SEISMIC STRENGTHENING OF RC BEAM-COLUMN CONNECTIONS

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SUMMARY:

In a frame system, the seismic energy is mostly dissipated through the development of plastic hinges located, in general, at the extremities of the elements. Thus, assuming a strong-column–weak-beam seismic design, the global structure response improvement can be attained through the strengthening of the beams in the beam-column connections. This fact justifies the search for new RC beam-column connections solutions with high seismic performance.

This experimental study is about the analysis of the beam behaviour subjected to a cyclic procedure starting from the gravity load effects. The improvement of the seismic performance can be achieved through stiffness, strength or ductility modification. For that purpose, two strengthening solutions were developed and tested: *unbounded post-tension tendons strengthening* in order to increase the resistance and to limit the residual deformations; *unbounded post-tensioning with jacketing of the RC beam with unidirectional fibre reinforced grout (UFRG)*, to limit the compression damage, improving the section confinement, delaying the concrete crushing and the buckling of the longitudinal reinforcement. The hysteretic behaviour of the tested connections are presented and analysed.

Keywords: RC beam-column connection, cyclic test, gravity load effects, seismic strengthening, fibre reinforced concrete, post-tension

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 [fib Nº. 24 (2003)]. The requirement to improve the seismic behaviour of structures can be related, not only to possible structures deficiencies, but also, to new usage demands and new design recommendations, such as, increase of a load carrying capacity to meet a higher level of function or to minimize damage during an earthquake in order to maintain operational important civil protection structures [EN 1998-1 (2004)].

The structural intervention with the aim to correct or to improve the seismic performance of a structure - *retrofit* - can be achieved through two approaches: decreasing of earthquake demands or increasing deformation capacity. The implementation of the first approach involves global modifications of the existent structure so that the earthquake demands are lower than their capacities, achieved through stiffness or strength modifications, introduction of seismic isolation and energy dissipation devices, or mass reduction. The aim of the second approach is to increase the deformation capacity of deficient components, leading to a local modification, in order to attain the original earthquake demands. The implementation of this approach leads to structural modifications of isolated components or elements through, e.g., traditional techniques such as steel and concrete jacketing, steel plate adhesion or externally bonded FRP composites (Fibre Reinforced Polymer), etc. The implementation of this approach aims an improvement of the overall response of the structure. In some cases, the retrofit of a structure can lead to the implementation of both approaches in order to increase deformation capacity and modify the demands [fib Nº. 24 (2003)].

The Part 3 of Eurocode 8 [CEN EN 1998-3 (2005)] recommends the following type of intervention: local or global or full replacement of damaged or undamaged elements, considering stiffness, strength and ductility modification of these elements; addition of new structural elements; modification of the structural system thought elimination of vulnerable joints or elements, in order to improve regularity or ductility; addition of a new structural system that sustain a part or all of the seismic action; possible transformation of existing non-structural elements in structural; introduction of passive protection devices through base isolation systems or dissipative bracings; mass reduction; restriction or change of use of the building; and/or partial demolition.

2. REVIEW OF RELEVANT RESEARCH WORK

The aim of the present research work was the improvement of the seismic structural behaviour of frame systems, through the enhancement of the hysteretic behaviour of an element or a component. In frame systems, the plastic hinge regions located, in general, in the extremities of the elements, are mostly responsible for dissipating energy [CEB BI Nº. 220 (1994)]. Therefore, the main goal is to improve the structure performance through the beam-column connection strengthening. Assuming a strong-column–weak-beam seismic design [EN 1998-1 (2004)], the experimental study of the beam-column connection was limited to analysing the beam behaviour.

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, shear walls and, eventually, including joints) [fib Nº. 24 (2003)]. For once, experience from past earthquake has shown a higher level of damage in the vertical elements. Besides, an inadequate behaviour concentrated in the vertical elements can induce a global failure mechanism, e.g., soft-storey. Furthermore, the strengthening of a beam is technically more difficult to attain than of a vertical element due to the presence of a monolithic connection with the slab. Thus, in this domain, scientific research efforts have been focused in the study of the hysteretic behaviour and on upgrading techniques of the vertical elements.

