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SEISMIC ASSESSMENT OF PRECAST BEAM-TO-COLUMN CONNECTIONS AND RETROFITTING SOLUTIONS

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Abstract

The inadequacy of beam-to-column connections in RC precast structures can cause catastrophic collapses due, for instance, to loss of support phenomena in the case of absence of mechanical devices. In order to achieve an adequate global seismic capacity, hence, the retrofitting of these connections is a necessary step for existing precast structures.

An experimental campaign is performed in order to investigate the seismic behavior of typical beam-to-column connections for precast one-story buildings.

The reference connection is a dowel beam-to-column connection, tested under cyclic shear loads up to collapse. It showed a very brittle failure with concrete cover splitting in the column and a non-symmetric behavior for the two loading directions. In particular, for pulling loads (i.e. horizontal loads against the column frontal cover) a significant strength degradation occurs after the attainment of the maximum shear strength, corresponding to the occurrence of the first crack in the column concrete cover.

After the cyclic shear test, the described beam-to-column connection was retrofitted. The proposed retrofitting solution is based on two main mechanical principles: the three hinged arch and the dowel effect so that the total seismic force applied to the beam is transferred to the other two hinges on the column by two steel profiles. The cyclic global behavior in terms of force-displacement curve was investigated and the damage patterns after the test were described by means of both visual inspections and instrumentation records.

The experimental results demonstrate a good behavior under seismic actions, since no significant damage in the concrete was recorded due to the large concrete covers in the retrofitted system which prevented brittle failures in the connected elements. The horizontal shear force was mostly sustained by the three hinges mechanism, ensured by the two steel profiles under axial loads.

Moreover, the comparison between the retrofitted and the dowel beam-to-column connection also allow to define the main critical features of this connection system, as the concrete cover of steel bars in the connected structural elements. The retrofitted connections showed larger shear strength as well as larger dissipated energy values than the standard dowel connection.

Keywords: RC precast buildings; beam-to-column connections; cyclic tests; seismic retrofitting; three-hinged steel system.

1. Introduction

During some recent earthquakes, like L'Aquila (Italy), 2009[1], Van (Turkey), 2011 [2], and Emilia (Italy), 2012 [3-5], earthquakes, the poor seismic response of RC precast structures was mostly caused by the inadequacy of the connection systems between both the structural elements and the structural and nonstructural components [6]. In many structures, indeed, the connections were not designed for any seismic action and their premature failure during the seismic excitation caused catastrophic collapses and structural damages [5, 7].

Magliulo et al. [8] performed several nonlinear analyses on existing precast structures in order to assess their seismic response. The analyses results demonstrated that the strength of the frictional beam-to-column connections can be lower than the seismic demand in low-medium seismic zones in Italy: in these areas the collapse of the structures could occur due to the loss of the support in the beam-to-column connections. Moreover, in the following years the same authors experimentally defined the frictional strength for the typical existing frictional connections (neoprene-concrete) [9] and they found out that the frictional coefficient values were lower than the values adopted in the previous study, giving an even lower structural safety.

The underlined seismic vulnerability sources encouraged the scientific and the technical community in addressing growing efforts for the study of seismic retrofit of RC precast structures. Some authors studied innovative retrofitting solutions for existing precast buildings; however, few efficient solutions were defined in the last years, such as mechanical devices for connections [10, 11], dissipative systems [7] and retrofitting actions for vertical elements (columns) and foundations[11, 12], typically used for RC frame structures.

In the presented paper, the cyclic behavior of a dowel beam-to-column connection is investigated by means of a full scale shear test. The specimen shows a brittle failure mode, characterized by the spalling of the concrete cover due to poor seismic details, confirming the evidences of recent experimental researches on precast structures [13, 14]. Consequently, a retrofitting system for precast connections is applied and studied, consisting of a three-hinged steel device. The system was applied to the damaged dowel beam-to-column connection and the seismic performance is investigated by means of cyclic shear tests. The experimental results demonstrated the capacity of the new connection system; moreover, the comparison with the cyclic behavior of the standard dowel connection shows the more efficient seismic performance of the three-hinged steel device in terms of both shear strength and energy dissipation.

