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PRELIMINARY COMPARISON BETWEEN DIFFERENT SOFTWARE MODELING OF CONFINED CONCRETE

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Abstract. *The aim of the work is, on the one hand, the presentation of a theoretical fiber model able to predict the moment-curvature behaviour of confined RC columns and, on the other hand, the comparison between the moment-curvature provided by common structural programs. The theoretical fiber model presented in the paper is implemented in a visual basic software and it is able provide moment-curvature ($M-\chi$) diagrams for sections with or without axial load. The software considered in this work are Sap2000, Seismostruct and Opensees. The moment-curvature curves provided by these softwares, given the same modeling have been compared to those provided by the theoretical fiber model. In particular, the modeling has been carried out by subdividing the sections in three category of fibers: unconfined concrete fibers, confined concrete fibers and rebar fibers. The constitutive model adopted for concrete is the one proposed by Mander et al. (1988) [1] for both the confined and unconfined concrete. The constitutive model adopted for the steel rebars is an elastic perfectly plastic law. The parametric analysis has been led on rectangular column sections with different level of axial load. The accuracy of the modelling of the considered structural programs has been investigated by comparing the results belonging to them with those obtained by applying the theoretical fiber model. Besides the calculation of the moment-curvature it is possible to observe that the curves representative of SAP2000 are more in accord with the curve representative of the theoretical software, on average. Form the Seismostruct side, it is possible to observe that the resistance is well captured by the software but for increasing levels of the axial load the Seismostruct overestimate the resistance. Results become more different from the theoretical model when the axial load level increases.*

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1 INTRODUCTION

It has long been recognized that strength, as well as ductility of concrete, increase whenever its state of stress is a triaxial compression. The concrete affected by this favorable action of the transverse reinforcement is called confined concrete.

Confinement offers two main advantages regarding the seismic behaviour of concrete structural elements: it increases strength of concrete, which compensates for possible losses caused by spalling and it reduces the slope of the descending branch of the $\sigma_c - \varepsilon_c$ curve.

In this paper, the results of various software able to predict the moment-curvature behaviour of confined RC columns are reported with reference to a rectangular cross section of a R.C. columns extrapolated from a building designed according to the modern seismic codes. The aim of the work is, on the one hand, the presentation of a theoretical fiber model able to predict the moment-curvature behaviour of confined RC columns and, on the other hand, the comparison between the moment-curvature provided by common structural programs. The theoretical fiber model presented in the paper is implemented in a visual basic software and it is able provide moment-curvature (M−χ) diagrams for sections with or without axial load basing on the the constitutive model of confined concrete proposed by Mander et al. (1988) [1]. The software considered in this work are Sap2000, Seismostruct and Opensees.

2 REVIEW OF CONFINED CONCRETE MODELS

The confined concrete theoretical model assume a stress-strain constitutive law different for different zones of the same sections. Concrete can be considered effectively confined or not by the actions of the lateral reinforcement. Therefore, in the same section, different constitutive laws could be adopted for the part of the concrete effectively confined and for the unconfined one.

As regards the confined concrete, it has been demonstrated that the strength and the corresponding longitudinal strain at the strength of concrete confined by an active hydrostatic fluid pressure can be represented by the following simple relationship:

$$f'_{cc} = f'_{co} + k_1 f_l \tag{1}$$

$$\varepsilon_{cc} = \varepsilon_{co}\left(1 + k_2 \frac{f_l}{f'_{co}}\right) \tag{2}$$

where f'_{cc} and ε_{cc} are the maximum concrete stress and the corresponding strain, f_l is the lateral fluid pressure, f'_{co} are ε_{co} the unconfined concrete strength and the corresponding strain, k_1 and k_2 are coefficients functions of the concrete mix and the lateral pressure.

Richart et al. (1928) [1] found the average values of the coefficients for the tests they conducted to be $k_1 = 4{,}1$ and $k_2 = 5k_1$. Instead, Balmer (1949) [3] found from his tests that k_1 varied between 4,5 and 7,0 with an average value of 5,6, the higher values occurring at the lower lateral pressures. Richart et al. (1929) [4] also found that the strength of concrete with active confinement from lateral (fluid) pressure was approximately the same as for concrete with passive confinement pressure from closely spaced circular steel spirals causing an equivalent lateral pressure.

