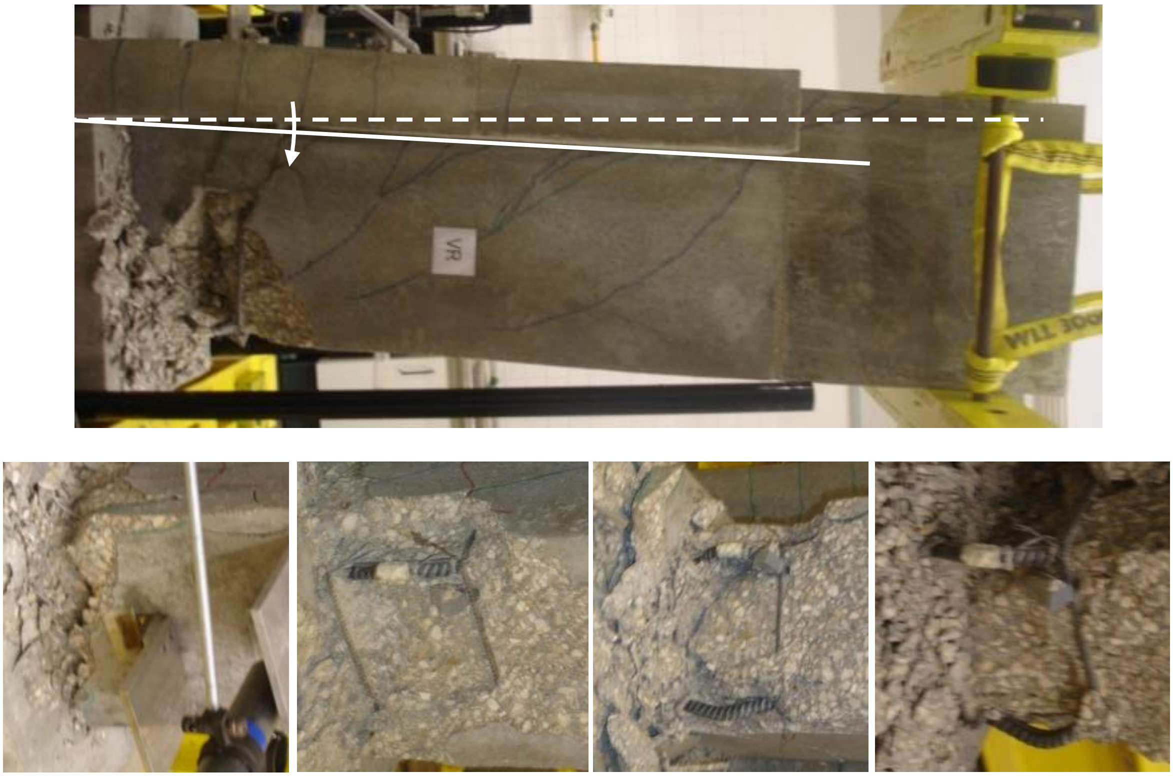


Fig. 9. Force-displacement hysteretic diagram of Specimen VR2

Specimen VR2 exhibited failure controlled by the gradual deterioration of the compressive zone and progressive buckling of the longitudinal bottom bars. Figure 10 shows specimen VR2 after failure.

The test was stopped due to excessive deformation despite the fact that the beam resistance was still higher than the pre-established gravity load (Fig. 9).



Gradual deterioration of the compressive zone **Progressive buckling**

Fig. 10. Failure mode of Specimen VR2

4. Numerical simulations

The aim of the numerical simulation is to understand the effects of the gravity load in the hysteretic response of a beam subjected to cyclic loads and to assess the ability to predict such behaviour numerically. For this, the hysteretic response of a cantilever beam subjected to a displacement history, similar to the one of the experimental tests, was analysed using a nonlinear analysis software - *Opensees: Open System for Earthquake Engineering Simulation* [20], which uses finite element nonlinear analysis.

4.1. Nonlinear behaviour

This software achieves the simulation of the nonlinearity behaviour on *element* level through a force-deformation model, on *section* level through a moment-curvature model or, as used in the present study, a fibre level through the material stress-strain model [20].

In our study the nonlinear behaviour was considered at a fibre level using the material stress-strain hysteretic models [21, 22, 23], which were calibrated from the material test results.