The main deficiencies point out in the few research works related with beams are inadequate seismic design, lack of continuity of bottom bars over the supports and limited deformation capacity of the compression zone. However, in the first case, which corresponds to beams designed only for gravity loads, the top reinforced over the supports (including the slab bars within the effective flange width) and the typical closed stirrups within the critical zone of the beam provide enough resistance capacity. In fact, this additional capacity of the beams due to the participation of the full slab width, determines the formation of plastic hinge on the columns which may lead to undesirable failure mode, such as, soft-storey mechanisms. The lack of continuity of bottom bars, eventually, leads to an increase of the lateral deformations [Bracci et al. (1995); El-Attar et al. (1997); Calvi et al (2002)].

Therefore, taking into consideration the lack of research works related with the hysterical behaviour of the plastic hinges that should be formed in the RC beams, especially in the presence of significant gravity loads, and of the upgrading of their performance in order to optimize the behaviour of beam-column connection, justifies the present experimental research. The reference specimen is a RC T-beam which has been designed to exhibit normal ductility, as detailed in section 3.1. The 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 [ECCS (1985), ACI T1.1-01 (2001) and ATC Report Nº 24 (1992)]. In this study, an alternative procedure for RC cyclic tests was used [Gião et al. (2009)] which reproduces the demands on a critical zone more realistically and also considers the asymmetries of the section in terms of geometry and reinforcement. This alternative 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.

As mentioned, the aim of the presented experimental study was to correct or improve the hysteretic behaviour of the beam-column connection. In the search of improved seismic solutions, it should be mentioned the interesting approaches and concepts presented by some researchers. For instance, Pinho and Elnashai (1998) presented an experimental work on retrofitting of RC walls. A *selective techniques approach* is proposed through stiffness, strength or ductility modifications of structural elements, intended to improve the overall structural behaviour. Pampanin (2006) presents the concept for an alternative seismic retrofit strategy - *selective weakening approach* - which focuses on reduction the earthquake demands and protecting undesirable seismic response mechanisms by first strategically weakening specific elements within a structure. Ireland et al. (2006) present an experimental work related to the implementation of a selective weakening retrofit approach to shear deficient structural walls in order to eliminate an undesirable shear mechanism. The implementation of this strategy involves a vertical cut of the wall, ensuring the formation of a ductile failure mechanism. In a second stage, the authors propose an upgrading of the element behaviour through the application of recent technological developments in building systems [Pampanin (2005)]. Such as, ensuring *rocking behaviour* to minimize damage (achieved through a horizontal cut) and a *self-centring behaviour* in order to minimize the residual displacements after seismic response (through the introduction of post-tensioning). Kam et al. (2010) present a summary of a research work developed regarding the implementation of a selective weakening approach to non-ductile RC beam-column joints, proposing a cut at the interface beam/column and/or introduction of post-tensioning, in order to achieve a ductile failure mechanism.

To increase the deformation capacity of the compressive zone, several researchers have report significant improvements in the seismic behaviour of RC subassemblages, such as, beam-column joints regions, strengthening with HPFRC (High Performance Fibre Reinforced Concrete) [Dogan and Krstulovic-Opara (2003); Fischer and Li (2003); Parra-Montesinos (2005); Shannag et al. (2005)]. Gião et al. (2012) presented a strengthening solution for reinforced concrete structures with a unidirectional fibre reinforced grout small thickness jacketing (UFRG), in order to delay concrete crushing and buckling of longitudinal reinforcement in the compression side of the RC element. Knowing that the behaviour of a composite is influenced by the properties of the cementitious matrix and fibres, continuous and unidirectional steel fibres (set in the form of a mat) exhibited the appropriate features in order to achieve the required mechanical properties of the composite.

3. EXPERIMENTAL PROGRAM

The experimental program included the development and testing of a full scale beam-column reference connection (specimen S1). The experimental test was carried out according with a cyclic test procedure starting from the gravity load effects.
In order to correct or improve the observed hysteric behaviour of the reference beam-column connection, a selective technique approach was implemented and two strengthening solutions were developed and tested. In the first solution unbonded post-tension tendons were used (specimen S2). In a second stage, a small thickness jacketing with unidirectional fibre reinforced grout (UFRG) was added to the post-tension system (Specimen S3).