2. Cyclic shear test on the dowel beam-to-column connection

The reference connection is a dowel beam-to-column connection, typically used in precast structures [15, 16]. This connection was tested under cyclic shear loads up to collapse before the installation of the retrofitting system. A more accurate description of both testing protocol and results of the cyclic test on the dowel connection is reported in Magliulo et al. [17].

The concrete of the structural elements (beam and columns), designed according to European provisions [18, 19], had a characteristic cubic compressive stress equal to 55N/mm^2 (i.e. design class equal to C45/55) and the steel reinforcement consists of threaded bars (B450C) with a mean strength at yielding, f_y, equal to 473N/mm^2. The longitudinal and transversal reinforcement for the columns consists of 12ϕ20 and stirrups ϕ8/15cm, respectively. The longitudinal reinforcement, in compression and in tension, for the beam consists of 4ϕ20. Cross section details are provided in Fig. 1.

The dowel connection is performed only on one side of the test specimen (left side in Fig. 1(a)), whereas on the other side (right side in Fig. 1(a)) two teflon sheets avoided undesirable frictional strength between beam and column. The dowel connection consists of two vertical steel dowel (with a cross section diameter equal to 30mm), embedded in the column and passing through the beam, providing a frontal cover (i.e. in the direction of the beam longitudinal axis) equal to 130mm and a lateral cover (i.e. in the transversal direction) equal to 100mm. In order to have an uniform distribution of normal stresses on the column, a neoprene pad (15cmx60cmx1cm) was placed on the dowels side, designed according to the CNR provisions [20].

The specimen was tested under cyclic loads along the beam axis direction. During the shear test, several cracks occurred in the concrete covers of the column up to the complete spalling of the frontal cover at the end of the test. The observed failure was due to the small concrete cover of the steel dowels with respect to the dowel diameter [13, 21] and to the reduced confinement of the concrete because of the large depth of the transversal reinforcement in the column [22]. Fig. 2(a) shows the final configuration of the damage pattern on the lateral surfaces of beam and column.

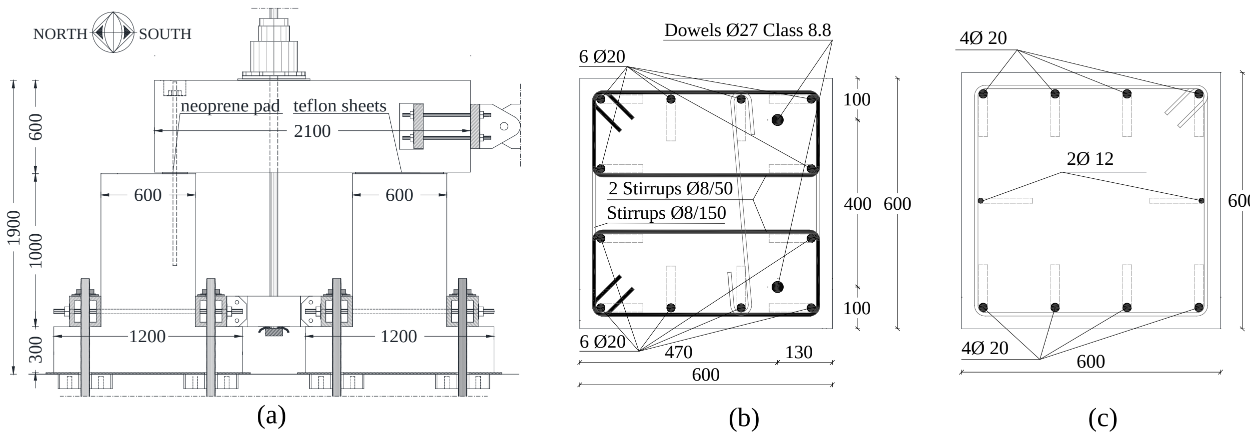

Fig. 1 - Setup of the cyclic shear test on the dowel connection: (a) specimen dimensions (in mm), (b) column and (c) beam cross section details

The connection response is described in Fig. 2(b) in terms of force-displacement curve of the whole cyclic test (solid gray line). In this figure, the negative values of both forces and displacements correspond to pulling loads (i.e. horizontal loads against the column frontal cover), while the positive values of both forces and displacements correspond to pushing loads (i.e. the horizontal loads are applied against the column core).