There are several hysteretic models in OpenSees that simulate the stress-strain relation of the materials. In this case, the uniaxialMaterialConcrete02 model (with linear tension softening) and uniaxialMaterialSteel02 – Giuffré-Menegotto-Pinto model with isotropic strain hardening – were used, since they gave closer approximations to the material test results, with fewer numerical and convergence problems.

Figures 11 to 14 present the material stress-strain hysteretic diagrams observed for cross-section 1 (corresponding to the first integration point) in the top fibre – Sec1FibT – and in the bottom fibre – Sec1FibB, related to the response of the cantilever beam model subjected to a lateral displacement history similar to the experimental tests (ECCS cyclic test and the cyclic test procedure including gravity load effects).

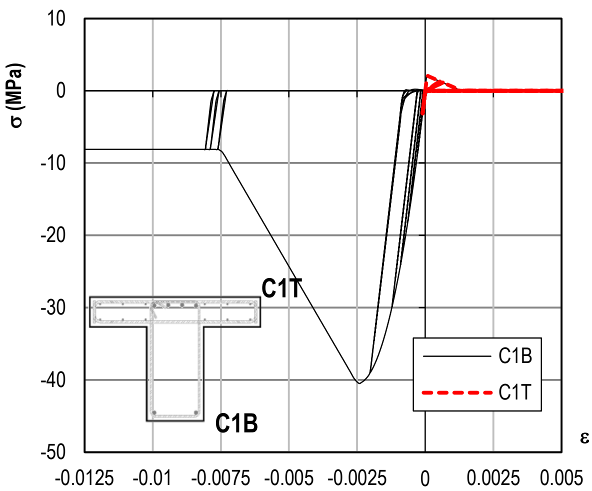


Fig. 11. Stress-strain hysteretic diagrams of the concrete model for the ECCS cyclic test: cross-section 1 – Bottom (C1B) and Top (C1T) fibre

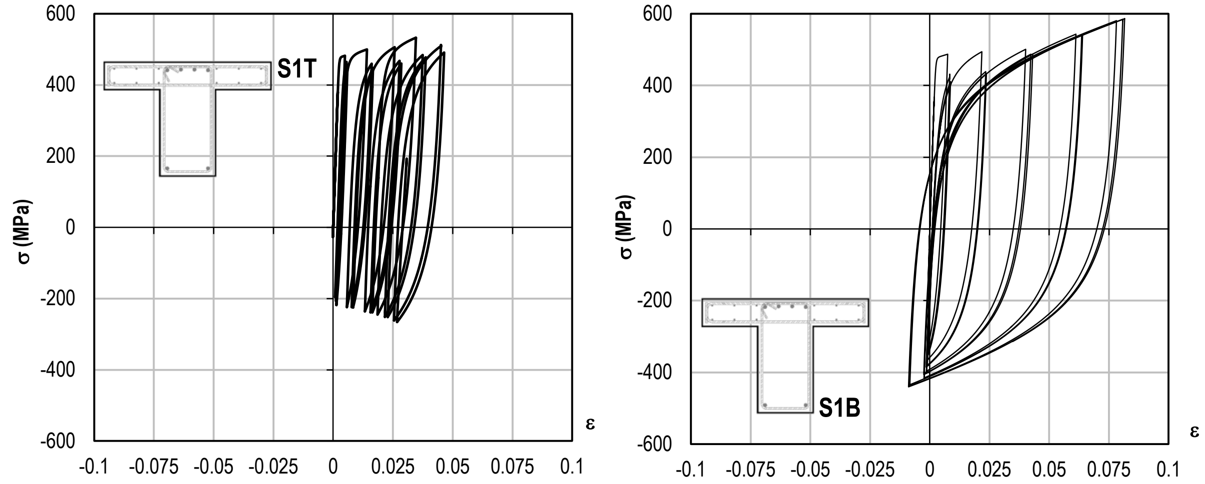


Fig. 12. Stress-strain hysteretic diagrams of the steel model for the ECCS cyclic test: cross-section 1 – Bottom (S1B) and Top (S1T) fibre