3.1. Specimens geometry and reinforcement details

Assuming that the basic principle of the weak beam - strong column is attained [EN 1998-1 (2004)], i.e., that the plastic hinge forms in the beam, the experimental study focused on the analysis of the behaviour of the RC beam.
The reinforced concrete reference specimen was a T-beam, designed to exhibit normal ductility, with a cross-section 250 mm wide by 500 mm high (Fig. 3.1).
In terms of mechanical characteristics the average cylindrical compressive strength at the time of the

tests was 44.8 MPa, 41.7 MPa and 43.1 MPa, respectively, for specimen S1, S2 e S3. The steel yield strength of the longitudinal reinforcing bars was 473 MPa.
The specimen is a cantilever T-beam that simulates roughly 1/3 of the clear span of a beam connected to columns at both ends. The column is modelled by a rigid block. The T-beam reinforcement detailing and the location of twenty-four internal strain-gauges used in the test programme are shown in Fig. 3.1.

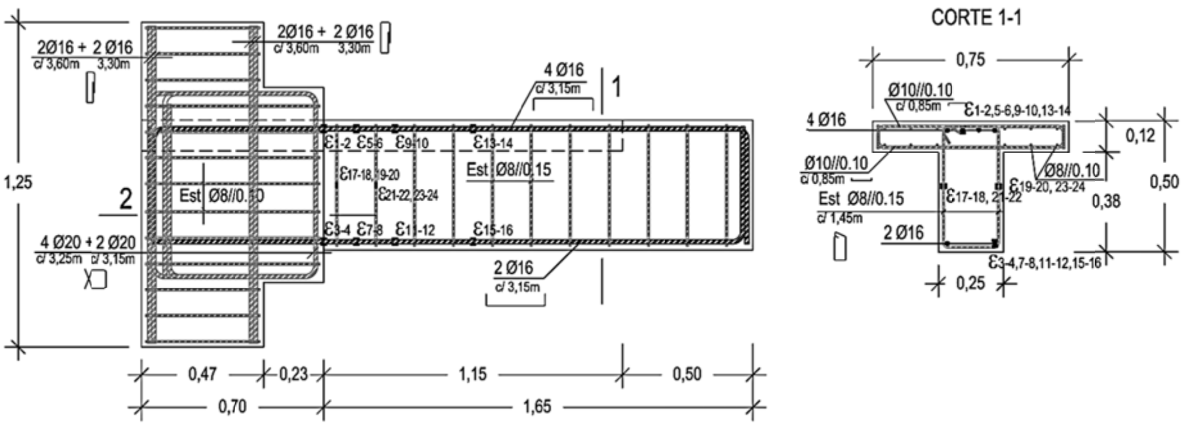


Figure 3.1. Geometry, detailing and internal instrumentation of the reference specimen (S1)

3.2. Description of the beam-column strengthened specimens

In a first stage, the aim was to limit the residual deformations and to increase the strength. Therefore, a strengthening solution with two external post-tensioned strands of grade Y1860 with nominal diameter of 0.60" was designed. It was expected an increasing of the dissipated energy provided by the yielding of the ordinary reinforcement and a strength increment due to post-tensioning. Assuming a 1:5 inclination and a reduced eccentricity at the support section (as illustrated in Fig.3.2.), the post-tensioning strand profile was optimized, so the post-tension steel remained elastic at the required drift (that was pre-established as 3.5%).

