BEHAVIOURAL INVESTIGATION ON A PTED BEAM-TO-COLUMN CONNECTION BASED ON NUMERICAL ANALYSES

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ABSTRACT :

Post-Tensioned Energy Dissipating (PTED) beam-to-column connections are innovative structural systems conceived for providing steel moment resisting frames with self-centring and energy dissipation capacity. Their validation is ongoing on the basis of both experimental and numerical studies. The work presented in this paper is focused on the detailed analysis, assisted by numerical investigations, of the cyclic behaviour of a PTED connection already tested in laboratory. Particular attention is paid to the deformation and stress states of the most important component parts in the connection during all the phases of the considered cyclic displacement history, in order to examine aspects difficult to evaluate within the experimental tests, but useful for the comprehensive understanding of the local behaviour of the examined PTED systems, aiming at their optimization.

KEYWORDS: Seismic resistant steel frames, beam-to-column connections, post-tensioned energy dissipating systems, numerical analyses

1. INTRODUCTION

Post-Tensioned Energy Dissipating (PTED) beam-to-column connections may be a suitable alternative to welded rigid connections for steel Moment Resisting Frames (MRFs) in seismic areas, since they combine self-centring capability and energy dissipation capacity by means of ad-hoc Post-Tensioned (PT) and Energy Dissipating (ED) systems (Ricles et al., 2001; Christopoulos et al., 2002; Garlock et al., 2005; Rojas et al., 2005; Wolski et al., 2006; Chou et al., 2006; Tsai et al., 2007). The peculiar kinematics of PTED connections requires the conception of particular constructional details, which mainly depend on the selected PT and ED systems. The related validation and optimization processes are ongoing, from both the experimental and numerical points of view.
This paper focuses on the detailed investigation of the cyclic behaviour of a specific PTED connection, conceived and studied by Christopoulos et al. (2002), which is based on a refined numerical analysis carried out by means of the advanced computer program ABAQUS (2004). The aim is providing useful information on behavioural aspects difficult to catch during the experimental tests.
After a brief description of the numerical model features and the related validation based on the available experimental results, the paper points out on the deformation and stress states of the most important PTED connection component parts during the imposed displacement cyclic history, contributing to the comprehension of the system local behaviour.

2. THE NUMERICAL MODEL

The numerical model of the PTED beam-to-column connection is a 3D faithful reproduction of the specimen tested by Christopoulos et al. (2002), which consists in an external node composed by a W14x211 column, 1900 mm long, and a W24x76 beam, 7300 mm long. It represents an improvement as respect to the Esposto et al. (2006) model, which takes advantage of the system symmetry. The PT system is made by two 46 mm diameter bars, whereas the ED system is made by four 22 mm diameter confined bars. The detail of the nodal area is shown in Figure 1a, where all the component parts in the connection are visible. The finite element mesh of the node is shown in Figure 1b. It is made by tri-dimensional first-order continuum elements with reduced integration, which are suitable for performing complex nonlinear analyses involving contact, plasticity and large deformations.

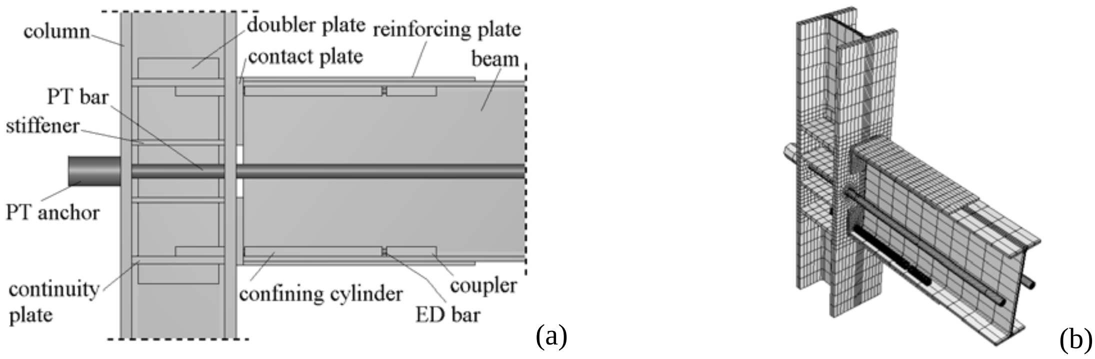


Figure 1 The PTED connection nodal area: (a) the component parts; (b) detail of the mesh