1) Afterwards, the problem of the confined concrete has been widely investigated. It has been demonstrated that confinement is improved if:
2) The transverse reinforcement is placed at relatively close spacing;
3) Additional supplementary overlapping hoops or cross ties with several legs crossing the section are included;
4) The longitudinal bars are well distributed around the perimeter;

5) The volume of transverse reinforcement to the volume of the concrete core or the yield strength of the transverse reinforcement is increased;
6) Spirals or circular hoops are used instead of rectangular hoops and supplementary cross ties.

However, it is important to be able to quantify these effects of confinement on the stress-strain behavior of concrete. The stress-strain model of Kent and Park (1971) [5] for concrete confined by rectangular transverse reinforcement was based on the test results of Roy and Sozen (1964) [6] and others available at the time. This model neglected the increase in concrete strength but took into account the increase in ductility due to rectangular confining steel. Subsequently, Park et al (1982) [7] and Scott et al. (1982) [8] have tasted near full-size specimens based on real building columns and modified the Kent and Park [5] stress-strain equations to take in account the enhancement of both the concrete strength and ductility due to confinement and the effect of strain rate. Other monotonic stress - strain equations for concrete confined by rectangular - shaped transverse reinforcement have been proposed by Vellenas et al. (1977) [9] and Sheikh and Uzumeri (1980, 1982) [10], [11]. In particular, Sheikh and Uzumeri [10], [11] proposed a stress-strain model of similar form the one proposed by Park et al. [7]. This model incorporates the confinement effects by adjusting the peak stress and setting a confinement effectiveness coefficient. The confinement effectiveness coefficient depends on the configuration of the hoop reinforcement. Stress-strain equations for concrete confined by spiral reinforcement have been proposed by Park and Leslie (1977) [12], Desay et al. (1978) [13], Ahmad and Shah (1982, 1985) [14], [15], Dilger et al. (1984) [16], and others.

Mander, Priestley and Park (1988) [1] proposed an unified stress - strain model for confined concrete, both for circular or rectangular sections, under static or dynamic loading, either monotonically or cycling applied. More recently, Mander and Chang (1994) [17] developed a hysteretic model for confined and unconfined concrete subjected to both tension or compression cyclic loading. This concrete stress-strain model is a modern version of the well-known Mander, Priestley and Park [1] model and has been enhanced to predict the behaviour of high strength concrete. The model is also capable of simulating gradual crack closure under cyclic loading. However, the monotonic part of the model is perfectly coincident with the Mander, Priestley and Park model.

The need to improve the seismic performances of existing buildings or to retrofit them according to the new-seismic regulations is a more and more pressing need in areas subjected to high seismic risk [18]-[25]. Among the new available technologies, great attention has received the confinement of structural members by applying one or more layers of fiber-reinforced materials in a polymeric matrix (FRP) bonded to the element's surface. The increasing use of confinement by FRP requires analytical models able to predict the behavior of confined concrete elements. Many researchers have developed and proposed different constitutive laws. Some of them require an iterative procedure, some require, as collapse condition, the attainment of the ultimate value of concrete axial strain, while others refer to the ultimate strain of FRP; finally, some of them consider only the maximum value of the lateral confining pressure, while others its whole development as a function of the concrete axial strain. Generally, these constitutive laws are based on the definition of the confined concrete maximum strength (f_{cc}) and the corresponding maximum strain (ε_{cc}). To estimate the ultimate strength of reinforced concrete elements confined with FRP, several relationships can be found in literature [25], [27]. They are based on the preliminary evaluation of the ultimate lateral confining pressure, and on the assumption that concrete collapse occurs when FRP layers reach their ultimate stress [28]-[37]. A large comparison of this constitutive models is reported in [38]-[39] while in this paper reference is made to unreinforced sections only. To take in account the confinement behavior of structural members is also important in the design phase. In fact, the benefic effects of confinement lead to a higher resistance with a consequent overstrength in the members that has to be taken in account in the application of beam-to-column hierarchy criterion as the same as of shear-bending hierarchy criterion. This consideration coupled with more sophisticated design approaches [40]-[43] allows to assure that structures are able to exploit at the collapse their full dissipative capacity leading to a collapse mechanism of global type.

