Structural response of RC buildings with Dual-Phase reinforcing steel

Silvia Caprili[a], Francesca Mattei[a], Walter Salvatore[a], Rosario Gigliotti[b]
[a] *Dipartimento di Ingegneria Civile e Industriale, University di Pisa, Largo L. Lazzarino 1, 56122 Pisa, Italy*
[b] *Dipartimento di Ingegneria Strutturale e Geotecnica, University di Rome, Via Eudossiana 18,00184, Rome, Italy*

Keywords: Dual-Phase steel; Incremental dynamic analysis; reinforced concrete structure; seismic performance

ABSTRACT

Modern codes for the seismic design of Reinforced Concrete (RC) structures aim to obtain a global ductile collapse mechanism with concentration of plastic deformations in pre-selected zones. The controlled development of *plastic hinges* at the ends of beams and first floor's columns of Moment Resisting Frames (MRF) underlines the importance of the structural ductility, directly related to the rotational capacity of elements and, therefore, to the mechanical performance of materials. Aggressive environmental conditions can, otherwise, lead to the rapid decrease of both the bearing and deformation capacity of structural components, with alteration of the collapse modality and reduction of the energy dissipation due the deterioration of the mechanical properties of both concrete and rebars. Corrosion phenomena highly affect the behaviour of reinforcements, causing relevant decrease of the deformation capacity, as widely evidenced in the case of traditional TempCore® rebars. Enhanced steel bars with Dual-Phase (DP) microstructure, characterized by improved durability towards aggressive environmental conditions, were therefore developed to provide a valid alternative to traditional reinforcements. Despite their competitive mechanical performance, the not-defined yielding stress-strain curve of DP rebars requires an accurate analysis of the sections, elements and whole structure performance, whose results are showed in the present work with reference to a RC-DP case study building. The execution of nonlinear incremental dynamic analyses (IDA) allows to highlight differences, pros and cons of the adoption of DP reinforcing bars.

1 INTRODUCTION

Dual-Phase (DP) steels are characterized by excellent performance in terms of strength, ductility and durability towards aggressive environmental conditions due to their particular microstructure, in which martensite and ferrite coexist in a unique matrix. Nowadays, DP steels of different grades (with ultimate strength even up to 800-1000 MPa) are commonly used in the automotive sector in flat products (plates and sheets, mainly). The possibility to produce DP steel reinforcing bars, promising possibility to increase the durability performance of reinforced concrete (RC) constructions, was widely studied in the last years highlighting the potential improvement of the structural behaviour of RC-DP sections and components (Maffei et al. 2008; Salvatore et al. 2008).

More recently, Caprili et al. 2018 – together with the support of industrial steel producers – deeply analysed the production process needed to achieve steel reinforcing bars with DP microstructure in actual plants, without requiring a strong economic effort to modify/adapt the industrial cycle. DP rebars, fully characterized in Caprili et al. (2019) in both uncorroded/reference and corroded conditions in comparison to TempCore® reinforcing steels, were achieved through the application of an additional thermal cycle to coils realized with pre-selected chemical composition (aiming to reduce as much as possible the C-content). The thermal cycle consisted in an Intercritical Quenching (IQ) step (temperature in the range 740-820°C) followed by a tempering phase (at 600°C) increasing the ductility.

Results of tensile and cyclic tests performed in corroded conditions highlighted the better durability of DP rebars respect to B450C TempCore® ones, with lower decrease of the deformation capacity for the same corrosion entity (Caprili et al. 2019). Since ductility and durability of rebars strongly influence the structural performance of RC buildings in seismic areas, affecting the behaviour of sections (*moment/curvature*), of elements (*moment/rotation*) and of the whole structure (*force/displacement*), Dual-Phase rebars can be considered a valid tool to mitigate corrosion effects, alternative to TempCore® grades. As shown in the current scientific literature, the residual values of A_{gt} of corroded B450C TempCore® steel bars (Caprili et al. 2015; Caprili and Salvatore, 2015; Apostolopoulos and Papadakis 2008; Imperatore et al. 2017; etc.) can be even lower than the minimum requirements imposed by actual standard for constructions in relation to the ductility class assumed in the design (EN1998-1:2005; D.M.17/01/2018) with the aim of pursuing a global ductile behaviour of MRF-RC constructions. Therefore, the adoption of DP reinforcements can help in the achievement of more durable ductile buildings.

The mechanical characterization performed by Caprili et al. (2019) evidenced, at the same time, a not-defined yielding stress-strain behaviour, unlike the traditional elastic-plastic with hardening behaviour of traditional TempCore® usually adopted for the elaboration of well-defined formulations for chord rotation (at yielding and ultimate), plastic hinge length, etc. The constitutive relationship of DP rebars can, of course, influences the whole resulting structural performance.

With the aim of exploring the influence of the adoption of DP bars for MRF-RC constructions, in the present paper the preliminary results of Incremental Dynamic Analyses (IDA) executed on a RC case study building designed using Dual-Phase (DP) ones are presented, in comparison to the adoption of traditional B450C TempCore® ones. In the numerical models, assumptions were made for the definition of parameters like plastic hinge length, chord rotation etc., whose formulation will be then elaborated and calibrated basing on the results of an experimental full-test campaign performed at the "*Laboratorio Ufficiale per le Esperienze sui Materiali da Costruzione*" of Pisa University, already presented in a companion paper.

The work has been developed within the European research project NEWREBAR "*New Dual-Phase steel reinforcing bars for enhancing capacity and durability of antiseismic moment resisting frames*" (2015-2019), funded by the Research Fund for Coal and Steel (RFSR-CT-2015-00023) of European Commission.

2 METHODOLOGY ADOPTED

The main objective of the present work is to analyse the influence of the adoption of DP steel reinforcing bars on the local and global structural performance of RC buildings, in comparison to traditional TempCore® steel rebars.

Numerical nonlinear analyses were performed both at section/element level and at whole building level, selecting opportune constitutive laws for the materials able to consider the effective deformation capacity resulting from experimental tests.