Tie constraints are used for modelling interactions between welded parts, whereas surface-to-surface contact interactions are selected in the case of component parts which can be or not in contact during the analysis. Detailed information on the interaction formulations is provided in Esposto et al. (2006).
Three materials are defined in the numerical model. For all the component parts of the connection, except the PT and ED bars, a steel with 345 MPa yield stress is considered. PT bars are made of high resistant steel, with 1030 MPa yield stress. ED bars are modelled considering a hardening steel with 400 MPa yield stress.
The imposed drift cyclic history is shown in Figure 2a, the drift being defined as the ratio between the vertical displacement at the mid-span section of the beam and the beam mid-span length.
The numerical analysis well reproduces the experimental results, as it is shown in Figure 2b, where the experimental and numerical force-drift curves are plotted. The obtained numerical results prove the reliability of the finite element model of the PTED beam-to-column connection, which can be profitably used for investigating the system behaviour under the imposed cyclic drift history. Figure 2c shows the node deformed configuration at the maximum drift, which evidences the gap opening at the beam-to-column interface.

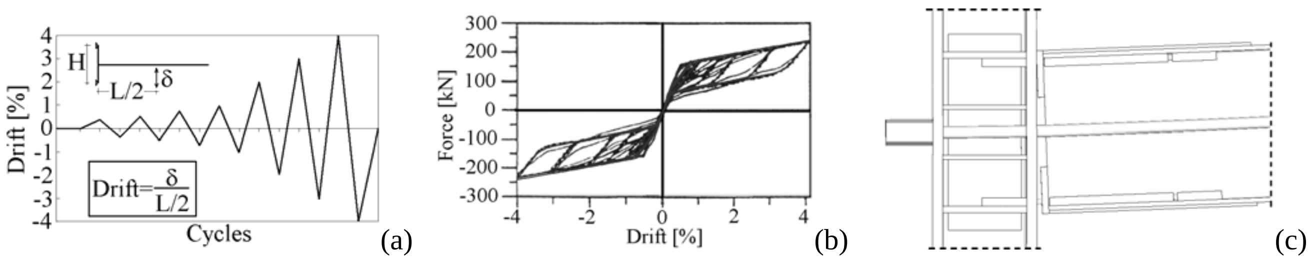


Figure 2 Numerical analysis: (a) imposed cyclic displacement history; (b) numerical vs. experimental results; (c) node deformed configuration at the maximum imposed drift

3. THE ANALYSIS OF THE CYCLIC BEHAVIOUR

3.1. Global Behaviour

The PTED connection behaves linearly up to about 0.375% drift, when a gap opens at the beam-to-column interface, then, the system behaviour is non-linear. The behavioural force-drift curve is flag-shaped, since no residual drift is present at the end of each cycle. The maximum reached drift is 4%. The system shows both re-centring and energy dissipation capabilities. Negligible inelastic deformations occur in small areas of the system, which anyway do not impair the flag-shaped behaviour.