3 MOMENT-CURVATURE OF REINFORCED CONCRETE COLUMNS

In this work, the moment-curvature of reinforced concrete columns affected by confinement has been provided by means of three software: SAP2000, SeismoStruct and Opensees programs which can simulate the inelastic response of structural systems subjected to static loads. In particular, push-over analyses have been carried out to obtain the plastic response. Obtained results have been compared with those provided by a research software based on a fiber modelling called MCCRCCS (Moment-Curvature Confined Reinforced Concrete Column Sections).

The philosophy which the fiber hinge model is based on, subdivides the cross section of the structural element in three types:

1) fibres used for modelling the longitudinal steel reinforcing bars;
2) fibres used to define the nonlinear behaviour of confined concrete
3) fibres used to define the nonlinear behaviour of unconfined concrete which includes cover concrete.

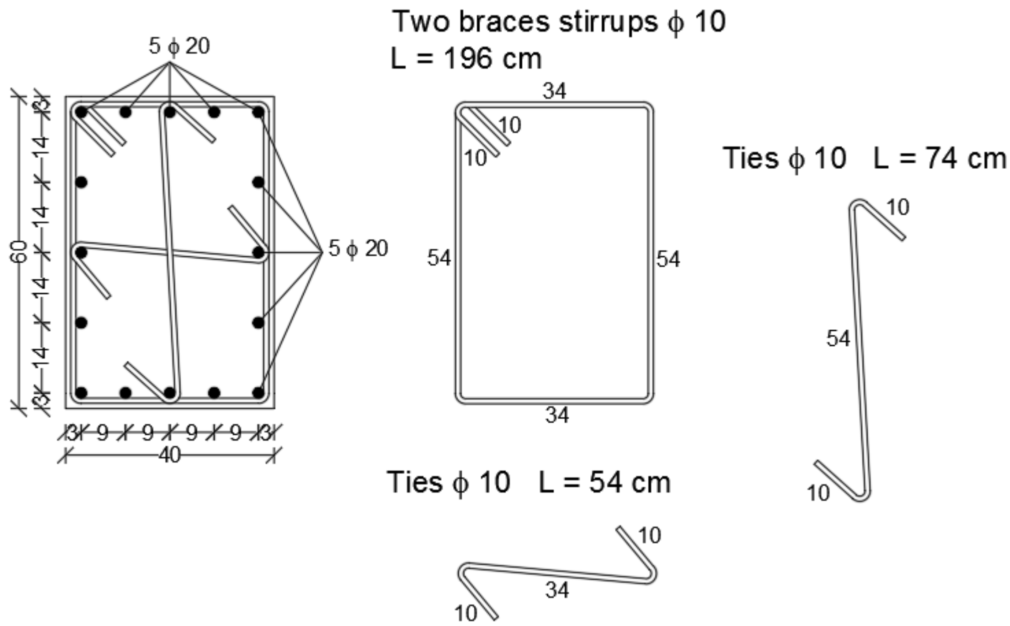

Fig. 1. Cross section of column specimens

For each fiber, the stress-strain (σ-ε) constitutive law is determined. The geometry, dimensions and reinforcing details of the specimens are shown in Fig. 1. Each specimen represents a cantilever column whose length is 3.00 m. The specimens have rectangular cross-sections with dimensions 0.40x0.60 m^2. The longitudinal reinforcement of the columns in both lateral faces is composed of sixteen bars of 20 mm diameter. The shear reinforcement in the columns was composed of 10 mm diameter stirrups spaced at 0.12 m. The concrete material is a C25/30 and the reinforcement material is B450C steel.

Table 1 summarizes the mean values of the material properties used in the construction of the specimens, where f_{ck} is the cylindrical concrete compressive strength and ε_{co} is the corresponding strain; f_{cc} is the compressive strength of confined concrete and ε_{cc} is the corresponding strain; ε_{cu} is the ultimate strain; ε_{sp} is the concrete spalling strain; f_t is the tensile strength of concrete; E_c is the Young modulus of concrete; f_{yk} is the yield strength of the reinforcement; E_y is the Young modulus of steel.