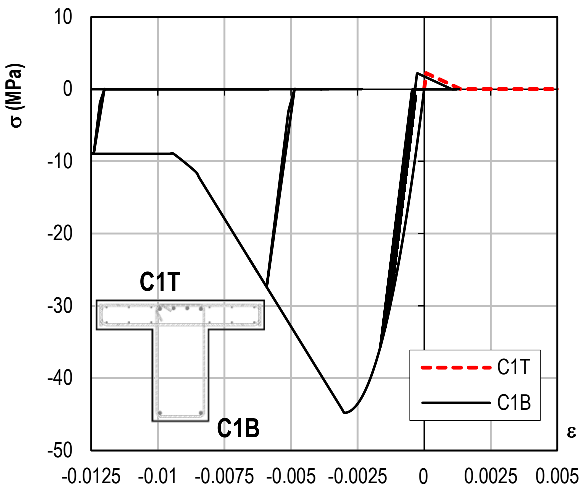


Fig. 13. Stress-strain hysteretic diagrams of the concrete model for the cyclic test including gravity load effects: cross-section 1 – Bottom (C1B) and Top (C1T) fibre

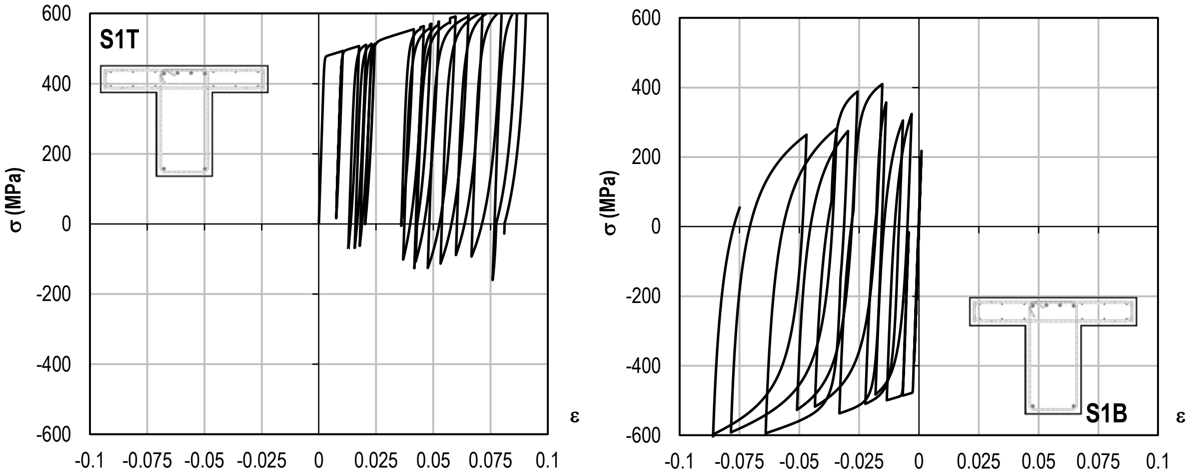


Fig. 14. Stress-strain hysteretic diagrams of the steel model for the cyclic test including gravity load effects: cross-section 1 – Bottom (S1T) and Top (S1T) fibre

As observed by Coleman and Spacone (2001) [24], larger inelastic strains in concrete were required for the number and position of the integration points used in order to regularize the postpeak element response. In fact, Coleman et al. (2001) suggested that the plastic hinge length and the section demands in the model depend on the location and number of integration points.

Therefore, in the numerical simulation a constant fracture energy criterion in the compression region was applied in order to obtain the assumed concrete constitutive law. So, a constant stress-displacement was assumed rather than a stress-strain law [24], in order to regularize the element post-peak response.

The hysteretic behaviour of a cantilever beam using a *distributed plasticity nonlinear model* is presented in this study.

4.2. Nonlinear model with distributed plasticity

In this case, a nonlinear element based on force formulation with spreading plasticity along the element was used: *nonlinearBeamColumn*. The integration along the element is based on the Gauss-Lobatto quadrature rule [20]. In this particular case four integration points were used.

The response of the distributed plasticity models of the cantilever beam subjected to a lateral displacement history similar to the experimental tests (ECCS cyclic test and the cyclic test including gravity load effects) are presented in Figures 15 and 16.