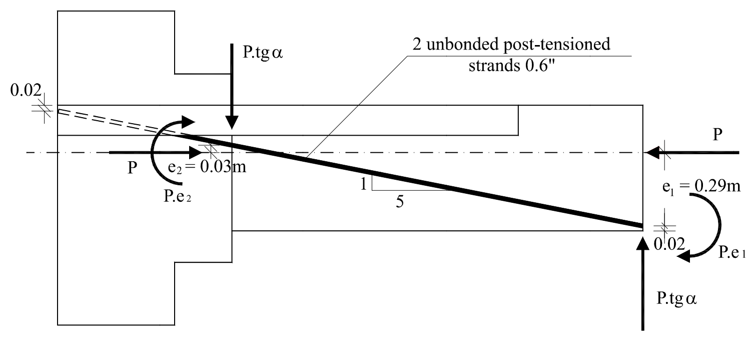


Figure 3.2. Detailing of the strengthening solution with unbonded post-tensioning system (specimen S2)

In a second stage, in addition to the unbonded post-tensioning system, a small thickness (t = 20 mm) jacketing with unidirectional fibre reinforced grout (UFRG) with 3% fibre volume was used – see Fig. 3.3. With this strengthening solution, it was expected to improve the confinement of the section, delaying the concrete crushing and the buckling of the longitudinal reinforcement.
The UFRG used, exhibits high compression strength normal to the fibre direction and high tensile strength in the fibre direction, respectively, 66 MPa and 12.3 MPa. The execution of the jacketing with unidireccional and continuous steel fibre (set in the form of a mat) reinforced grout was more efficient than current reinforced concrete solutions, allowing smaller thickness for the jacket.
The execution of the strengthening included the preparation of the concrete surface with water and sand blasting in order to improve the bond between the concrete and the strengthening. The

strengthening was cast against the specimen contact surface. During casting, the grout was poured into to the pre-placed fibres with exterior vibration.

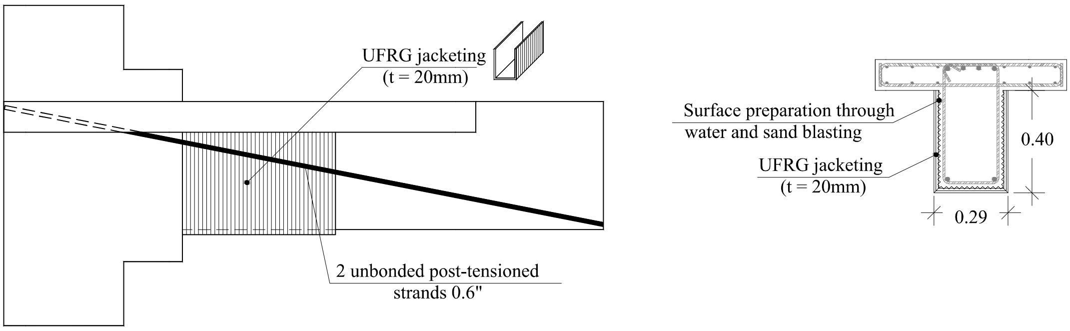


Figure 3.3. Detailing of the UFFG jacketing and unbonded strand post-tensioning system (specimen S3)

A brief description of the experimental specimens is presented in Table 3.1.

Table 3.1. Description of the beam-column specimens

Specimen	Description	Initial Post-tensioning force (kN)	UFRG jacketing
S1	benchmark specimen	-	-
S2	Strengthening solution: External post-tensioned (PT)	300	-
S3	Strengthening solution: External PT + UFRG jacketing	300	20 mm UFRG jacketing

3.3. Test setup

The experimental campaign was carried out in the Laboratory of Structures of the UNL. This laboratory has two reaction walls and a strong floor. The equipment used for the tests was a mechanical actuator with ±500 kN capacity for horizontal loads and up to 400 mm (±200 mm) for displacements, a double-action load cell with ±500 kN capacity (FIMEI CS-24) and seven displacement transducers with the range of 100mm (CDP100 TML) - Fig. 3.4. Four data loggers (8-channel Spider8) from HBM were used for data acquisition.