Table 1. Mechanical properties of steel and concrete

		Confined Concrete				Unconfined Concrete			Steel	
s	E_c	f_{cc}	f_t	f_{cc}	f_{cu}	f_{ck}	ε_{co}	ε_{sp}	E_y	f_{yk}
[cm]	[MPa]	[MPa]	[MPa]	[-]	[-]	[MPa]	[-]	[-]	[MPa]	[MPa]
12	25000	31.375	2.5	0.00455	0.017173	25	0.002	0.01	210000	450

The Eq. (5) proposed by Mander et. al. [1] has been applied to define the stress-strain constitutive model of both confined and unconfined concrete according to the mechanical properties reported in Table 1. In Fig. 2, the constitutive laws referring to confined concrete and unconfined concrete are reported. In particular, the distance b_c and d_c are taken to center lines of perimeter hoop in x and y directions as suggested by Mander et al. [1]. In fact it has been observed that, taking the distance b_c and d_c net of the cover concrete does not affect the results in terms of stress-strain constitutive law. In addition, 5 level of vertical loads have been applied by considering a percentage of the resistant axial load (N_{Rd}= 8136 kN) of the section. The selected percentage are 0%, corresponding to simple bending, 10%, 20%, 30% and 40%.

For the steel reinforcements an elastic-perfectly plastic constitutive law has been adopted according to the mechanical properties reported in Table 1.

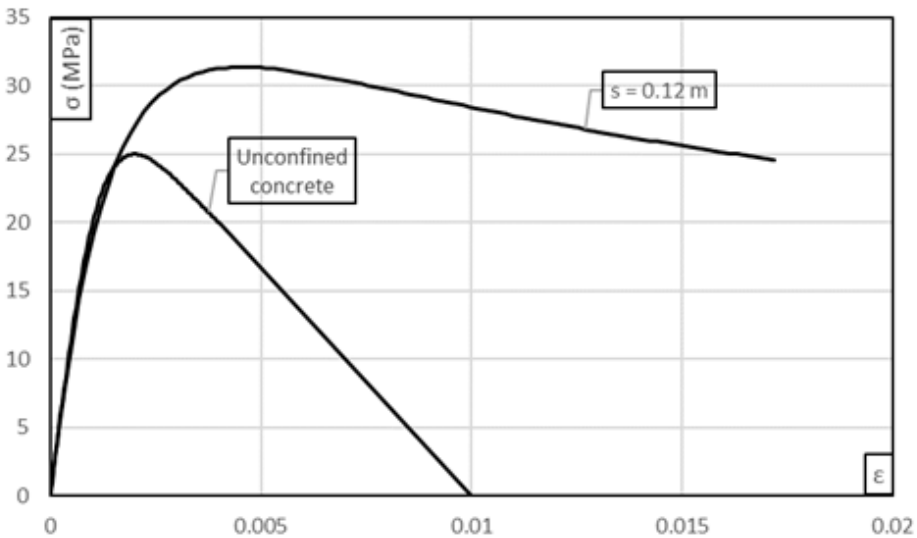

Fig. 2. σ-ε constitutive law for concrete modelling

4 SOFTWARE ADOPTED

4.1 MCCRCCS Research software

Starting from the stress-strain models reported in Fig. 2, a procedure for computing the moment-curvature diagram can be easily outlined on the basis of a fiber model. The cross section has been subdivided into rectangular elementary areas which have been characterized by an appropriate constitutive law: unconfined concrete, confined concrete and steel of the longitudinal reinforcements. In order to account for the effect of the load acting on the unstrengthened structural member, the deformations occurring in each elementary area before the strengthening intervention have to be computed and considered in the subsequent analysis. The different zones of the section, both confined and unconfined, need to be preliminarily recognized. To this aim, the longitudinal confining bars, which are those located in the corners or those out of corners, but restrained by steel ties, have to be identified. Starting from these restraining points, it is possible to determine the parabola arches dividing the zones of effectively confined concrete from the zones of unconfined concrete, as it is shown in Fig. 3.