3.2. Beam

During the cycles of imposed drifts, the beam essentially behaves in elastic range, except for some yielding occurring in very small areas next to the beam-to-column interface and at the end of the reinforcing plates. The deformation and stress states in the beam at the end of the post tensioning, at drifts equal to 0.375% and 4%, and at the cycles end are shown in Figure 3. At the end of the post tensioning (Fig. 3a) a stress concentration appears next to the contact plates (located on the left end of the beam), due to the contact pressure. At a drift equal to 0.375% (Fig. 3b), stress concentrations are present in the compressed area (top flange on the left of the beam), whereas no stresses are present in the bottom part of the left end of the beam, due to the loss of contact between beam and column. At a drift equal to 4% (Fig. 3c) the stress distribution evidences the increasing of the stress values in the whole beam and the attainment of the yield stress (plotted in black) in very limited areas of the beam flange, at the interface with the column and in the section at the end of the reinforcing plates, the latter is of concern, it being the most engaged section. In fact, it is subjected to the combined action of axial force and bending moment, taking no advantage of the reinforcing plates effect. In addition, some residual stresses are visible in the bottom area of the beam left end, which are due to the yielding of the related contact and reinforcing plates occurred during previous cycles. At the end of the cycles (Fig. 3d) the stress distribution is essentially the same as the one after the initial post tensioning, with the only difference that the stress values in the beam left end, next to the contact plates and to the reinforcing plates end, is slightly larger, due to the occurred yielding of contact plates and beam flanges in very small areas.

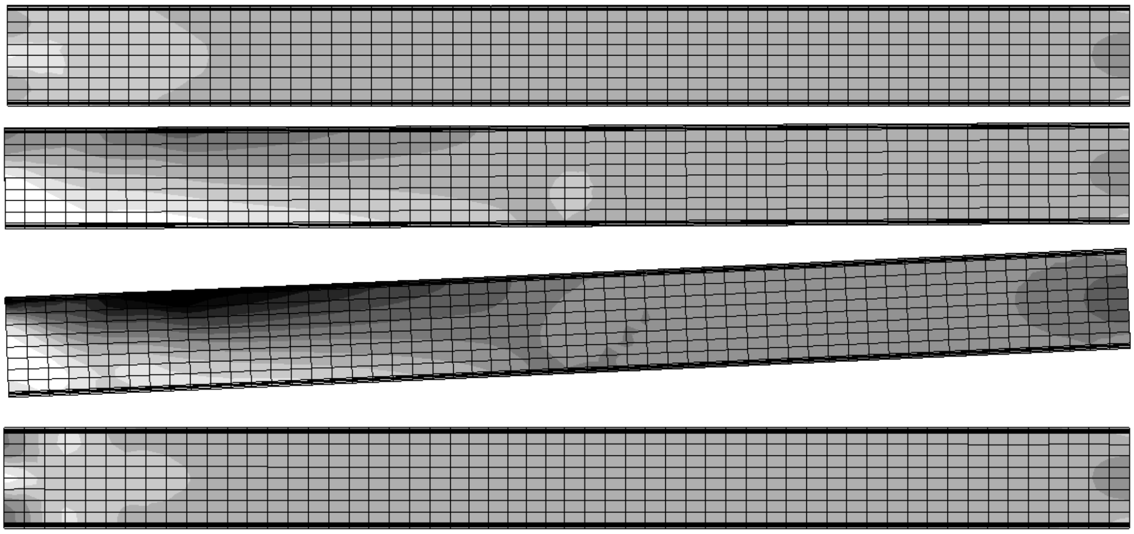

(a) (b) (c) (d)

Figure 3 Deformation and stress states of the beam in the PTED connection: (a) after the post tensioning; (b) at a 0.375% drift; (c) at a 4% drift; (d) at the end of the cycles

3.3. Column

During the cycles of imposed drifts, the behaviour of the column is always within the elastic range. The deformation and stress states for the relevant drift values are shown in Figure 4. At the end of the post tensioning (Fig. 4a) stress concentrations at the contact areas, namely, on the left, next to the location of the PT bars anchors, and, on the right, next to the location of the beam-to-column contact plates, appear. At a drift equal to 0.375% (Fig. 4b), the stress flow in the column web is clearly visible. At the column bottom some stresses are present, due to the restraint reactions. The stress state at 4% drift (Fig. 4c) shows the engagement of a large part of the column and, above all, the high stress concentrations in the column web interested by the flow of compression stresses. The latter aspect is worth of notice, since it evidences the strong demand in terms of shear on the column web. At the end of the cycles (Fig. 4d) the stress distribution is exactly the same as the one due only to post tensioning system, in fact no inelastic deformation has occurred.