For pushing loads, the connection exhibits higher shear strength and more limited stiffness degradation than in the case of pulling loads. In particular, for pulling loads a significant strength degradation occurs after the attainment of the maximum shear strength (176.57kN), corresponding to the occurrence of the first crack in the column concrete cover (red point in Fig. 2(b)). The black curve in Fig. 2(b) represents the force-displacement curve up to the 6th step of the loading history, which corresponds to the 20% of shear strength reduction. Such a strength reduction can be assumed as the connection collapse; indeed, after this step the negative values of the force-displacement curve are mainly related to the steel dowel behavior.

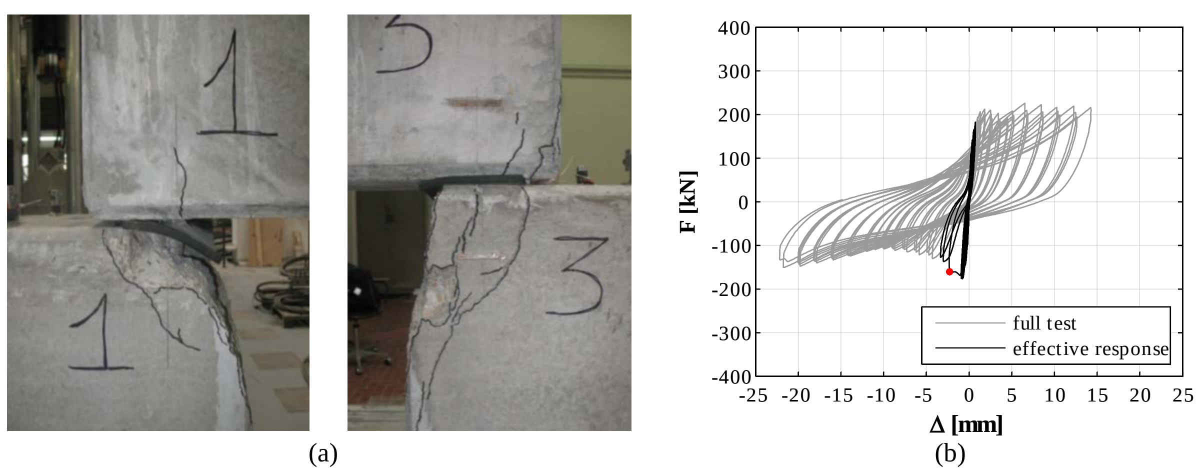

Fig. 2 - Dowel beam-to-column cyclic response: (a) final damage pattern of the tested connection; (b) force-displacement curve of the whole cyclic test (gray curve) and up the 6th step (black curve)

3. The retrofitting system

After the cyclic shear test, the described beam-to-column connection was repaired, restoring the concrete elements, and retrofitted by means of a three-hinged steel system, which is a connection system patented by Capozzi and Magliulo [23] and Capozzi et al. [22]. In this kind of application, it consists of two inclined steel profiles anchored to the concrete elements, by means of horizontal steel dowels passing through holes in the concrete elements, and tightened by means of nuts and washers (Fig. 3). In the reference specimen the horizontal dowel, passing through the beam, is covered by a rubber sheath to avoid high local stresses.