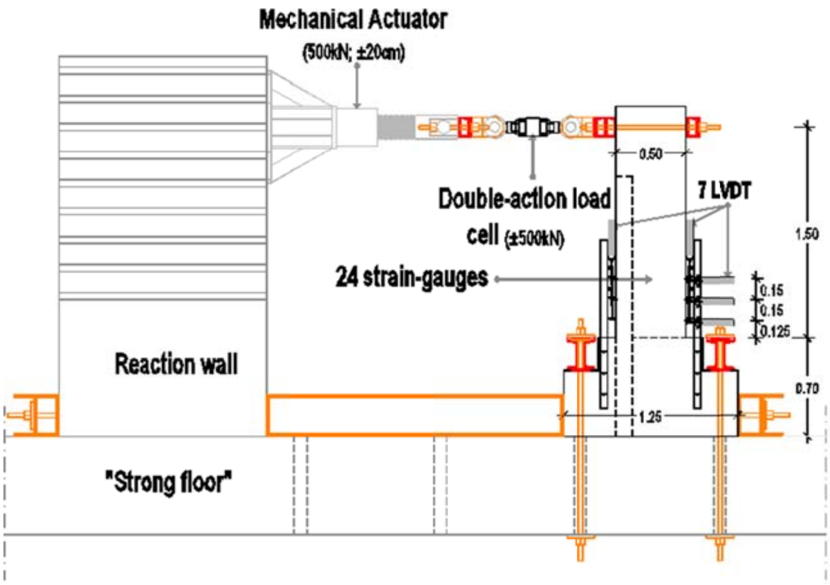


Figure 3.4. Test setup

3.4. Loading history

A quasi-static test procedure was implemented in order to simulate the gravity load on the beam with an asymmetrical cross-section geometry and reinforcement. The proposed procedure consists on imposing a reverse cyclic displacement history with increasing amplitude (wherein three complete cycles are performed for each amplitude step), starting from the gravity load effects. Failure occurs when the connection is either unable to resist the gravity loading or a maximum specified drift is attained.
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. 3.5 it is stage 0). The performance of a cycle consists of the following stages (illustrated in Fig. 3.5):

i. Imposition of the required displacement amplitude +Δ;
ii. Unloading until the value of the gravity load is re-established;
iii. Imposition of the intended displacement amplitude -Δ;
iv. Loading until the value of the gravity load is re-established.

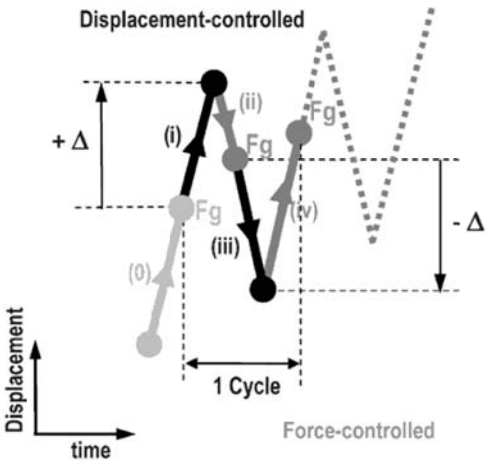


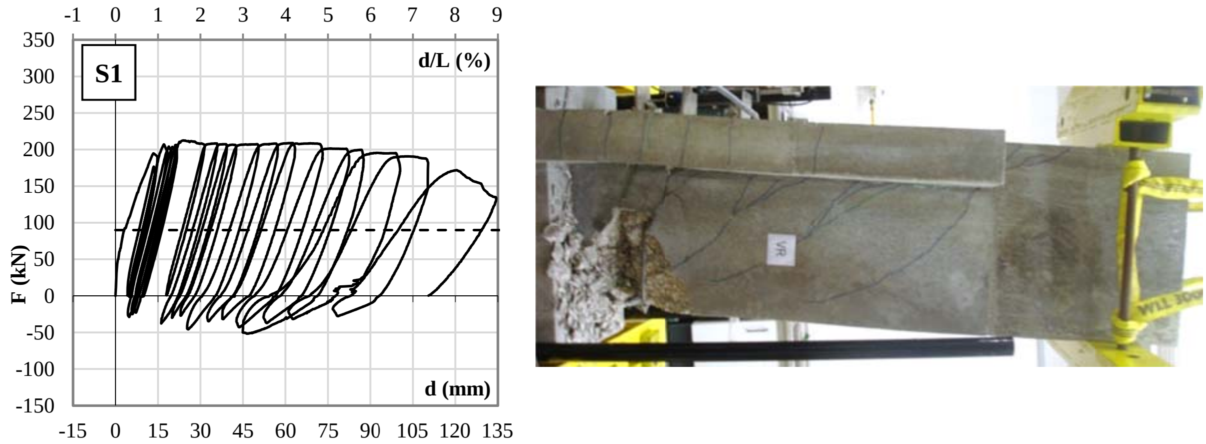
Figure 3.5. Typical load cycle in the test procedure [Gião et al. (2009)]