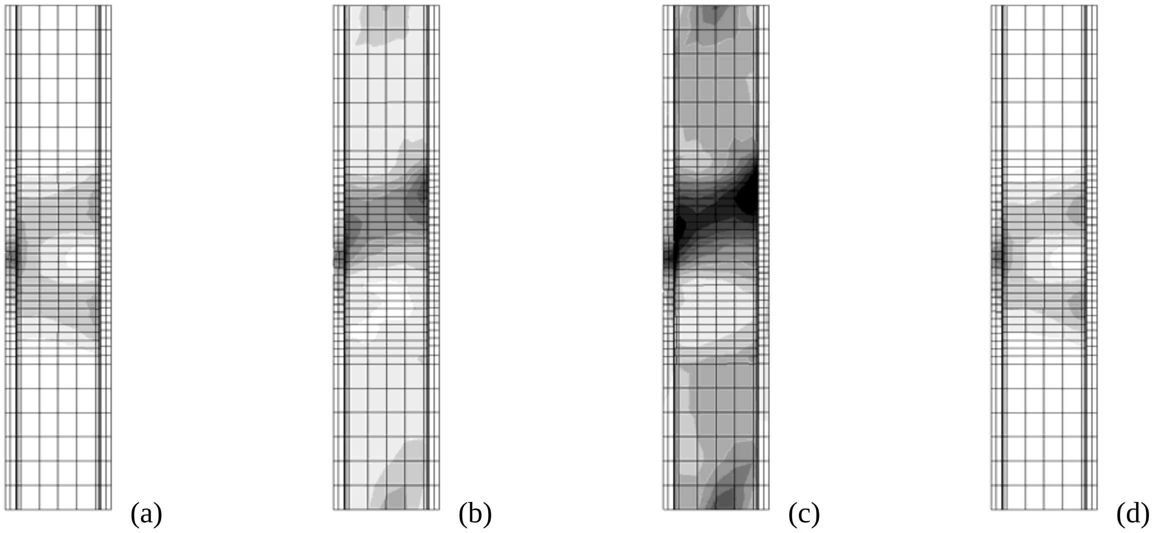


Figure 4 Deformation and stress states of the column in the PTED connection: (a) after the post tensioning; (b) at a 0.375% drift; (c) at a 4% drift; (d) at the end of the cycles

3.4. Contact Plates

The contact plates at the beam-to-column interface undergo a large amount of plastic deformations, starting from small values of imposed inter-storey drifts (0.5%). The stress distributions in the top contact plate (Fig. 5a), for the relevant drift values, are shown in Figure 5. After the application of the post tensioning force (Fig. 5b), the stress concentrations correspond to the area in contact with the beam flange and web. At a 0.375% drift (Fig. 5c), a stress concentration is visible at the top edge. The first yielding occurs at a drift equal to 0.5%, and the yielded zone extends as the drift increases. The stress distribution referred to the 4% drift is shown in Figure 5d. At the end of the cycles, the stresses in the contact plates are larger than those corresponding to the post tensioning, due to the occurred yielding, added to the effect of the post tensioning action (Fig. 5e).