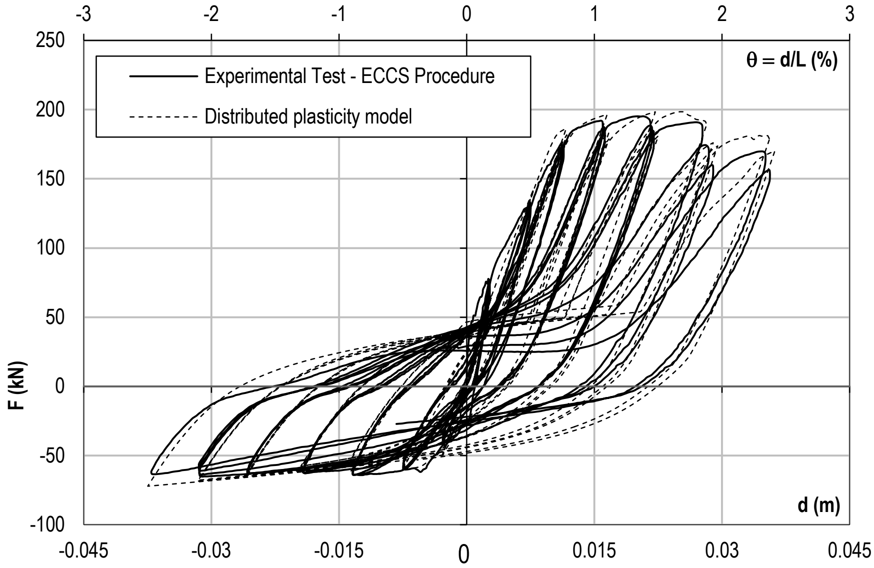


Fig. 15. Distributed plasticity model – ECCS cyclic test force-displacement hysteretic diagrams

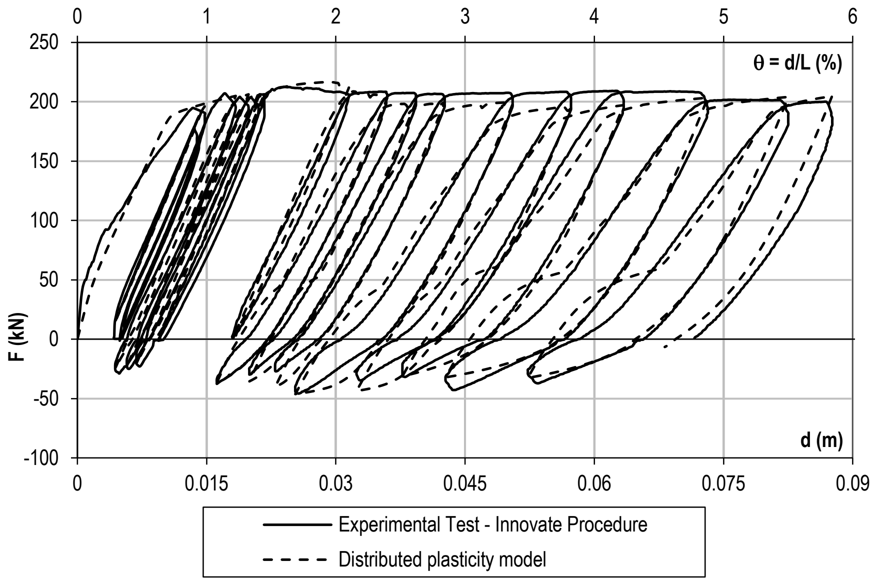


Fig. 16. Distributed plasticity model – cyclic test including gravity load effects force-displacement hysteretic diagrams

The force-displacement hysteretic diagrams allow the conclusion that the model simulates the global element behaviour very well, as there is a reasonable approximation to the hysteretic loops obtained experimentally. It is particularly interesting to observe a slight reduction of the stiffness over the course of the cycles due to degradation and, in the loading stage of the cycles, the “pinching” effect related to the closing of the upper cracks with subsequent stiffness increase.

The apparent differences may be related to the simplifications considered in the model, which were: the assumption of a T-section along the overall span; the use of four points of integration; the consideration of shear deformation only using an uncoupled elastic shear force-deformation relation to the existing fibre section.

It can be observed from the force-displacement hysteretic diagrams that the initial stiffness is approximately the secant stiffness.

The response of the numerical model subjected to the cyclic test procedure including gravity load effects was limited to a level of deformation of 6% of cantilever span (beam drift).

5. Discussion

The influence of the gravity load on the behaviour of a structure subjected to cyclic loads can be sustained by the experimental results of the beam specimens.

The procedure proposed by ECCS (1985) [7] consists of applying a symmetrical cyclic displacement history with increasing amplitude, leading to a reversing hysteretic response. In a frame system under cyclic loads this type of response corresponds to the formation of a reverse plastic hinge in the extremities of the beam [25] – Fig. 17.