The implementation of this procedure led to the following load sequence: application of a pre-established load equivalent to the gravity load effects on the beam’s fixed end (F_g = 90 kN - corresponding to 50% of the force that leads the top reinforcement of the reference specimen to yield F_y), 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 yielding displacement was determined experimentally in the first part of the reference specimen test, as the displacement associated to the yielding strain (established through observation of the strain-gauges on the longitudinal bars). The yielding displacement 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 base displacement (d_0) as the lower value obtained, i.e., 6 mm.

4. TEST RESULTS

4.1. General behaviour and failure mechanisms

4.1.1 Specimen S1
The hysteresis response of specimen S1 is shown in Fig. 4.1(a). Specimen S1 exhibited a maximum horizontal load of 212.5 kN and a drift limit of 9.0%.



(a) **(b)**

Figure 4.1. Specimen S1: (a) force-displacement hysteretic diagram; (b) failure mode

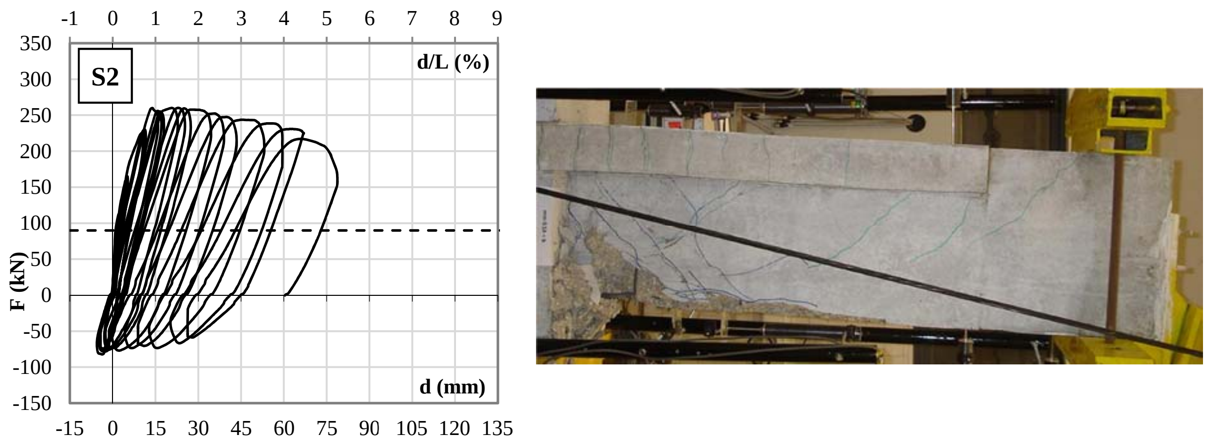
The failure mode was associated with gradual deterioration of the compressive zone and progressive buckling of the longitudinal bottom bars - Fig. 4.1(b). This test led to an accumulation of negative deflection (hogging), while for positive moments, the longitudinal bottom reinforcement remained on the elastic range until the end of the test. This fact is associated with the pre-compression induced by the gravity load bending moment, thus the tension in the reverse loading cycle was not enough to yield the bottom reinforcement. The top cracks remained open and no significant “pinching” effects were observed.

At the end of the test, the beam resistance was higher than the corresponding pre-established gravity load. Nevertheless, the force was lower than 85% of the maximum reached force and drift exceeded largely the predefined limit of 3.5% (see Fig. 4.1(a)).