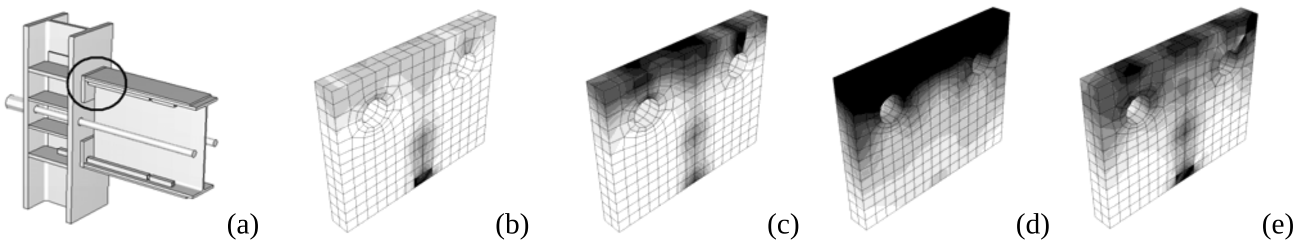
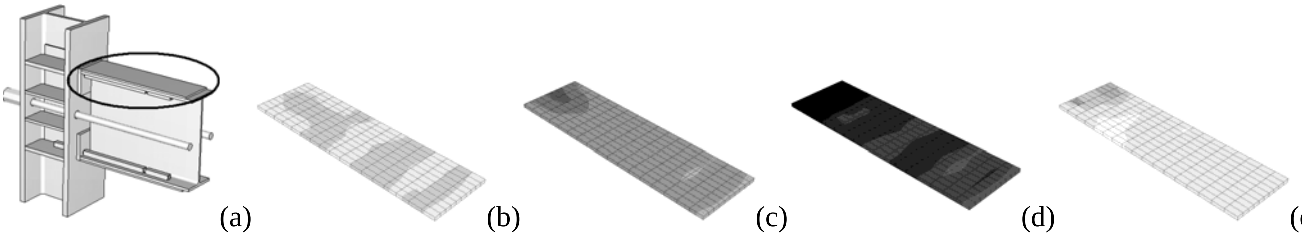


Figure 5 Deformation and stress states of the top contact plate (a) in the PTED connection: (b) after the post tensioning; (c) at a 0.375% drift; (d) at a 4% drift; (e) at the end of the cycles

3.5. Reinforcing Plates

The reinforcing plates support the beam flanges in bearing the compression stress concentrations due to the gap opening, according to the mechanical behaviour of the PTED connections. The behaviour of the reinforcing plates during the cycles of drifts shows some extent of inelastic deformations. The stress distributions of the top reinforcing plate (Fig. 6a) for the relevant drift values are shown in Figure 6. The stress state after the post tensioning (Fig. 6b) is not uniform and this is probably due to the presence of the couplers inside the beam flanges, since they are slightly loaded when the initial post tensioning occurs. At a drift equal to 0.375% (Fig. 6c) the overall stress in the reinforcing plate increases and stress concentrations are visible at the plate end, next to the location of the contact plates (left side in figure). The yielding of the reinforcing plate starts at a 3% drift; at a drift equal to 4% the extension of the yielded area is not negligible, as it appears in Figure 6d. After the end of the cycles, some residual stresses due to the previously occurred yielding are present at the plate end, as shown in Figure 6e.

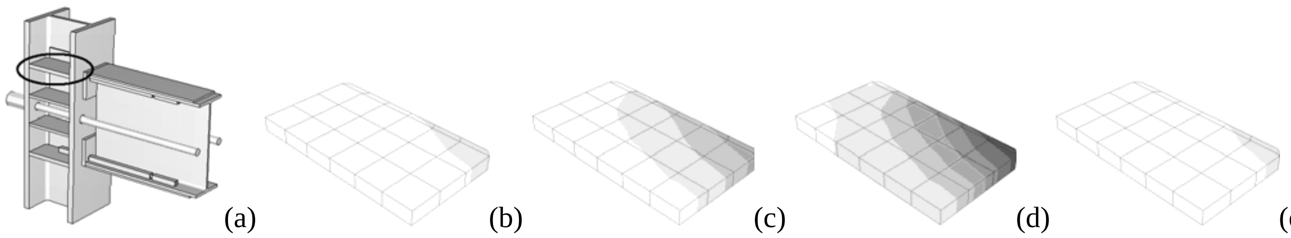


(a) (b) (c) (d) (e)

Figure 6 Deformation and stress states of the top reinforcing plate (a) in the PTED connection: (b) after the post tensioning; (c) at a 0.375% drift; (d) at a 4% drift; (e) at the end of the cycles