The proposed retrofitting solution is based on two main mechanical principles: the three hinged arch and the dowel effect. According to the former mechanism, the total seismic force applied to the beam is transferred to a couple of hinges on the column by means of two steel profiles. If the steel profiles have a planar configuration, they carry neither flexural nor shear stresses and can be designed only for axial loads. According to the dowel effect, these axial loads are transferred to the steel dowels.

The design of the retrofitting system was performed according to the Italian seismic code [24] (very similar to Eurocode 8 [19]) and Eurocode 3 provisions [25]. The three dowels for the steel profiles anchorage are threaded bars with a diameter of 30mm and with a characteristic yielding strength of 640N/mm^2 (Class 8.8). The dowels were designed according to the provisions [26] for pin connections and their maximum shear strength was also evaluated according to the provisions by CNR 10025 [27]:

$$V_{Rd} = c \cdot \phi^2 \cdot \sqrt{f_{cd} \cdot f_{sd}} \tag{1}$$

In Eq. (1): c is a numerical coefficient depending on the concrete confinement; in this study it is assumed equal to 1.6, in order to take into account the confining effect due to the presence of the steel profiles on both sides of the connection and tightened by nuts and washers; ϕ is the dowel diameter, assumed as the effective diameter; f_{cd} is the design compressive strength of the concrete; f_{yd} is the design yielding strength of the dowels. This formula assumes that the connection exhibits a “local” failure mode, with the yielding of the steel dowel and the crushing of the surrounding concrete. In order to avoid “global” failures with concrete covers spalling, a distance of 6-7 ϕ is ensured between the center of the dowel and the column/beam face [13, 28]. The adopted retrofitting system, provided with horizontal dowels instead of vertical dowels, as in the typical precast beam-to-column connections, simplifies the positioning of the shear dowels so that this geometrical requirement could be satisfied without intersection with existing steel reinforcement.

The design of the two steel profiles ($f_{yk,profile}$=275N/mm^2, $E_{y,profile}$=210000N/mm^2) was performed according to the geometrical requirements of Eurocode 3 [26] for pin ended members and their buckling failure was also prevented according to Eurocode 3 [25].

Further geometrical details of the retrofitted connection are provided in Fig. 4.

Fig. 3 - Retrofitting system configuration: test setup

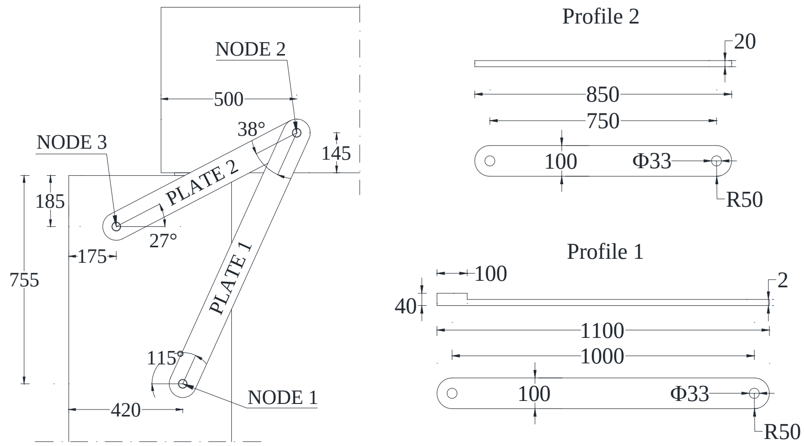

Fig. 4 - Retrofitting system configuration: geometrical features (dimensions are expressed in mm)

4. Cyclic shear test on the retrofitted connection

The performance of the described retrofitting system was investigated during a cyclic shear test: both vertical and horizontal loads were applied to the specimen, in order to simulate the gravity and seismic loads, according to the same loading protocol adopted during the cyclic shear test on the dowel connection. The vertical load, equal to 450kN, was provided by a vertical jack before tightening the connection device by means of nuts and washers.

The horizontal load was provided along the beam longitudinal axis by means of a hydraulic actuator controlling the displacements and performing 17 steps of incremental displacements, with three complete cycles (negative and positive semi-cycles) at each step.