At component level, investigations were made to evaluate the contribution of DP reinforcing steels on the rotational capacity of elements: in particular, the contribution of stirrups in the achievement of a higher level of ultimate deformation capacity (ε_{cu}) due to confinement was considered, in comparison to TempCore® B450C reinforcing bars.

At building level, Incremental Dynamic Analyses (IDA) were performed on nonlinear models of a RC case study commercial building representative of the actual European structures and designed through dynamic linear analysis with response spectrum (EN1998-1:2005; D.M.17/01/2018) for ductility class high (DCH). The elaboration of the nonlinear models for the execution of IDAs required the calibration of specific parameters (e.g. the plastic hinge length) to analyse the capacity of the structures designed with Dual-Phase steel rebars, for which the common laws literature formulations are not a-priori valid.

3 DESIGN OF RC-DP CASE STUDY BUILDINGS

To analyse the influence of DP rebars in the structural performance of RC buildings, within the NEWREBAR project several case studies buildings were designed for ductility class high and medium (HDC and MDC), considering different functional destinations and different design seismicity levels. In this paper, for sake of simplicity, only one case study is presented.

3.1 Materials' selection

Case study buildings were designed considering two different reinforcement grades, respectively called DPF (i.e. Dual-Phase steel characterized by a typical chemical composition with reduced C-content, indicated by the letter 'F') and B450C (TempCore® grade, coherent with actual standards' prescriptions).

The mechanical properties of steel reinforcing bars used for the execution of numerical analysis were already presented in Caprili et al. (2019). The average values of yielding and tensile strength and deformations achieved from tensile tests were used. Figure 1 shows the stress strain laws adopted, while Table 1 summarizes the real average values (not nominal) of the main mechanical performance.

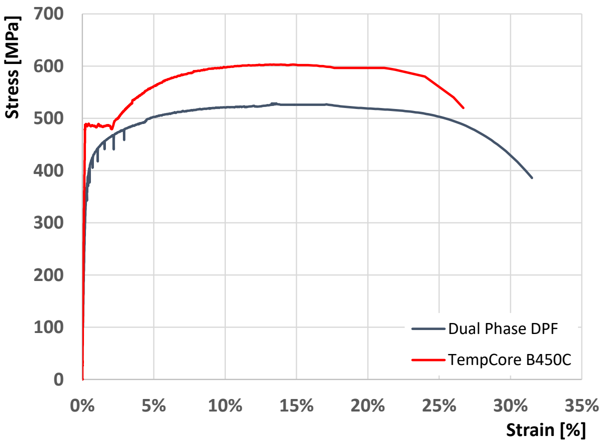


Figure 1. Stress-strain curves of DPF and B450C bars (Caprili et al. 2019).

Table 1. Average values of mechanical properties of the different rebars (DPF and B450).

Steel type	R_e $R_{p,02}$ (MPa)	R_m (MPa)	R_m/R_e (-)	A_{gt} (%)	A_5 (%)
DPF	403.6	525.1	1.30	13.9	31.5
B450C	485.7	594.8	1.22	15.7	26.7

For concrete material, strength class C25/30 were adopted in the design of RC case study.

3.2 Design of case study buildings

The design of RC case study buildings with Moment Resisting Frame (MRF) structure was executed considering the rules proposed by EN1998-1:2005. The plan was almost squared, with an area of 36x34 m^2 (Figure 2). The span length on both the X- and the Y-directions was in the range 4.0 - 6.0 m; stairs were located in central position. The building developed on 5 floors with interstorey height equal to 5.0 m (first floor) and 3.50 m (all other floors) for a resulting total height of 19.0 m

Vertical loads acting on selected case studies were defined in relation to the typology of structural and not structural elements (storey slabs, roof, infills, equipment, etc…) and to the functional destination, e.g. commercial building. In Table 2 structural, not structural and live loads are summarized.

Seismic action was defined using the Eurocode 8 design response spectra, considering a level of seismicity, expressed in terms of PGA (Peak Ground Acceleration), equal to 0.25g and soil category "B", characterized by a speed of propagation of shear waves in the first 30 m of depth between 360 and 800 m/s. Response spectrum of Type 1 was adopted. The global ductility of the structure was accounted for using a behaviour factor (q) equal to 5.85 (EN1998-1:2005, Figure 3).

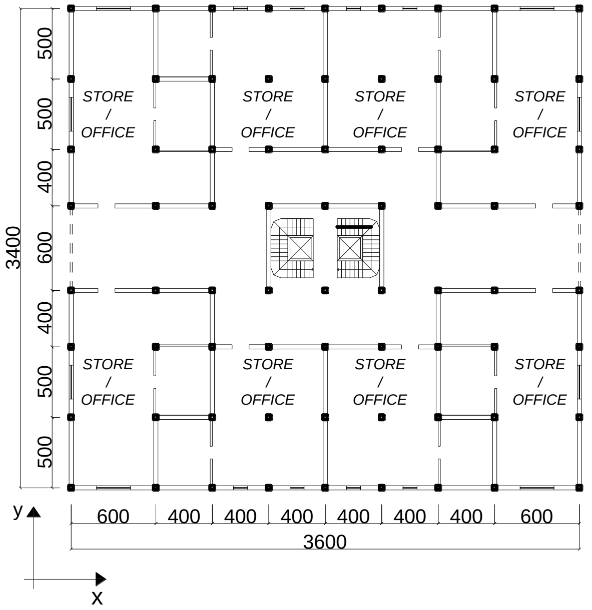


Figure 1. General plan of the RC commercial case study building.