3.6. Continuity Plates

The continuity plates support the column flanges in bearing the stresses coming from the beam flanges, above all when the gap at the beam-to-column interface opens. The behaviour of the continuity plates during the cycles of drift is always in the elastic range. The stress distribution of the top flange continuity plate (Fig. 7a) for the relevant drift values is shown in Figure 7. After the initial post tensioning, the stress level in the continuity plates is very small (Fig. 7b), some stresses being visible in the area next to the intersection between the flange and the web of the column, at the beam side. When the imposed drift increases, the stress in the continuity plates grows in terms of both extension and values (Fig. 7c, d). At the end of the cycles (Fig. 7e), the deformation and stress state at the contact plates is exactly the same as the one after the post tensioning application, since no inelastic deformation occurs in the continuity plates. The stress values are always largely lower than the yield stress, with a maximum of about 160 MPa, reached at a drift equal to 4%.



(a) (b) (c) (d) (e)

Figure 7 Deformation and stress states of the top continuity plate (a) in the PTED connection: (b) after the post tensioning; (c) at a 0.375% drift; (d) at a 4% drift; (e) at the end of the cycles

3.7. Stiffeners

The stiffeners are used to support the column flanges in bearing the stresses due to the action provided by the PT bars anchors. The behaviour of the stiffeners during the cycles of drift is always in the elastic range. The stress distribution of the top stiffener (Fig. 8a) for the relevant drift values is shown in Figure 8. The most engaged areas in the stiffeners are located next to the PT anchors (left in Fig. 8). As it is evident since the application of the post tensioning action (Fig. 8b), the stress engagement of the stiffeners increases as the drift amplitudes do (Fig. 8c, d) and returns to the initial values and distribution at the end of the cycles (Fig. 8e). Moreover, after the application of the post tensioning action, the stress in the stiffeners never falls below 115 MPa, due to their engagement for both positive and negative imposed drifts, they being very close each other. In addition, above all for the smallest drift values, the stress peaks in the top stiffener occur for negative drifts.

In fact, due to the local rotations of the PT anchors, the top stiffeners are compressed at negative drifts while the bottom stiffeners at positive drifts. The maximum stress achieved in the stiffeners during the cycles is equal to about 185 MPa.

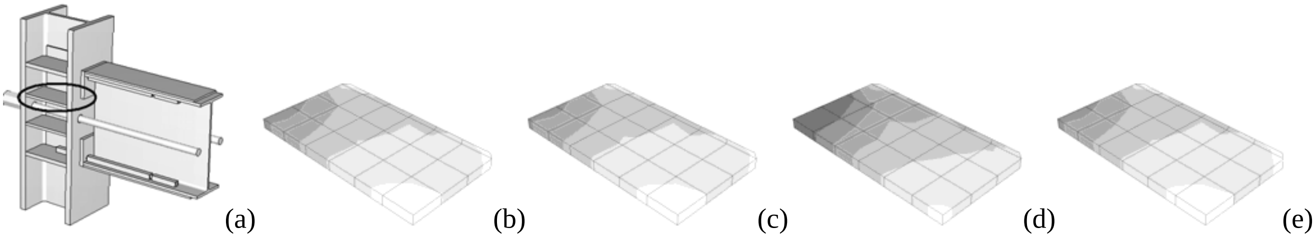


Figure 8 Deformation and stress states of the top stiffener (a) in the PTED connection: (b) after the post tensioning; (c) at a 0.375% drift; (d) at a 4% drift; (e) at the end of the cycles

3.8. Doubler Plates

The doubler plates (Fig. 9a) are subjected to a strong shear demand, as already evidenced for the column web. The deformation and stress states for the relevant drifts is shown in Figure 9. A symmetrical stress concentration occurs after the application of the post tensioning action (Fig. 9b), with stress peaks in the areas next to the beam-to-column contact plates. After the gap opening, stress concentrations occur on the side of the compressed beam flange (top part of the doubler plates, for positive drifts), as shown in Figure 9c, d, for drifts ranging from 0.375% to 4%. At the end of the cycles (Fig. 9e) the stress state of the doubler plates is the same as at the post tensioning action application, due to the absence of inelastic deformations. The maximum stress achieved in the stiffeners during the cycles is equal to about 250 MPa.