As observed experimentally, the consideration of the vertical load effects in the test procedure led to an accumulation of negative (hogging) deformation. In a portal frame system under cyclic loads this phenomenon occurs when the level of the vertical load effect is significant, leading to the formation of unidirectional plastic hinges [25], [26].

The bending moment due to cyclic load depends on the remaining bearing capacity at the support ends (MA, MB), i.e., after the vertical load effects. Thus, the bending moment diagram (E) due to the cyclic load is not symmetric.

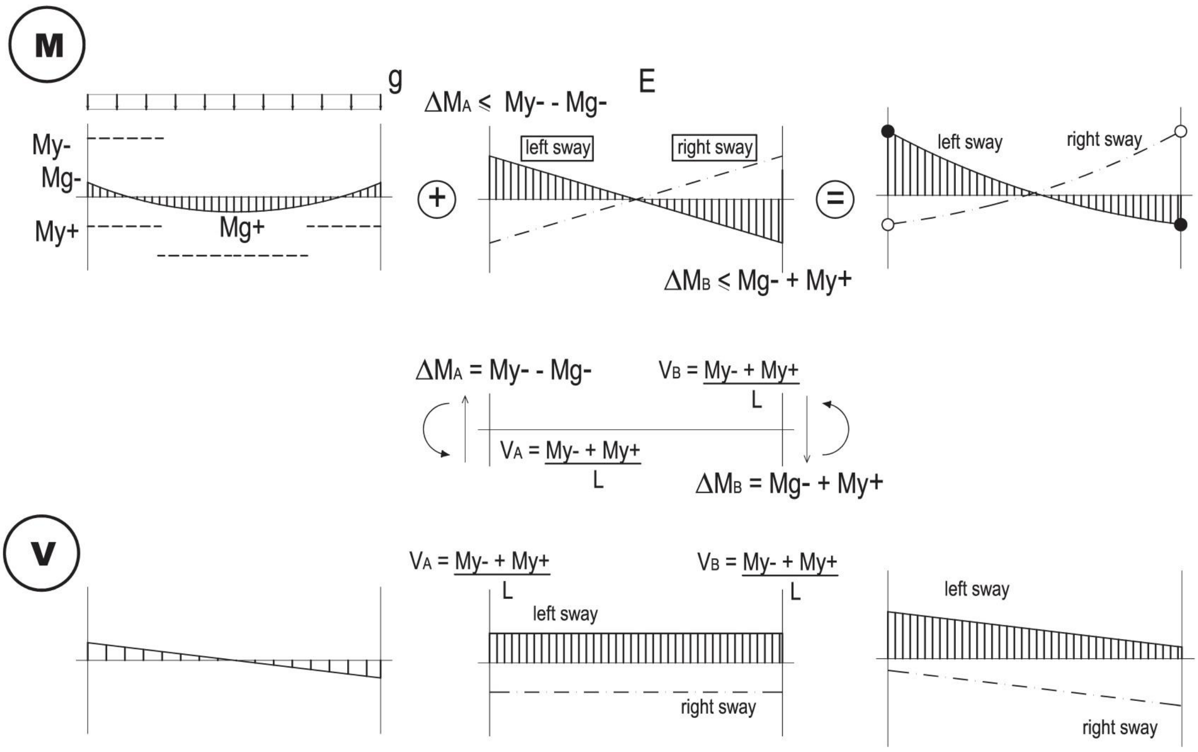


Fig. 17. Formation of reversing plastic hinges in a portal frame system without significant vertical load effect

In fact, the positive bending moment due to the vertical load can induce the formation of a beam span plastic hinge if the shear due to the vertical load at the beam ends exceeds the shear induced by the cyclic loads (which depends mainly on the bending moment resistance at the support) – Fig. 18.

In this case, the formation of four plastic hinges can be observed: when sway occurs towards the right a left span plastic hinge and a right support hinge are formed; when sway occurs towards the left a right span plastic hinge and a left support hinge are formed. Instead of being reversible, the rotation of the hinges increases in one direction, as observed in the experimental test.

The position of the plastic hinge in the span depends mainly on the strength of the cross-sections, on the level of vertical load imposed, on the beam span and on the reinforcement detail along the beam.