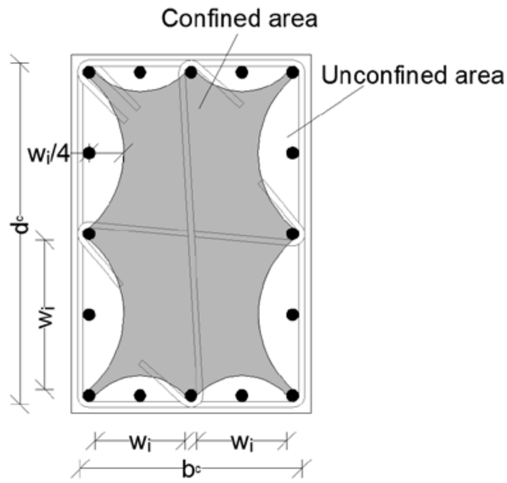

Fig. 3. Identification of confined and unconfined concrete

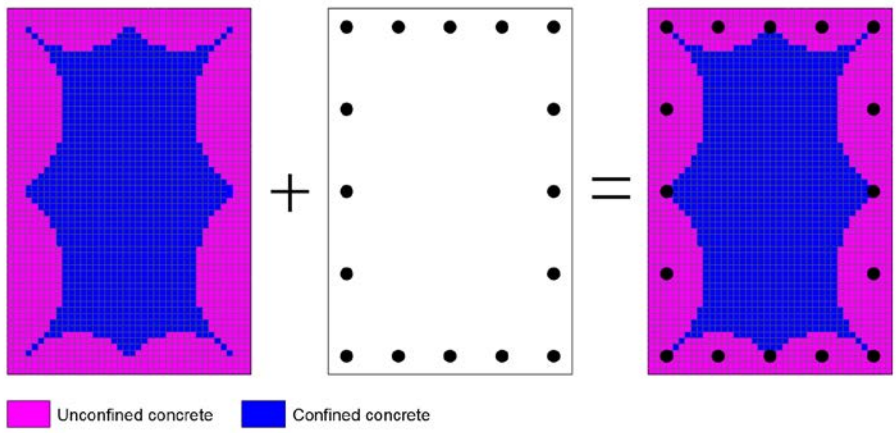

Fig. 4. Fiber subdivision of the cross section

On the bases of the constitutive laws of steel, confined concrete and unconfined concrete, the procedure for evaluating the moment-curvature diagram, for a given axial load has been codified into a computer program namely MCCRCCS. The same code has been used by Montuori and Piluso in a previous work dealing with the behaviour of reinforced concrete columns strengthened with angles and battens [33]. The fiber subdivision of the section is reported in Fig. 4 where it is possible to observe that 40 fibres longitudinally and 60 fibres transversally have been adopted. The areas of steel longitudinal bars have been introduce by their coordinates.

4.2 Sap2000

SAP2000 v. 14.0.0 is general-purpose civil-engineering software used for the analysis and design of any type of structural system [35]. As regard plastic analysis, it allows to account for lumped and spread plasticity by means of concentrated plastic hinges and fiber hinges whose length can be properly selected to capture the actual plastic behaviour of the members. In this work, fiber hinge modelling has been exploited by introducing in the software, a user defined fiber section. In particular, the section has been discretized in 60x40 small areas of 1 cm^2 following the same subdivision depicted in Fig. 4 and adopted for the MCCRCCS. For both confined and unconfined concrete the corresponding stress strain relationship has been implemented. Each rebar has been introduced as circular areas and applying a stress-strain relationship of the steel. Concrete materials have been introduced by means of the advanced properties of material ambiance accounting for the “Mander” shape of stress-strain behaviour already implemented for uniaxial material typologies. To provide the moment-curvature of the specimen sections push-over analyses have been carried out on a cantilever scheme whose length is 3 m. The elastic behaviour of the member has been simulated by means of a beam-column element with a 60x40 concrete section. To this element, a fiber hinge whose length is equal to the 10% of the global length of the cantilever has been applied to the base extreme. The analyses have been led in displacement control for each level of axial load, taking in account both geometrical and mechanical non linearities.

4.3 OpenSees

The Open System for Earthquake Engineering (OpenSees) [34] is an open source software framework for finite analysis and it was developed to simulate the response of structural and geotechnical systems subjected to earthquakes. Uniaxial material Concrete04 is used to construct a uniaxial concrete material whose envelope of the compressive stress-strain response is defined using the model proposed by Popovics (1973) [32]. If the user defines the Young modulus as $E_c = 5{,}000\sqrt{f'_{co}}$ then the envelope curve is identical to the one proposed by Mander et al. [1]. In this model the compressive stress is equal to zero when the crushing strain is achieved. In addition, it is possible to introduce a tensile stress different to zero.