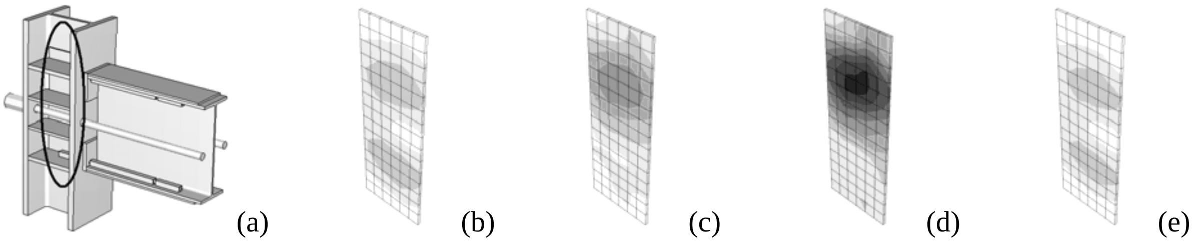


Figure 9 Deformation and stress states of the a doubler plate (a) in the PTED connection: (b) after the post tensioning; (c) at a 0.375% drift; (d) at a 4% drift; (e) at the end of the cycles

3.9. PT Bars

The PT bars, together with the ED bars, are the actual core of the PTED connection system. They have two main functions: 1) compressing the columns to the beams, in order to provide the necessary capacity of transferring the vertical shear and the bending moment in the nodes; 2) re-centring the structure after the occurrence of a seismic event. The PT bars behaviour must always be elastic, since their yielding would lead to the loss of the re-centring capability and, what is of more concern, the loss of the capacity of bearing the shears due to vertical loads. Both numerical and experimental results (Christopoulos et al., 2002), show that no yielding occurs for the particular considered system.

Some concern is caused by the possible contact between the PT bars and the perimeter internal surface of the holes in the column flanges where they are located (Fig. 10a), since the consequent local rotations of the bars, occurring at large drifts, could create a dangerous bending effect on the PT bars, which would increase the tensile stresses caused by the already present tension state, the latter being due to the initial post tensioning and to the PT bars elastic elongation. The above condition is confirmed by the curves plotted in Figure 10b, where the stress history in three remarkable points is shown. The NLR curve is referred to a cross-section of the PT bars where no relative rotations occur. The initial stress is equal to about 400 MPa and it cyclically increases when the interface gap opens, due to the elastic elongation of the PT bars. It is worth noticing that, in such section, the stress variation is not influenced by the sign of the drift, since the PT bar is located at the mid-depth of the beam and its elongation is the same for both top and bottom gap openings. The stress value at a 4% drift is equal to about 600 MPa, largely lower than the 1030 MPa limit for the considered high resistant steel. The TLR and BLR curves, on the contrary, are referred to top and bottom points of a cross-section of the PT bars where local rotations occur, next to the holes in the column flange. The local rotations cause a dangerous condition in the bars, since the added bending increases the stress up to about 1000 MPa. This evidence confirms the necessity of particular care in the design of the PT system, by adopting adequately large safety factors. At the end of the cycles, the stress value in all the considered elements is equal to the initial one, as it was expected due to the elastic behaviour of the PT bars.