Table 2. Vertical loads acting on RC case study

Functional destination	Structural Loads (kN/m^2)	Non Structural Loads (kN/m^2)	Live Loads (kN/m^2)
Commercial	3.35	2.35	5,0

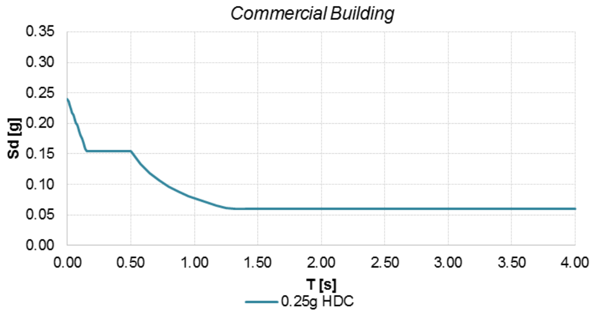


Figure 3. Design response spectrum for the case study buildings.

The *capacity design approach* was adopted to achieve a ductile global collapse mechanism avoiding local brittle ones (e.g. shear). The differences in the design of sections realized using B450C and DPF steel rebars, assuming the same geometrical dimensions (for columns 55x55 cm, 50x50 cm and 45x45 cm and for beams 40x55 cm), resulted essentially in the number and in the diameter of longitudinal and transversal rebars. DPF reinforcing bars present, in fact, yielding strength equal to 334 MPa, lower than B450C (391.3 MPa): to achieve the same value of bearing capacity of the sections (bending moment) a different amount of reinforcing steel is then needed (see, for example, sections presented in Figures 4 and 5).

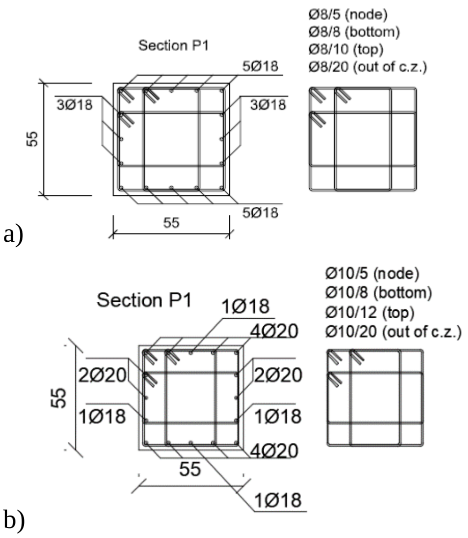


Figure 4. Sections of columns designed using a) B450 C and b) DPF steel reinforcing bars.

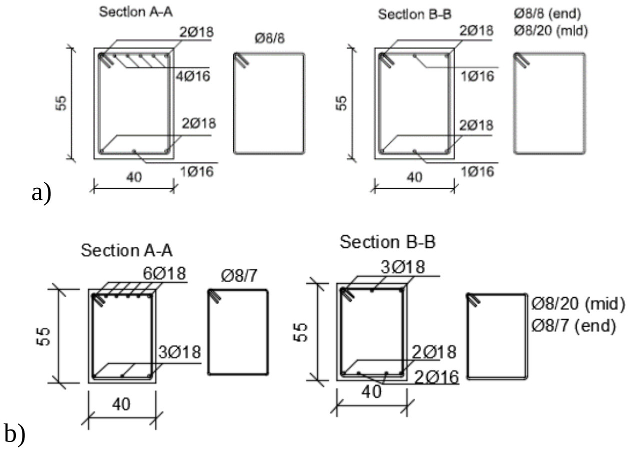


Figure 5. Sections of beams designed using a) B450 C and b) DPF steel reinforcing bars.

It’s interesting to note that in some cases, the design of rebars’ layout in the section was not governed by the bearing capacity (in particular for stirrups/shear) but by ductility requirements and by the need to satisfy the standards’ prescriptions, normally imposed for traditional reinforcements with defined yielding plateau.

To summarize, stirrups of diameter 8.0 mm were used both in beams and columns in case of B450C, while diameters equal to 8.0 or 10.0 mm were selected for DPF steel; in particular, rectangular double stirrups with four branches were used in columns, while simple rectangular stirrups were used in beams. Concerning longitudinal rebars, diameters from 16 and 18 mm were used in case of B450C while diameters of 18 and 20 mm were selected for DPF.

4 STRUCTURAL ASSESSMENT OF RC-DP SECTIONS AND ELEMENTS

The performance of elements designed following the capacity design approach is governed by the development of ductile collapse mechanism, since brittle shear is prevented through a proper selection of design action and executive details. The ultimate rotation then represents the entity describing the deformation capacity of elements, while curvature shall be evaluated at section level.

For the determination of the ultimate curvature (χ_u) three different criteria can be assumed, corresponding to different phenomena possibly occurring at section level; in particular:

I. *Core concrete failure*, corresponding to the achievement of the maximum concrete core deformation (ε_{cu}), normally reached in presence of high axial forces in the section.

II. *Steel rebars failure*, corresponding to the achievement of the maximum steel deformation, normally reached in presence of low axial forces (or no axial forces) in the section.

III. The achievement of the 80% of maximum bending moment is reached (on the descending branch), corresponding to a reduction of the bearing capacity of the section.

The evaluation of the ultimate maximum deformation (ε_{cu}) in the confined concrete core is fundamental for the first criterion (I), affecting the resulting ultimate curvature.

Several formulations are provided in the current scientific literature for ε_{cu}: for example, Mander et al. (1984) related the additional available ductility of the confined concrete to the energy stored in stirrups, and consequently to the ultimate deformation (at failure) of transversal reinforcements, according to equation (1).

$$U_{sh} = U_{cc} + U_{sc} - U_{c0} \qquad (1)$$

being U_{sh} the energy (unit volume) dissipated by stirrups, U_{cc} the energy dissipated by the confined concrete, U_{sc} the energy dissipated by longitudinal rebars and U_{c0} the energy dissipated by unconfined concrete.

This approach was selected even in the present work since able to account for the available ductility of stirrups’ material: as visible from Figure 1, the *ultimate* elongation of DPF was significantly higher than the one associated to B450C (31.5% vs 26.7%) and its influence needs then to be considered in the analyses. For the stress-strain curves of Figure 1, the energy dissipated by stirrups, evaluated until ultimate steel deformation ε_{su}, were respectively equal to 148 MPa and 156 MPa in the case of B450C and

DPF, highlighting the improvement due to DP rebars.