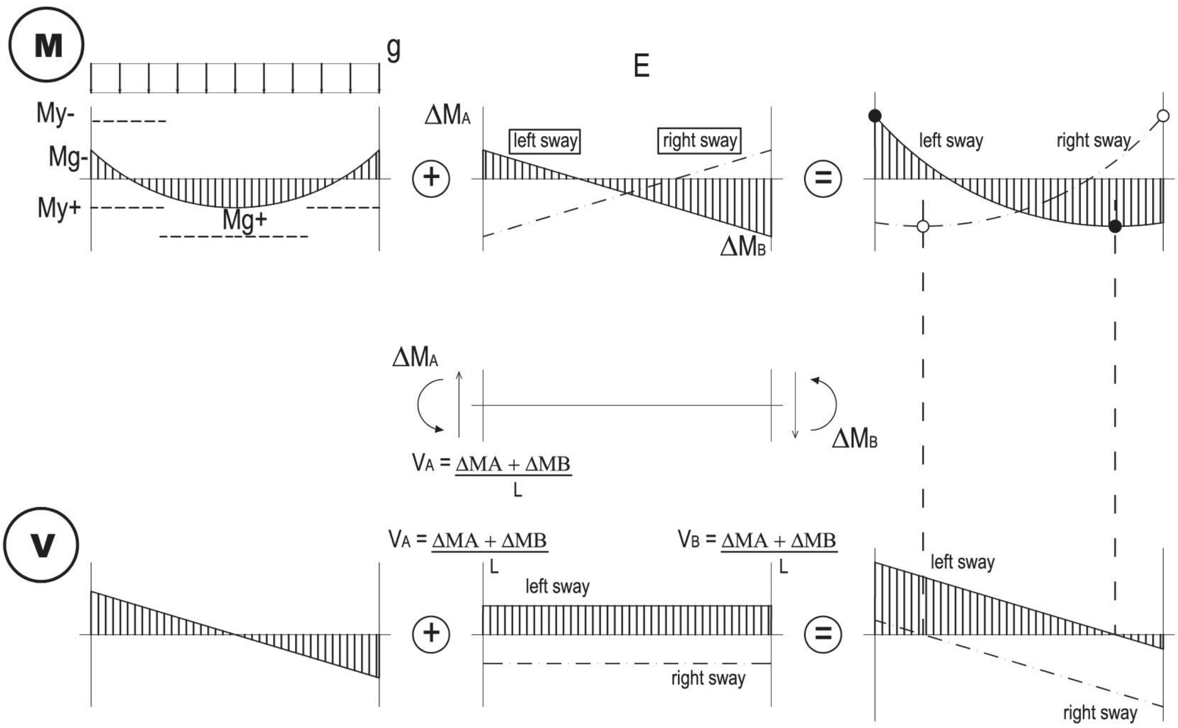


Fig. 18. Formation of unidirectional plastic hinges in a portal frame system with significant vertical load effect

The corresponding deformed frame configuration is shown in Figure 19.

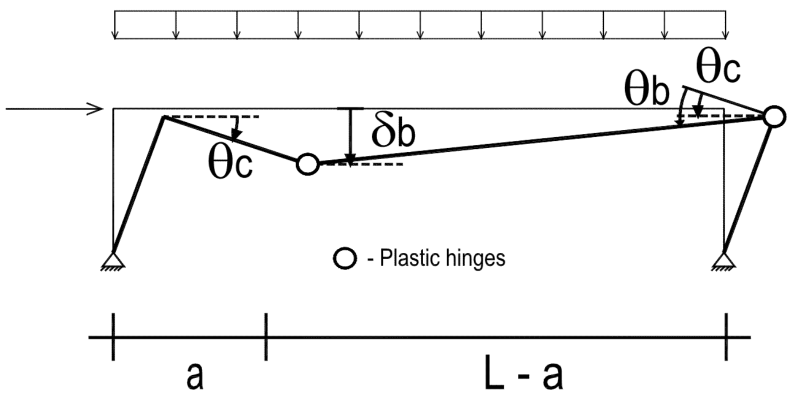


Fig. 19. Deformed frame configuration related to the formation of unidirectional plastic hinges with significant vertical load effect

The beam rotation (θ_b) can be related to the column rotation (θ_c) through the following expression:

$$\theta_b = \theta_c + \frac{\delta_b}{L-a} \quad (1)$$

The relation between the beam deformation and the column rotation is given by the expression:

$$\delta_b = \theta_c \cdot a \qquad (2)$$

Equation (2) can be substituted in equation (1), then equation (1) becomes

$$\theta_b = \theta_c \cdot \left(\frac{L}{L-a}\right) \qquad (3)$$

The drift demands on a beam with unidirectional plastic hinge are greater than on a reversing plastic hinge. This is because the beam's drift in a reversing plastic hinge is directly related to the column drift. But, as referred above, the rotation sustained by a unidirectional plastic hinge is also greater.