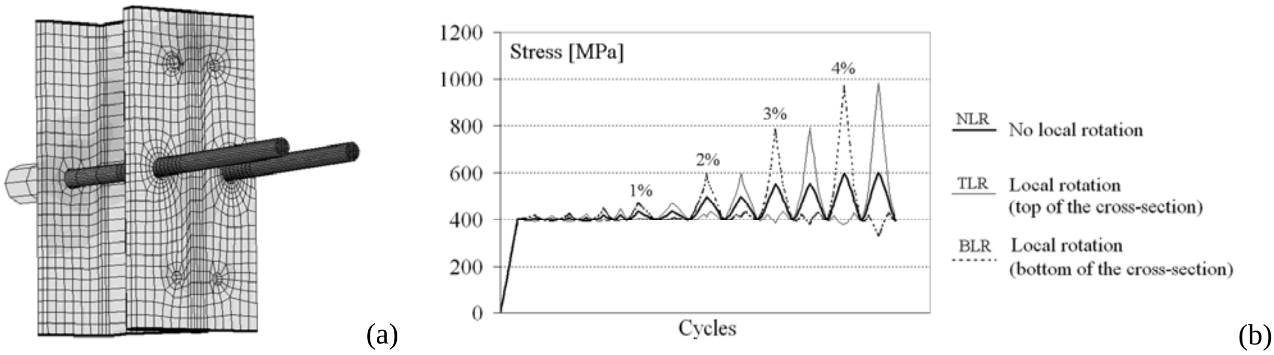


Figure 10 Behaviour of PT bars: (a) deformed configuration at 4% drift; (b) stress history

3.10. ED Bars

The ED bars are the dissipative part of the study PTED beam-to-column connection. Dissipation of the input energy occurs by means of cycles of inelastic axial deformations. Due to the slenderness of such steel bars, they are confined by steel cylinders, which prevent the possible buckling in compression (Christopoulos et al., 2002). The stability of the cyclic behaviour of the considered ED bars is shown in Esposto et al. (2006). The deformed shape and the stress distribution of ED bars shows inelastic deformations mainly in the middle parts. The presence of transversal displacement components demonstrate the tendency to buckle of the bars in compression after the hardening elongation, which are restrained by the steel confining cylinders.

4. CONCLUSIVE REMARKS AND FURTHER DEVELOPMENTS

Based on the numerical evidence, the following behavioural aspects of the study PTED beam-to-column connection are worth to be noticed, aiming at the optimization of the system
The beam essentially behaves in elastic range, with the attainment of the yield stress in very limited areas, namely at the interface with the contact plates and at the end of the reinforcing plates. Besides, the contact plates are the component parts of the PTED connection which undergo the larger inelastic deformations, with the obvious exception of the ED bars, starting from small drift values, whereas the reinforcing plates well support the beam flanges in carrying the compression for drifts up to 3%, when the first yielding occurs.
The column clearly shows a strong shear demand in a limited portion of the web, when the interface gap opens. Stress values close to the yield limit are evidenced in a small area of the column flange, at the interface with the contact plate. However, these are not of concern because the column always behaves in elastic field.
Concerning the specific PTED system, the PT bars adequately re-centre the connection, behaving in elastic

range for all the considered drifts. However, the analysis shows dangerous local rotations in the bars due to the contact with the column flange holes which noticeably increase the stresses, requiring particular care and large safety factors in the design of PT bars. The ED bars dissipate the input energy in a stable way, thanks to the prevention of buckling phenomena provided by the confining cylinders.
Apart from the ED bars, no other component parts in the PTED connection should yield. However, in the study connection, non negligible yielding occurs in the contact and reinforcing plates. In addition, the yield stress is attained also in very limited areas of the beam. This undesirable condition can be prevented by using high strength steel for the contact and reinforcing plates, as suggested by Christopoulos et al. (2002) and verified by Esposto et al. (2006). In fact, based on “ad-hoc” numerical analyses in which a 690 MPa nominal yield stress steel was used for contact and reinforcing plates, no yielding occurred in any part of the connection, with the exception of the ED bars.
The quantitative information provided in this paper on the local behaviour of a PTED connection contribute to the knowledge and development of such innovative system. Further studies are needed, which should be focused on the influence of the geometrical details on the connection performances. At this aim, parametric numerical analyses can be carried out, by means of the set up reliable numerical models, with the ultimate goal of achieving the optimization of the structural system and defining design rules specific for moment resisting frames equipped with PTED connections.

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