The constitutive laws obtained for the confined concrete of representative beams and columns of the RC case study buildings with DPF and B450C rebars are presented in Figures 6 and 7.

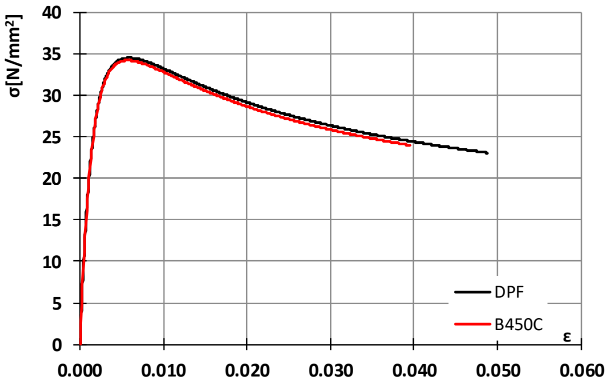


Figure 6. Constitutive law for confined concrete core – columns' section P1.

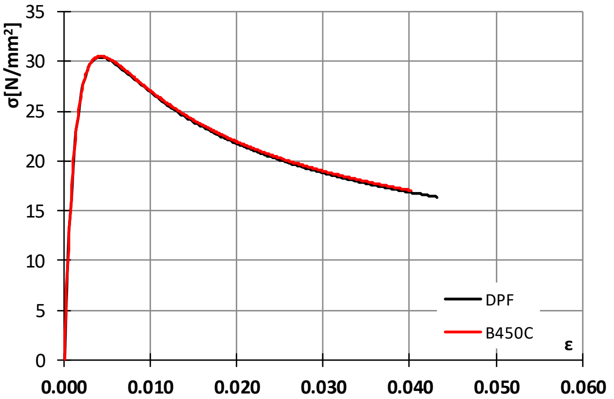


Figure 7. Constitutive law for confined concrete core – beams' section A-A.

The moment/curvature diagrams achieved for beams and columns with DPF and B450C, with constitutive laws before discussed, evidenced some differences, as visible form Figures 8 and 9 – respectively for columns (section P1) and beams (section A-A). The yielding curvature (χ_y) always resulted higher in case of DPF respect to B450C: this is due to the fact the effective yielding deformation (ε_{sy}) is higher in DP steel respect to B450C.

For the evaluation of the ultimate curvature (χ_u), moreover, additional considerations are necessary, being the ultimate curvature highly influenced by the value of axial force acting in the section. For high axial loads, χ_u is usually associated to concrete core failure (*criterion I*) and the achievement of ε_{cu}; on the contrary, in absence or in case of lower values of the axial force, χ_u corresponds to rebars' ultimate deformation (*criterion II* – achievement of ε_{su}).

Starting from the previously evidences, it can be stated that the ultimate curvature of elements characterized by high axial force (e.g. 1st floor's columns) is higher in the case of RC-DP buildings respect to B450C ones and this is due to the higher ultimate concrete core deformation. On the contrary, beam sections, characterized by the lack of axial force, evidence higher χ_u in case of B45C respect DPF. This last condition is due to the fact the ultimate deformation of rebars considered (for longitudinal reinforcement) is higher in case of B450C, with average A_{gt} values equal to 15.7% vs 13.9 % of DPF. It shall be otherwise noted that TempCore® A_{gt} values are, normally, lower than values presented in Table 1 (see, for example, data presented in Caprili et al. 2015; Caprili and Salvatore, 2015), so that the results presented below can be slightly varied in relation to effective mechanical performances.

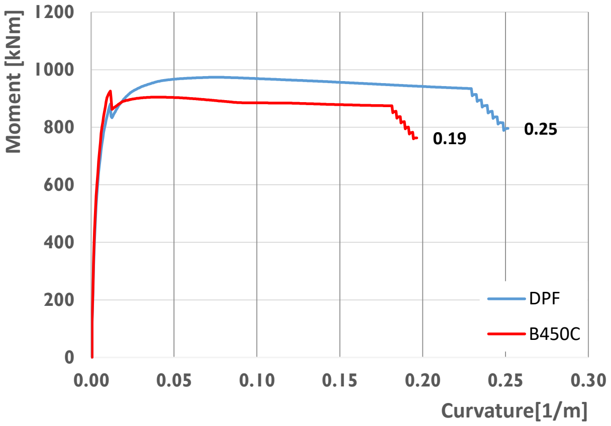


Figure 8. M-χ diagram for column section P1.

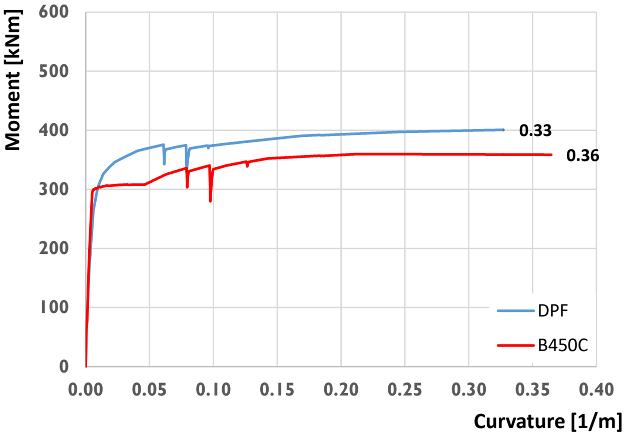


Figure 9. M-χ diagram for beam section A-A.

Considering results of analysis at 'element level', similar considerations in terms of yielding and ultimate chord rotation can be made, as presented in Figure 11 and Figure 12.

The element rotation can be evaluated by integrating the curvature along the length interested by dissipative phenomena (e.g. the so defined plastic hinge length). For the definition of the plastic hinge length preliminary values coming from Paulay and Priestley (1992) were adopted. Of course, as presented in the following paragraph, additional considerations and further developments will be assessed using values of the plastic hinge length calibrated according to the results of experimental tests on RC-DP elements and substructures.