In this study the connection subjected to ECCS displacement history leads to the formation of a reversing plastic hinge. In ACI T1.1-01 (2001) [8] is defined an acceptance criterion for the experimental tests that consist in demonstrate the ability to retain structural integrity and support specified gravity loads through peak displacements equal to or exceeding a drift ratio of 0.035. In this case, admitting that a 3.5% drift is required in the column (see Fig. 7), it can be concluded that the hysteretic response of the tested beam would not have sufficient ductility and the section should be strengthened.

Furthermore, the displacement history procedure including gravity load effects leads to the accumulation of deformation that corresponds to the formation of a unidirectional plastic hinge (which cannot be observed in the ECCS test procedure). In this case, the connection had sufficient ductility but it could not be fully exploited (see Fig 9). If improved energy dissipation is required the beam critical region resistance should be increased, rather than the ductility.

This could lead to the unacceptable level of deformation associated with excessive damage after an earthquake, if the only failure criterion established is the instant when the connection

is no longer able to sustain the gravity load. A failure criterion should also be established based on the drift [6, 25, 27] and on the residual stiffness of the beam connection to the column.

6. Proposed procedure for RC beam-to-column cyclic tests

In order to better reproduce the demands on the beam critical zone, a cyclic test that includes the gravity load effects is proposed. This test procedure involves the imposition of a history of reverse cyclic displacement, starting from the gravity load effects. This results in a non-symmetrical loading history where failure takes place when the beam is either unable to resist the gravity load or a specific drift is attained.

The proposed procedure for RC beam critical zone cyclic tests is summarized as follows:

i. Establish the load (F_g) equivalent to the gravity load effects, dependent on the yielding force (F_y) of the beam: $F_g = \alpha \times F_y$;

ii. Establish the values of the positive (d_0^+) and negative reference displacement (d_0^-). It should be noted that the displacement history will not necessarily be symmetrical;

iii. Establish the value of the maximum drift in the beam (*d/L*). Assuming a linear relation between rotations and displacements in the column, the maximum drift in the beam is usually higher than in the column;

iv. The test begins with the imposition of the pre-established load (F_g) equivalent to the gravity load effects;

v. Then, a cyclic displacement history between positive ($+\Delta$) and negative amplitude ($-\Delta$) is imposed, with 3 cycles at each step. After each step, the displacement is successively increased until the rupture criterion is attained. The development of

this procedure leads: in a first stage, to a displacement-controlled test corresponding to the imposition of the displacement amplitude; in the next stage, to a force-controlled unloading test until the value of the gravity load is restored; subsequently to the application of the reverse displacement amplitude, and, finally, to a force-controlled test whereby the value of the gravity load is re-established.

During the test, the restoration of the gravity load corresponds to larger displacements, leading to different starting points at which the cyclic displacements are imposed and the displacement history will not be necessarily symmetrical;

vi. Failure occurs when the connection is either unable to resist the gravity force (F_g) or the maximum drift in the beam (*d/L*) is attained.

7. Conclusions

The traditional protocols for quasi-static cyclic tests on RC beams do not consider the gravity load effects. In this study, a procedure for RC cyclic tests that reproduce demands on the beam critical zone more realistically than the traditional procedures is presented and analysed.

In order to assess the influence of the gravity load on the hysteretic behaviour of a beam critical region, the experimental program carried out involved cyclic tests on the specimens complying ECCS recommendations [7] and cyclic tests following the proposed procedure. This test consists of imposing a reverse cyclic displacement history, starting from the gravity load effects, and rupture occurs when the connection is either unable to resist the gravity forces or the maximum drift in the beam (*d/L*) is attained.

The test results have been presented, compared and analysed. A numerical simulation of the tests was performed using nonlinear structural analysis software – *OpenSees* – and the results were analysed and compared with the experimental results.

The inclusion of the gravity load effects in a procedure for RC beam critical region cyclic conducted to more realistic results than the traditional ECCS cyclic test procedure. The proposed test procedure led to an accumulation of negative (hogging) deformation, reproducing the behaviour of a RC beam critical region inserted in a portal frame system under cyclic loads and subject to a significant level of the vertical load, i.e., leading to the formation of unidirectional plastic hinges.

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