The material Steel01 is used to construct a uniaxial bilinear steel material object with kinematic hardening and optional isotropic hardening described by a non-linear evolution equation. It has been used in both the nonlinear model to simulate the stress-strain behaviour of the reinforcing bars. The hardening has been assumed very low (0.0001) to represent an elastic-perfectly plastic behaviour. To provide the moment-curvature of the specimen sections, push-over analyses have been carried out on a cantilever scheme whose length is 3 m. The nonlinear-BeamColumn element has been introduced to model the cantilever scheme and it is represented by unidirectional fibres which are assigned by the proper material stress-strain relationships describing the materials monotonic response. It is based on the non-iterative force formulation and considers the spread of plasticity along the element. The section discretization is the same reported in Fig. 4 and it has been introduced by using the “fiber” section command in the software input file. In addition, five integration points were adopted for the column element. Analysis has been led in displacement control take in account geometrical and mechanical non linearities for each axial load level.

4.4 SeismoStruct

The SeismoStruct 2016 [36] is a finite element package capable of predicting the large displacements behaviour of space frames under static or dynamic loading, taking into account geometric nonlinearities and material inelasticity. For each specimen section a nonlinear model was developed. The model was built with inelastic displacement based frame elements. In Seismostruct ambiance it is not possible to define a user defined fiber section so that, the material models con_ma (Mander et al. [1]) has been adopted for both the confined and unconfined concrete. This is a uniaxial nonlinear constant confinement model that follows the constitutive relationship proposed by Mander et al. [1].