During the cyclic test, the connection response was recorded by several instruments. Fig. 5 shows the location of the two LVDTs at the beam end, which recorded the horizontal beam-to-column relative displacements and the possible horizontal rotations of the beam. Fig. 6 shows the strain gauges placed along the two steel profiles.

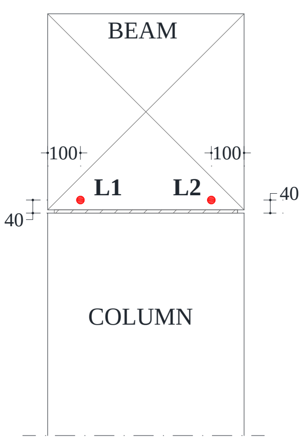

Fig. 5 - Geometrical layout of the LVDTs at the beam end (dimensions are expressed in mm)

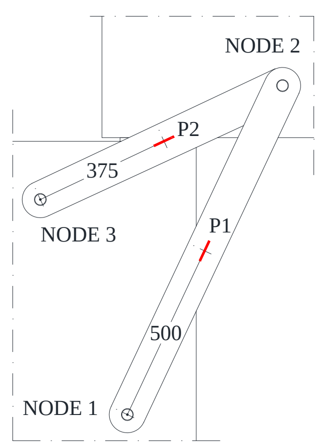

Fig. 6 - Geometrical layout of the strain gauges on the steel profiles (dimensions are expressed in mm)

At the end of the test, the rubber sheath around the steel dowel in the beam was significantly damaged (Fig. 7) and the surrounding grout crushed. Moreover, the neoprene pad showed large deformations due to the high compressive loads (Fig. 8). Several inclined cracks appeared in the concrete around the node in the beam at both the sides of the specimen (Fig. 9). However, the thickness and the length of the crack were small.

Fig. 7 - Rubber sheath deformation

Fig. 8 - Neoprene pad deformation

(a) (b)

Fig. 9 - Cracks pattern at the node in the beam at the end of the test: (a) West and (b) East view

The axial strains of the horizontal dowels in the column are recorded by means of strain gauges (D1 at node 1 and D3 at node 3): they did not reach the yielding value of the threaded bars (Fig. 10).

The records of the strain gauges on the steel profiles show the high axial forces in the upper profile (Fig. 11); however, neither of the two profiles reached the yielding strength. The axial deformations trend of the two steel profiles confirms the effectiveness of three hinged arch mechanism, since the two profiles work in tension and in compression, alternatively.

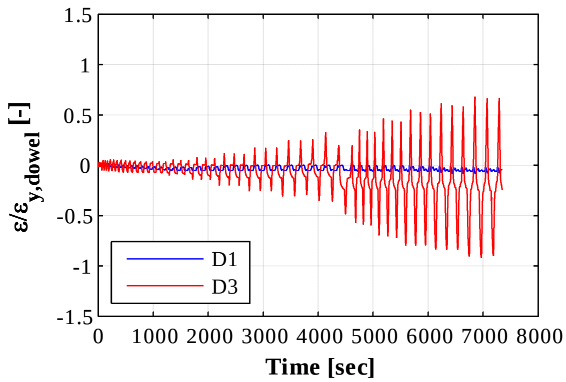

Fig. 10 - Records of the strain gauges on the horizontal steel dowels

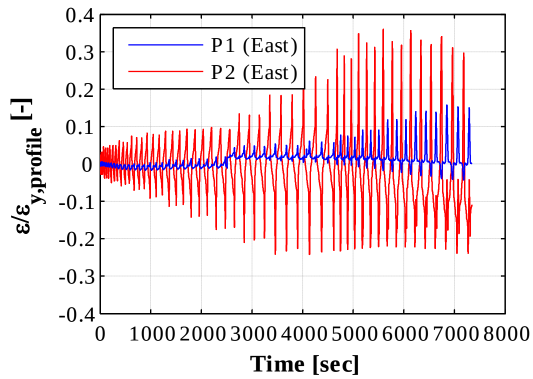

Fig. 11 - Records of the strain gauges on the steel profiles (East side)