4.1.2 Specimen S2

Before the test procedure, the post-tensioning system was installed along with the respective end anchorages. The next step consisted in the incremental application of the post-tensioning force until 150kN in each strand. The load was imposed using two Enerpac hydraulic jacks with a capacity of 200kN. The load imposition was conducted by a hydraulic pressure control system ENERPAC CDT 6343. Two load cells, with a capacity of 300kN, were placed and connected to the data acquisition unit for continuous measurement of the applied load.

The hysteresis response of specimen S2 is shown in Fig. 4.2(a). Specimen S2 exhibited a maximum horizontal load of 260.1 kN and a drift limit of 5.3%.

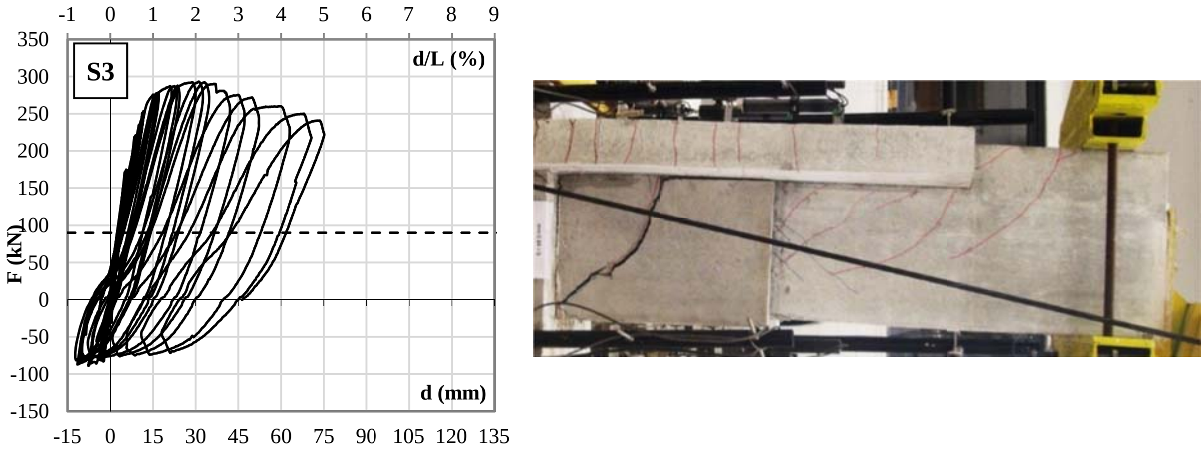


(a) **(b)**

Figure 4.2. Specimen S2: (a) force-displacement hysteretic diagram; (b) failure mode

Failure mode was prompted by gradual deterioration of the compressive zone. As expected, comparatively to the reference specimen, this connection exhibited a resistance increase and lower residual deformation. However, during testing, it was observed progressive degradation of the compression zone and buckling of the compressive longitudinal reinforcement. Specimen S2 presented significant damage at rupture - see Fig. 4.2(b).

4.1.3 Specimen S3
The hysteresis response of specimen S3 is shown in Fig. 4.3(a). Specimen S3 exhibited a maximum horizontal load of 293.0 kN and a limit drift of 5.0%.



(a) (b)

Figure 4.3. Specimen S3: (a) force-displacement hysteretic diagram; (b) failure mode

In this solution, the level of damage at rupture was lower than the observed in the specimen 2 and buckling of the compressive longitudinal reinforcement did not occur. The UFRG jacketing was able to delay concrete crushing and prevent buckling of the compressive longitudinal reinforcement. In fact, until the penultimate load cycle, corresponding to a "drift" of 4.7%, the connection didn't exhibit significant damage. In specimen S3 test, a failure mode associated with fracture of the jacketing material at the compressive side of the beam was observed (see Fig.4.3(b)).

The analysis of the load-displacement hysteretic diagrams shows that the addition of the post-tensioning system allowed a significant reduction of the residual deformation and an increase of the maximum force. The strengthened connection with addition of the UFRG jacketing shows a more stable load-displacement hysteretic response since significant damage in the compressive zone was delayed until near failure. The behaviour of the strengthened connections exhibited an evolution towards a more recentred behaviour.