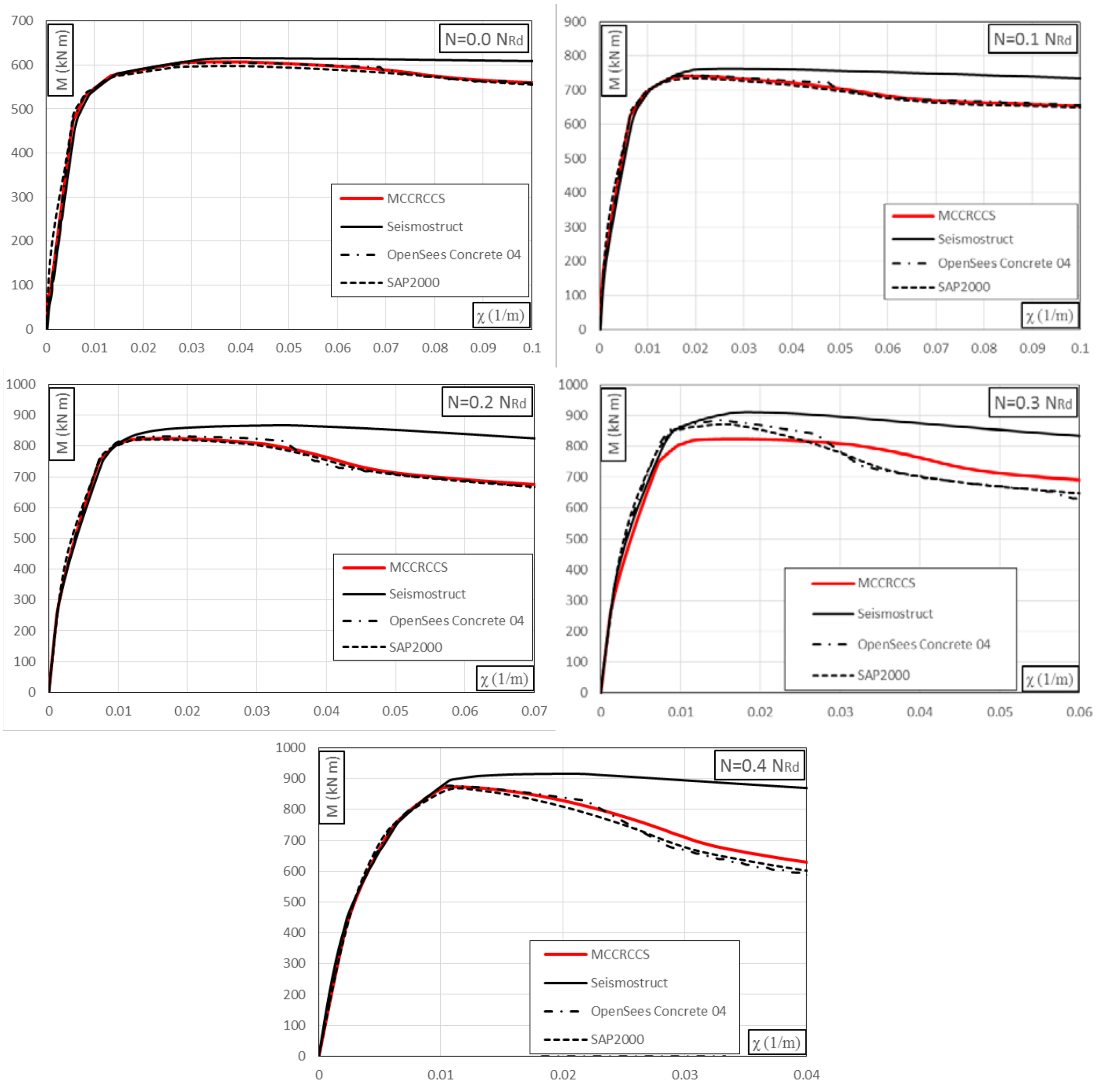

Fig. 5. Moment curvature (M−χ) diagrams

The confinement effects provided by the lateral transverse reinforcements are incorporated through the rules proposed by Mander et al. whereby constant confining pressure is assumed through the entire stress-strain range. The effectiveness of the Seismostruct modelling has been preliminarily validated by checking the confinement ratio parameter (f'_{cc}/f_c) provided by the software. In the case of unconfined concrete a confinement ratio equal to 1 has automatically assumed by the software.

In addition, stl_bl is adopted for the reinforcement with a very low hardening parameter to simulate an elastic-perfectly plastic behaviour (0.0001). The section has been discretized into

1000 fibers (the maximum number of fibers available in the software). To provide the moment-curvature of the specimen sections, push-over analyses have been carried out on a cantilever scheme whose length is 3 m discretized in 4 parts for each level of axial load.

5 RESULTS

Besides the calculation of moment-curvature ($M-\chi$) diagrams the aim of the work is to discover how the different software modelling affects the shape of $M-\chi$ diagram. In Fig. 5, the moment-curvature diagrams of the section with the stirrups spacing of 0.12 m are reported, respectively. In addition, in the same figures the moment-curvature diagrams are reported with reference to different levels of the axial load. In a first comparison it is possible to observe that the curves representative of SAP2000 are more in accord with the curve representative of MCCRCCS on average. In particular, SAP2000 is able to well catch the resistance but it is not able to reproduce the softening branch of the research program. Form the Seismostruct side, it is possible to observe that the resistance is well captured by the software but for increasing levels of the axial load the Seismostruct overestimate the resistance. The OpenSees well captures both the resistance than the softening branch of the curve. Finally, the softening branch of the Seismostruct diagrams are always higher than those provided by other models. Generally speaking, it is possible to observe that the resistance is well captured by the largest part of the software. In addition, the results between the curves became more different as the axial load increase. It is also important to observe that curves has to be stopped at the occurrence of the section collapse which can be achieved in correspondence of the confined concrete cracking or the achievement of the ultimate deformation of rebars. Being this work only preliminary the attention has been focused on the resistance and on the shape of the softening branch of $M-\chi$ curves. Further investigations on different sections with different stirrups spacing have to be performed to achieve a more robust conclusion.

6 CONCLUSIONS

- In this work, a theoretical model to provide moment-curvature of confined reinforced concrete sections has been presented.
- The results obtained with such methodology have been compared with those provided by common structural programs such as Sap2000, OpenSees and Seismostruct.
- Besides the calculation of a moment-curvature ($M-\chi$) it is possible to observe that the curves representative of SAP2000 are more in accord with the curve representative of MCCRCCS on average.
- Form the Seismostruct side, it is possible to observe that the resistance is well captured by the software but for increasing levels of the axial load the Seismostruct overestimate the resistance.
- The OpenSees well captures both the resistance than the softening branch of the curve.
- In future works the parametric analysis will be extended to other sections with different stirrups spacing, placing the attention also on the point in which the section achieve the collapse.

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