Figures 11 and 12 show the moment-rotation diagrams achieved for structural elements with, respectively, section P1 (column) and A-A (beam) and DPF and B450C reinforcing steels. The ultimate values of rotation – as indicated in the diagrams – are associated to the failure criteria before determined (*criterion I* – concrete core ultimate deformation; *criterion II* – ultimate deformation of rebars; *criterion III* – 20% of decrease of bearing capacity). As the rotation is related to the curvature though plastic hinge length, similar considerations about the results in terms of ultimate rotations can be made.

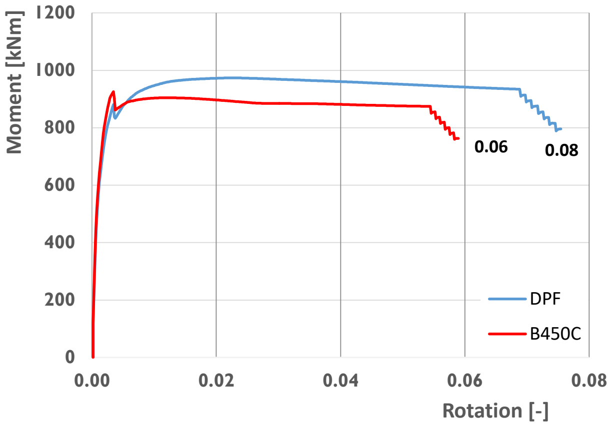


Figure 11. M-θ diagram for column section P1.

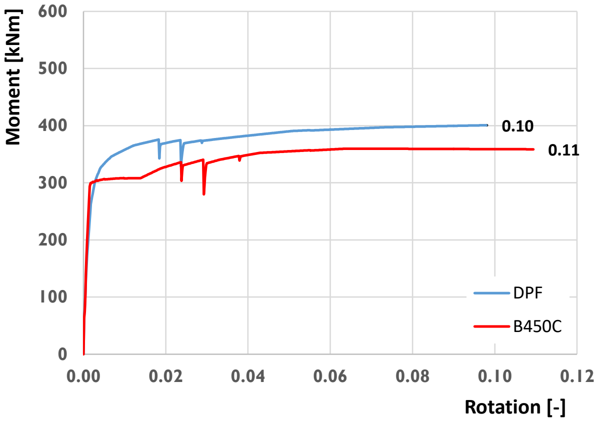


Figure 12. M-θ diagram for beam section A-A.

5 STRUCTURAL ANALYSIS OF DESIGNED RC BUILDINGS

5.1 *Elaboration of nonlinear models*

Nonlinear bi-dimensional models reproducing the effective distribution of stiffness and masses of the designed case-study buildings were elaborated using OpenSees software (Mazzoni et al. 2007). Beams and columns were modelled as *“beam with hinge*” element, in which each single element was divided into three different portions, two plastic hinges in correspondence of the ends, where non-linear phenomena are expected according to the capacity design, and an elastic central part. To take into account cracking phenomena of the concrete, a reduced elastic modulus of the concrete material was adopted in the elastic central portion of the element.

To represent the behaviour in correspondence of the dissipative zones, a fibre approach was used for the modelling of sections; specific constitutive laws, calibrated basing on the results of experimental monotonic and cyclic tests were assigned to each material fiber.

Truss elements for the contribution of diaphragms of storey slabs were used, columns are fixed at the base and masses are concentrated in nodes. The length adopted for the plastic hinges (L_P) was, once again, preliminarily calibrated basing on experimental tests’ results on RC-DP prototypes, presented in a companion paper and briefly hereafter summarized (§5.2.1).

5.2 *Local capacity of elements*

The assessment of structural performance of elements in case of ductile mechanism required the evaluation of the rotational chord capacity evaluated, as an example, through Eurocodes 8 equations. The rotation demand coming from nonlinear analyses was then compared with the corresponding capacity.

For yielding chord rotation *(θ_y)* Eq.A10a from EN1998-3:2005 Annex A was used; note that the above-mentioned formulation was calibrated basing on classical steel grades (like TempCore®) and that, therefore, its validity was preliminarily checked using the results of section and element level analyses previously presented (in terms of curvatures and rotations).

For ultimate chord rotation *(θ_u)*, again, formulations are provided by current standards. Of course, in case of building structural analyses, it is needed to consider simplified reliable equations due to the large number of elements to assess. Eurocode 8 provides two expressions, the first one derived from regression on a great number of experimental results based on RC elements’ tests using ordinary reinforcing steels, and the second one directly depending on the properties of steel grades adopted for rebars, in terms of yielding curvature and ultimate curvature too, as reported in (2), being φ_y and φ_u respectively the yielding and ultimate curvatures, L_p the plastic hinge length and L_v the shear span.

$$\theta_{um} = \frac{1}{\gamma_{el}}\left(\theta_y + \left(\varphi_u - \varphi_y\right)\cdot L_P\left(1 - \frac{0.5\cdot L_{PL}}{L_V}\right)\right) \qquad (2)$$

The difference between achieved values using the two different expressions provided by Eurocode 8 varies in relation to the material used (for TempCore® is around 20% but arrives till 50% in the case of DPF).

For the aims of the present work, equation (2) was adopted since allowing to account for the effective ultimate and yielding curvatures of sections, depending on the properties of reinforcements adopted. Besides, the plastic hinge length value was calibrated according to the results of experimental tests.

5.2.1 *Calibration of plastic hinge length*

An experimental test campaign on reinforced concrete internal and external joints and column bases using DP and TempCore® reinforcements, were performed at *Laboratorio Ufficiale per le Esperienze sui Materiali da Costruzione* of Pisa University, as presented in Figures 13 and 14.

Experimental tests' results show that the damage was mainly concentrated in the beam, in the portion close to the joint (that was not affected by problems) extending for a length of about 300 mm.