4.2. Performance evaluation

In order to assess the performance of the proposed strengthening solutions, the following parameters were selected: *displacement ductility* (μ)*; energy dissipation (W) and residual displacement* (d_r). The parameter displacement ductility is defined as the ratio between the maximum and yielding displacement. The energy dissipation capacity is obtained from the area under the load-displacement diagrams. For each specimen, the obtained performance parameters are presented in Table 4.1. The dimensional parameters were undimensionalized in relation to the benchmark specimen values.

Table 4.1. Performance evaluation parameters

Description		$F_{máx}$ (kN)	$F_{máx}/F_{S1}$	Displacement ductility –/+ (*) $\mu=d_u/d_y$		Energy dissipation W (kNm)	W/W_{S1}	Residual deformation d_r (mm)	d_r/d_{rS1}
S1	specimen	212.5	-	10.4	-	28.6	-	126.2	-
S2	PT	260.1	1.22	7.7	2.4	43.8	1.53	71.2	0.56
S3	PT + UFRG jack.	293.0	1.38	6.4	6.1	57.2	2.00	58.7	0.47

(*) – corresponds to negative moments bending direction (hogging)
+ corresponds to positive moments bending direction (sagging)

The ratio $F_{máx}/F_{s1}$ corresponds to the increase of the bearing capacity, through which can be concluded that the strengthening solution with external post-tensioned achieved a 22% increasing in the resistance of the connection. The addition of the UFRG jacketing on the bottom side of the RC beam it was attained a strength increase of 38% relatively to the reference specimen.

Through the analysis the parameter W/W_{S1}, that represents the energy dissipated gain, it should be noted that with the strengthening solutions a considerable increasing can be attained. The connection strengthened with external post-tensioning had an energy dissipation increase of 53% relatively to the reference specimen. On the other hand, the connection strengthened with external post-tensioned and UFRG jacketing had energy dissipation increase of 100% relatively to the reference specimen.

The reference specimen exhibit a large accumulation of negative deflection (hogging), however ductility for positive moments (sagging) wasn´t mobilized because longitudinal bottom reinforcement remained on the elastic range until the end of the test. On the other hand, the first strengthening solution mobilized a level of ductility in the direction of negative moments, which is higher than the level of ductility in the direction of positive moments. However, the second solution showed a level of ductility similar in both directions. This behaviour is due to the recentring capacity of the strengthening system.

From the analysis of the parameter dr/dr_{S1}, it can be observed that with the strengthening solutions a considerable reduction of the residual deformation was attained. The connection strengthened with external post-tensioning had a reduction of 44% relatively to the reference specimen. The connection strengthened with external post-tensioning and UFRG jacketing had a decrease of residual deformation of 53% relatively to the reference specimen. These observations indicate a more recentring behaviour and an increase in the restoring capacity of the strengthening connections.

It can be concluded that there was an increase of dissipated energy with the strengthening solutions, combined with increased strength, and a reduction of the residual deformation.

5. CONCLUSION

The cyclic test of specimen S2 shows an improvement of the beam-column connection hysteretic behaviour through an increase of energy dissipation capacity, combined with strength increase and reduction of the residual deformation. The test starts from the gravity effects of the strengthened connection with external post-tensioning and its behaviour indicates a more recentred hysteretic response and an increase in the restoring capacity of the connection.
The strengthening solution with UFRG (unidirectional fibre reinforced grout) jacketing, in addition to the external post-tensioned - specimen S3-, was able to delay concrete crushing and buckling of longitudinal reinforcement. Therefore, the connection presents a more stable response and less damage than in the other tests performed.
The analysis of the performance parameters of the strengthened connections (S2 and S3), compared to the reference specimen (S1), leads to the following observations:

- The strengthening solution S2 achieved a strength increase of 22% whereas the solution S3 registered a strength increase of 38%;
- In terms of energy dissipation, the specimen S2 had an improvement of 53% and specimen S3 an

increase of 100%;
- The connection strengthened with UFRG jacketing exhibit a level of ductility similar in both directions;
- The reduction of residual deformation in specimen S2 was 44%, whereas in the specimen S3 it was 53%.

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