In Fig. 12, the behavior of the connection during the test is shown in terms of horizontal forces and relative displacements. The horizontal displacements are the mean values of the LVDT records at the beam end and the shear force values are the load cell records of the horizontal actuator. The specimen showed a quite symmetrical behavior up to the end of the test. The recorded total shear strength accounts for the retrofitting system strength, the neoprene elastic and plastic internal forces, the neoprene-concrete frictional strength, and the other setup resistances; however, the setup resistances can be neglected and the total shear strength (red curve in Fig. 12) can be assumed as the effective retrofitted connection response. The maximum value of the retrofitting system shear force occurred under pulling loads (negative values) and it is equal to 284.54kN.

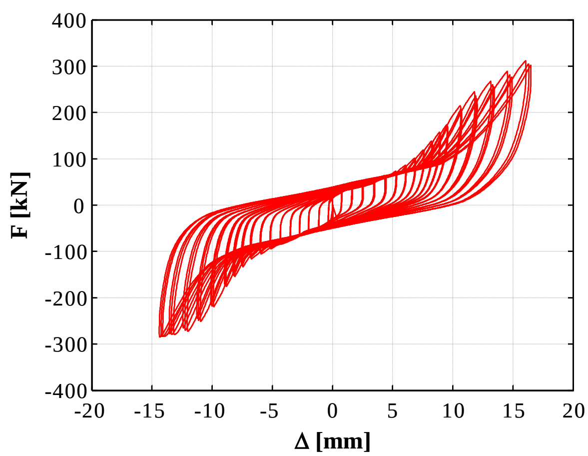

Fig. 12 - Force-displacement curve of the cyclic shear test on the retrofitted connection

5. Comparison between dowel and retrofitted connection

This section aims at comparing the cyclic behavior of the dowel beam-to-column connection with the retrofitted connection in terms of both global behavior and dissipated energy.

Fig. 13 shows the envelopes of the force-displacement curves of the investigated cyclic tests. As already written, for the investigated tests the load protocol consisted of increasing displacement steps and, for each step, three complete cycles (negative and positive semi-cycles) were performed. Since, at each step, the maximum value of the shear force was reached at the first cycle, the envelope takes into account only the first cycle of each step. Moreover, in Fig. 13 the envelope of the shear test on the dowel connection (black solid curve) is showed up to the 20% strength degradation, assumed as the attainment of the connection failure.

The comparison demonstrates that the dowel connection (black solid curve in Fig. 13) shows higher initial stiffness with respect to the retrofitted connection (red dashed curve in Fig. 13); however, it has lower shear strength in both the considered load directions. Moreover, the seismic behavior of the dowel connection is strongly not symmetric in the two loading directions: for pulling loads a sudden decrease of strength and stiffness was recorded. This evidence is justified by the failure mechanism that occurred for pulling loads (force negative values) with the spalling of the lateral concrete cover in the column. On the contrary, the retrofitted connection (red dashed curve in Fig. 13) shows a good seismic performance, with higher shear strength values and a very symmetric response thanks to the presence of the rubber sheath around the horizontal dowel in the beam.