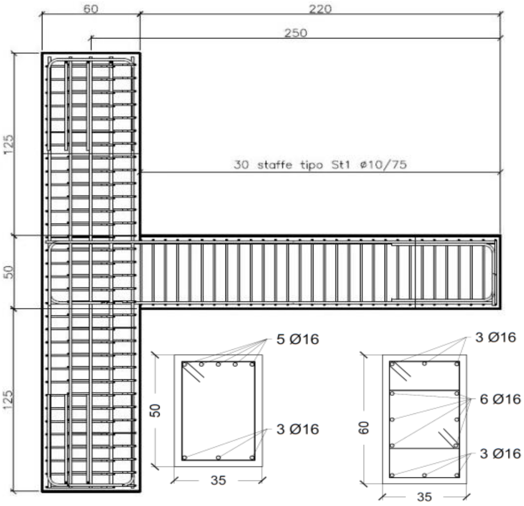


Figure 13. Prototype for tests on external joints.

Figure 14. Tests on exterior joint: dissipative region.

To calibrate plastic hinge length value a dedicated structural numerical model was realized, as schematized in Figure 2. In the model, the following assumptions were made:

- the beam-to-column joint was modelled as *rigid*, in relation to what observed during the experimental tests' campaign.
- The column was considered perfectly pinned in correspondence of the base, according to the schematization assumed for the tests.
- For materials, concrete C30/35 was modelled with *uniaxialMaterial Concrete04*, while for DPF steel grade the multilinear material was calibrated basing on the experimental tensile tests on rebars.

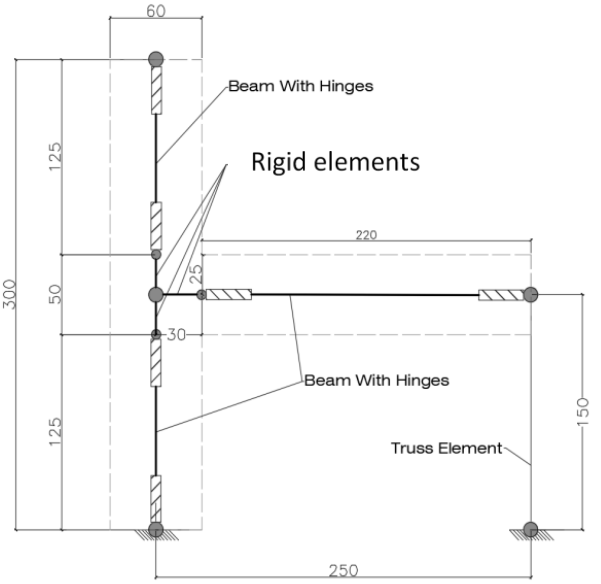
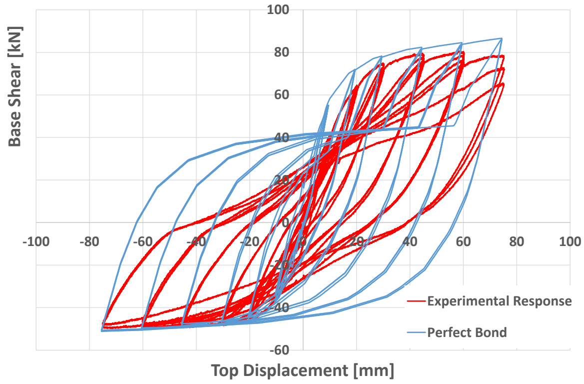


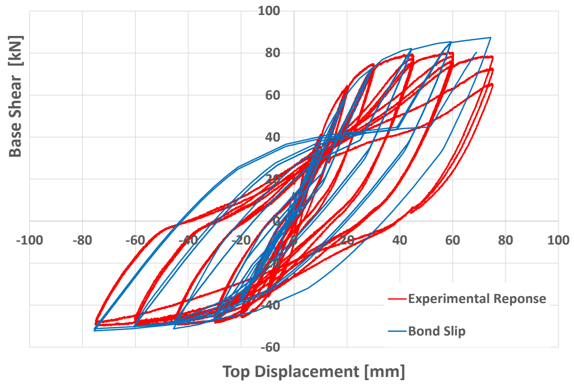
Figure 15. Scheme of FEM Model adopted for calibration

Two different modelling approaches were considered accounting for perfect-bond and, otherwise, including relative slip between steel reinforcing bars and concrete. Bond slip effects were implemented trough a simplified model (Caprili et al. 2018), considering a modified stress strain law of rebars tacking into account the effects of slip.

As visible from Figure 16, the adoption of bond slip hypothesis is fundamental to correctly evaluate to strength and mainly the dissipated energy. Based on the improvement of the simplified bond slip law (in particular to reach a better result in terms of dissipated energy), a value of plastic hinge length equal to 300 mm was assumed.



a)



b)

Figure 16. Comparison between experimental results (blue) and numerical results too: a) full bond and b) relative slip hypothesis.

5.3 *Execution of incremental dynamic analysis*

Nonlinear analyses (both pushover and Incremental Dynamic Analyses – IDA) were performed on the so-elaborated models of the building, allowing to assess the different structural performance adopting TempCore® B450C and DPF steel reinforcing bars. The structural assessment was executed at global level, by analyzing both ductile (e.g. rotation) and brittle (e.g. shear) mechanisms in structural elements.

Selection and scaling of seismic input to be used for IDAs were performed considering both the site characteristics and the dynamic features of the RC case study buildings. 30 accelerograms were applied in two directions (horizontal and vertical); for sake of simplicity, in the present paper only the results related to one ground motion (GM15) are reported (Figure 17).

5.3.1 *Results of Incremental Dynamic Analyses*

The results of nonlinear analyses (Figure 18-Figure 23) are presented in terms of capacity curve (shear at the base vs top displacement) coming from pushover analysis and from IDA, adopting a PGA increment equal to 0.05g; besides, the trend of interstorey drift and the propagation of plastic hinges in the structure are reported for GM15.

The structural performance was assessed by comparing the demand from the analysis with the capacity (i.e. rotation of the elements ends from the analysis vs capacity chord rotation at yielding and ultimate level).

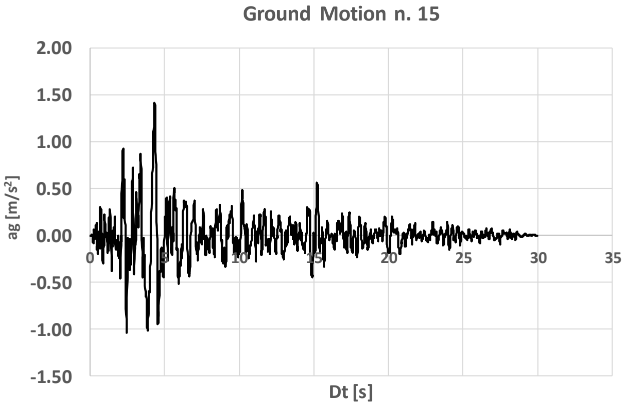


Figure 17. Ground motion used for IDAs presented in the following (GM15).

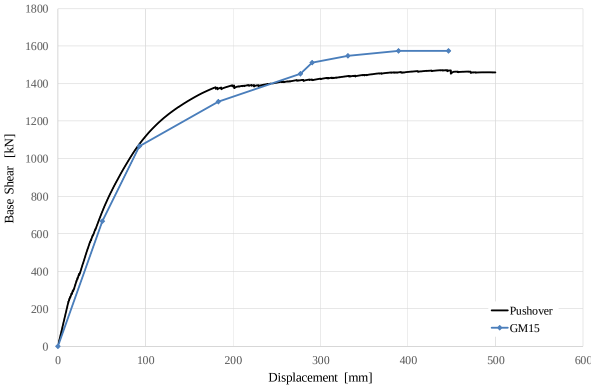


Figure 18. Base shear vs Top Displacement: pushover vs Ground Motion GM15 (B450C rebars).

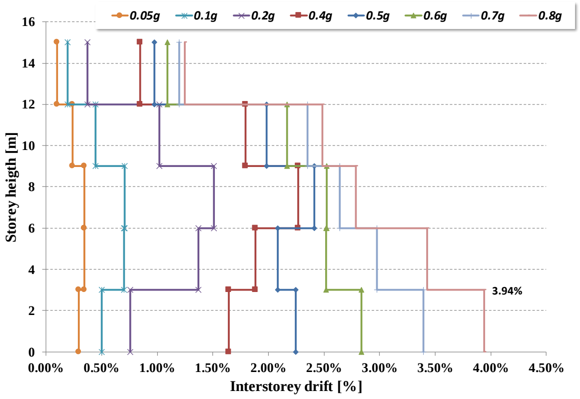


Figure 19. Drift of R.C. case study building evaluated for different level of intensity (B450C rebars).

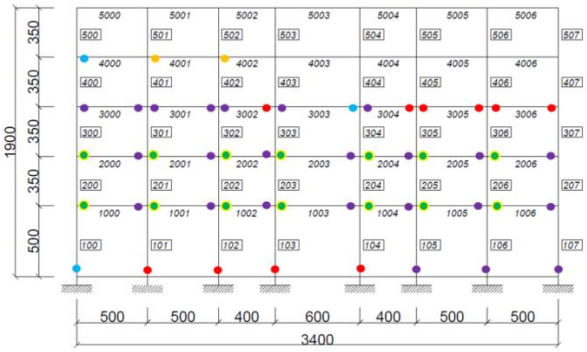


Figure 20. Propagation of plastic hinges in the structure (B450C rebars).

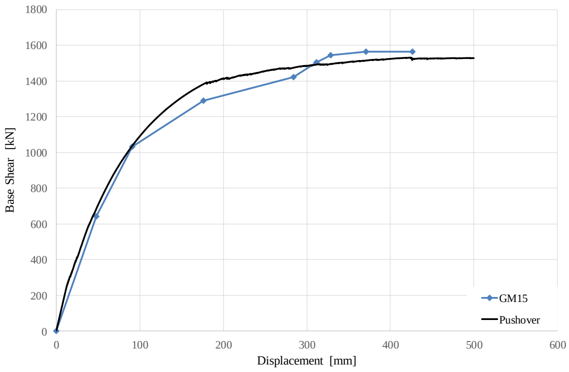


Figure 21. Base shear vs Top Displacement: pushover vs Ground Motion GM15 (DPF rebars).

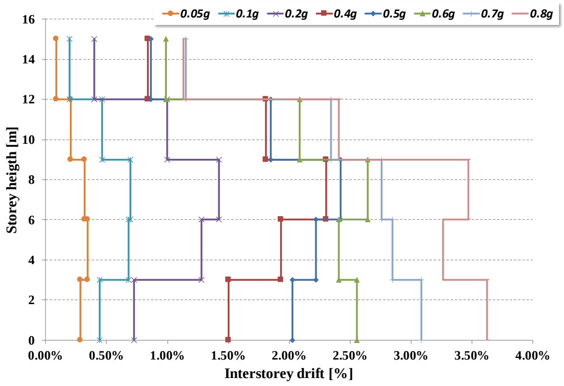


Figure 22. Drift of RC case study building evaluated for different level of intensity (DPF rebars).

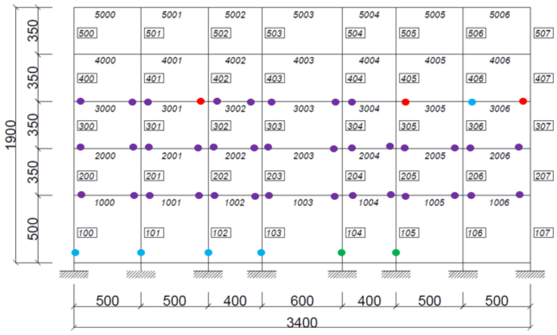


Figure 23. Propagation of plastic hinges in the structure (DPF rebars).