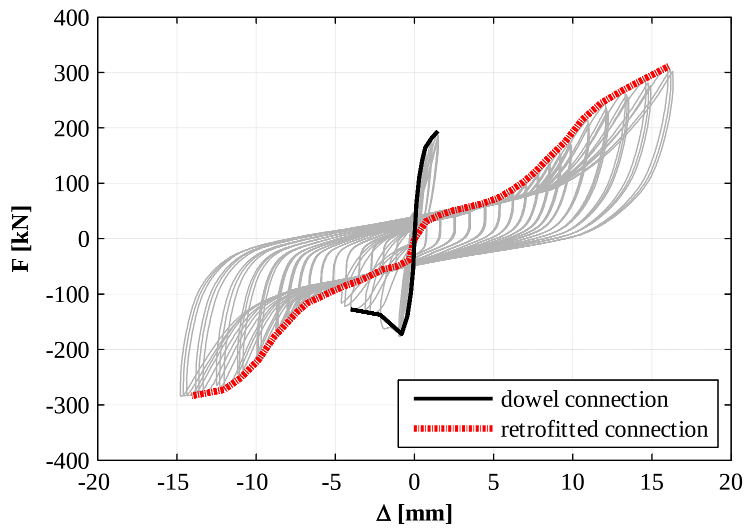

Fig. 13 - Force-displacement envelopes of the tests on the dowel beam-to column connection (black solid curve) and on the retrofitted connection (red dashed curve)

Fig. 14 shows the dissipated energy at each negative semi-cycle, corresponding to pulling loads, for the investigated tests: the dowel connection (black bars) and the retrofitted connection with the rubber sheath (gray bars). The dissipated energy of the dowel connection is plotted only for the first six steps, i.e. until the assumed failure of the connection. Up to the fourth step of the test on the dowel connection (i.e. the step which corresponds to the first crack formation), its dissipated energy was strongly lower than the dissipated energy in the retrofitted solutions because of the high initial stiffness. After the first concrete cracking, the dissipated energies in the dowel connection and in the retrofitted solutions were quite similar, because of the increased deformability of the dowel connection due to the concrete damage. The dissipated energy in the retrofitted connection increased up to the end of the shear test.

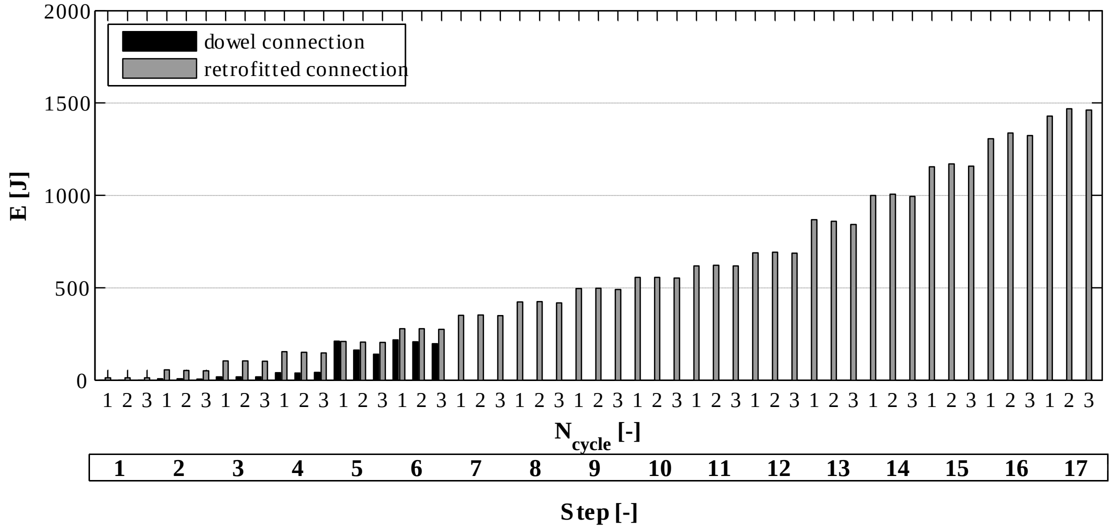

Fig. 14 - Dissipated energy during the negative semi-cycles of the shear tests on the dowel beam-to column connection (black bars) and on the retrofitted connection (gray bars)

Fig. 15 shows the dissipated energy at each positive semi-cycle (corresponding to pushing loads) for the investigated shear tests. The comments concerning the dissipated energy of the negative semi-cycles are confirmed. As in the pulling direction, at each step, the dissipated energy during the first semi cycle is generally lightly greater than the dissipated energy during the second and the third ones. The dissipated energy of the dowel connection is always much lower than the one recorded in the retrofitted solution, because of its large stiffness.