In case of RC building designed with B450C TempCore® steel reinforcing bars, the maximum PGA corresponding to the achievement of the maximum interstorey drift for MRF structures, equal to 3.9% according to FEMA limitations for RC structures, was 0.80g.

Column elements of the first floor, in particular columns, exceeded the yielding chord rotation for PGA equal to 0.40g, while the ultimate rotation was overcome for PGA level up to 1.10 g. Beams, otherwise, yielded for PGA equal to 0.20 g, reaching otherwise their maximum rotational capacity once again for PGA equal to 1.10 g.

No brittle-shear mechanisms were individuated, according to the capacity design approach for the sizing of structural elements.

In case of RC building designed with DPF rebars, the maximum PGA corresponding to the achievement of the max interstorey drift for MRF structures, equal to 3.6%, was 0.80g.

Column elements of the first floor, in particular columns, exceeded the yielding chord rotation for PGA equal to 0.60g, while the ultimate rotation was overcome for PGA level up to 1.20g. Beams, otherwise, yielded for PGA equal to 0.40 g, reaching otherwise their maximum rotational capacity once again for PGA equal to 1.10g.

No brittle-shear mechanisms were, also in this case, individuated, according to the capacity design approach for the sizing of structural elements. Table 3 summarizes the achieved results.

Table 3: Comparison between results of IDA with B450C and DPF steel grades for rebars.

		RC-B450C	RC-DP
	Max disp. [mm]	446	426
	Shear force [kN]	1570	1560
θ_y *[PGA for activation]*	Beam 1st floor	0.20 g	0.40 g
	Beam 2nd floor	0.20 g	0.40 g
	Beam 3rd floor	0.20 g	0.40 g
	Column 1st floor	0.40 g	0.60 g
θ_u *[PGA for activation]*	Column 1st floor	1.10 g	1.20 g

6 CONCLUSIONS

The influence of the adoption of Dual-Phase (DP) steel reinforcing bars on the performance of sections, elements and whole buildings was assessed by means of numerical analyses.

The mechanical properties of the materials and the following constitutive laws assumed in the models were calibrated basing on the experimental tests performed within the NEWREBAR project, both on steel reinforcing bars and on full-scale substructures.

Simulations showed the influence of DP rebars on moment-curvature diagrams, highlighting the different behaviour of columns and beams' section, i.e. the different influence of axial load. Incremental Dynamic Analyses (IDAs) were executed on MRF-RC frames designed with B450C and DPF reinforcements, with the aim of achieving the same bearing capacity of elements and whole building. Results were presented in terms of maximum peak ground acceleration (PGA) activating the different relevant collapse criteria, at global and element/local levels.

No relevant differences in the behaviour in terms of drift and ultimate chord rotation were revealed between RC-DP and RC-B450C buildings, highlighting the competitiveness of Dual-Phase rebars for the adoption in the design and realization of buildings. Besides, looking at the results of Table 3, the development of plastic hinges is slightly different and happens for higher PGA levels in case of DP rebars: this is coherent with the mechanical performance in terms of deformation of the two typologies of reinforcing steels.

Of course, it shall be noted that results of numerical analyses on RC buildings derive from models using parameters (such as plastic hinge length) calibrated only preliminarily basing on experimental tests' results, while additional investigations are still ongoing; the same considerations can be made concerning yielding and ultimate chord rotations. Further developments are still ongoing.

ACKNOWLEDGEMENTS

The present research was developed in the framework of the European Research project NEWREBAR "*New Dual-Phase steel reinforcing bars for enhancing capacity and durability of anti-seismic moment resisting frames"* (2015-2019), funded by the Research Fund for Coal and Steel of European Commission (RFSR-CT-2015-00023).

The Authors would like to thank all the partners for their active contribution.

REFERENCES

Apostolopoulos, C.A., Papadakis, V.G. (2008). Consequences of steel corrosion on the ductility properties of reinforcement bar, *Construction and Building Materials* **22**, 2316–2324.

Braconi, A., Braga, F., Caprili, S., Gigliotti, R., Salvatore, W. (2014). Seismic demand on steel reinforcing bars in reinforced concrete frame structures, *Bulletin of Earthquake Engineering*, **12**, 2633–2664.

Caprili, S., Moersch, J., Salvatore, W. (2015). Mechanical Performance vs. Corrosion Damage Indicators for corroded steel reinforcing bars, Advances in Material Science Engineering, Article ID 739625.

Caprili, S., Salvatore, W. (2015). Cyclic behaviour of uncorroded and corroded steel reinforcing bars, *Construction and Building Materials*, **76**, 168–186.

Caprili, S., Salvatore, W., Valentini, R., Ascanio, C., Luvarà, G. (2018). A new generation of high-ductile Dual-Phase steel reinforcing bars, *Construction and Building Materials*, **179**, 66–79.

Caprili, S., Salvatore, W., Valentini, R., Ascanio, C., Luvarà, G. (2019). Dual-Phase steel reinforcing bars in uncorroded and corroded conditions. *Construction and Building Materials*, **218**, 162–175.

D.M. 17/01/2018 Norme Tecniche per le Costruzioni – NTC2018 (*Italian Technical Standard for Constructions*), in Italian.

EN 1998–1:2005, 2005 Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings, CEN - European Committee for Standardization.

Imperatore, S., Rinaldi, Z., Drago, C. Degradation relationships for the mechanical properties of corroded steel rebars (2017). *Construction and Building Materials*, **148**, 219-230.

Maffei, B., Salvatore, W., Valentini, R. (2007). Dual-phase steel rebars for high-ductile r.c. structures, Part 1: Microstructural and mechanical characterization of steel rebars, *Engineering Structures*, **29**, 3323-3332.

Salvatore, W., Buratti, G., Maffei, B., Valentini, R. (2007). Dual-phase steel rebars for high-ductile r.c. structures, Part 2: Rotational capacity of beams, *Engineering Structures*, **29**, 3333-3341.

Paulay, Thomas, and MJ Nigel Priestley, 1992. Seismic design of reinforced concrete and masonry buildings, 135-146.