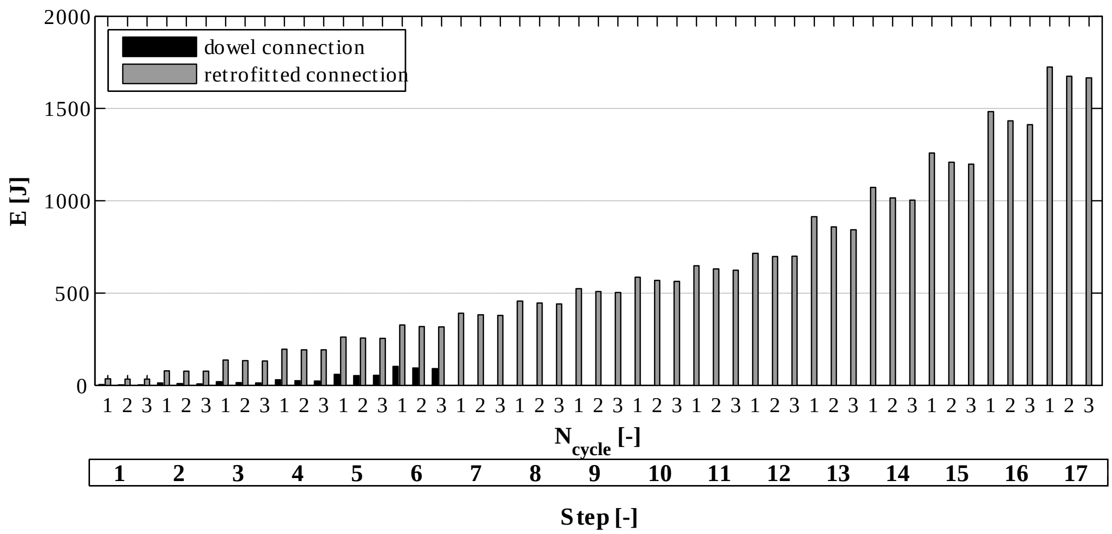

Fig. 15 - Dissipated energy during the positive semi-cycles of the shear tests on the dowel beam-to column connection (black bars) and on the retrofitted connection (gray bars)

6. Conclusions

In this paper, a retrofitting solution for RC precast beam-to-column connections is presented. An experimental campaign was performed in order to evaluated the seismic performance of this system by means of cyclic shear tests.

The reference specimen is a dowel beam-to-column connection, typically adopted in one-story RC precast structures. This connection was tested in a previous experimental campaign under cyclic shear loads up to the failure of the lateral concrete cover in the column, which caused the failure of the connection. The damaged specimen was retrofitted by a three-hinged steel connection system, with a rubber sheath around the dowel in the beam. The global behavior in terms of force-displacement curve was investigated and the damage patterns after the test was described by means of both visual inspections and instrumentation records.

The experimental results pointed out a good behavior of the retrofitting system under cyclic horizontal forces. In the retrofitted connection system, the horizontal shear force was mostly sustained by the three hinged arch mechanism, ensured by the two steel profiles pinned to the horizontal dowels.

Moreover, the retrofitted connections showed larger shear strength as well as larger dissipated energy values than the standard dowel connection. For loads against the column core (positive direction), the maximum shear force increased of 50% with respect to the dowel connection. For loads against the column cover (negative direction), the maximum shear force recorded in the test increased of 60% with respect to the dowel connection.

The initial stiffness of the retrofitted connections was significantly lower than the stiffness of the dowel connection. For the negative direction, it was about 10 times lower than the stiffness of the dowel connection. For the positive direction, it was about 30 times lower than the stiffness of the dowel connection.

In the test on the retrofitting system, no significant damage was recorded in the concrete. The large concrete covers of the horizontal dowels prevented brittle failures in the connected elements: the concrete damage was not severe up to the end of the test.

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