

Simplified analytical Moment-Curvature relationship for hollow circular RC cross-sections

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Abstract. The seismic vulnerability analysis of multi-span bridges can be based on the response of the piers, provided that deck, bearings and foundations remain elastic. The lateral response of an RC bridge pier can be affected by different mechanisms (i.e. flexure, shear, lap-splice or buckling of the longitudinal reinforcement bars, second order effects). In the literature, simplified formulations are available for mechanisms different from the flexure. On the other hand, the flexural response is usually calculated with a numerically-based Moment-Curvature diagram of the base section and equivalent plastic hinge length. The goal of this paper is to propose a simplified analytical solution to obtain the Moment-Curvature relationship for hollow circular RC sections. This based on calibrated polynomials, fitted against a database comprising 720 numerical Moment-Curvature analyses. The section capacity curve is defined through the position of 6 characteristic points and they are based on 4 input parameters: void ratio of the hollow section, axial force ratio, longitudinal reinforcement ratio, transversal reinforcement ratio. A case study RC bridge pier is assessed with the proposed solution and the results are compared to a refined numerical FEM analysis, showing good match.

Keywords: Moment-Curvature; hollow circular cross-sections; reinforced concrete; RC members optimisation; RC bridge piers; seismic vulnerability.

1. Introduction

Seismic vulnerability of existing bridge structures is a particularly relevant theme in earthquake-prone countries, given the need to have a vulnerability inventory for large infrastructures. Recent earthquakes, e.g. the 2016 Kaikoura earthquake in New Zealand (Palermo et al., 2017), demonstrated the crucial role of the road bridges in the aftermath of the earthquake, whose performance is desirable for the mitigation actions to take place. Therefore, regional-scale inventories of the seismic performance of bridges should be pursued.

Clearly, refined non-linear analyses is both time- and cost-ineffective for large portfolios (Pinho et al., 2009). Instead, multi-level approaches are preferred, starting with large-scale simplified analyses, creating a prioritisation scheme and refining the analysis only for the top-priority elements. Typically, large-scale analyses are based on semi-empirical calibrated indexes (Kircher et al., 2006). Other approaches are based on the definition of mechanically-based simplified capacity curves for classes of structures based on ideal case study bridges (Broglia et al., 2010). Alternatively, it is possible to calculate the non-linear capacity of bridges on a mechanical basis, although under simplified assumptions. In fact, the energy dissipation capacity of a bridge is concentrated in the

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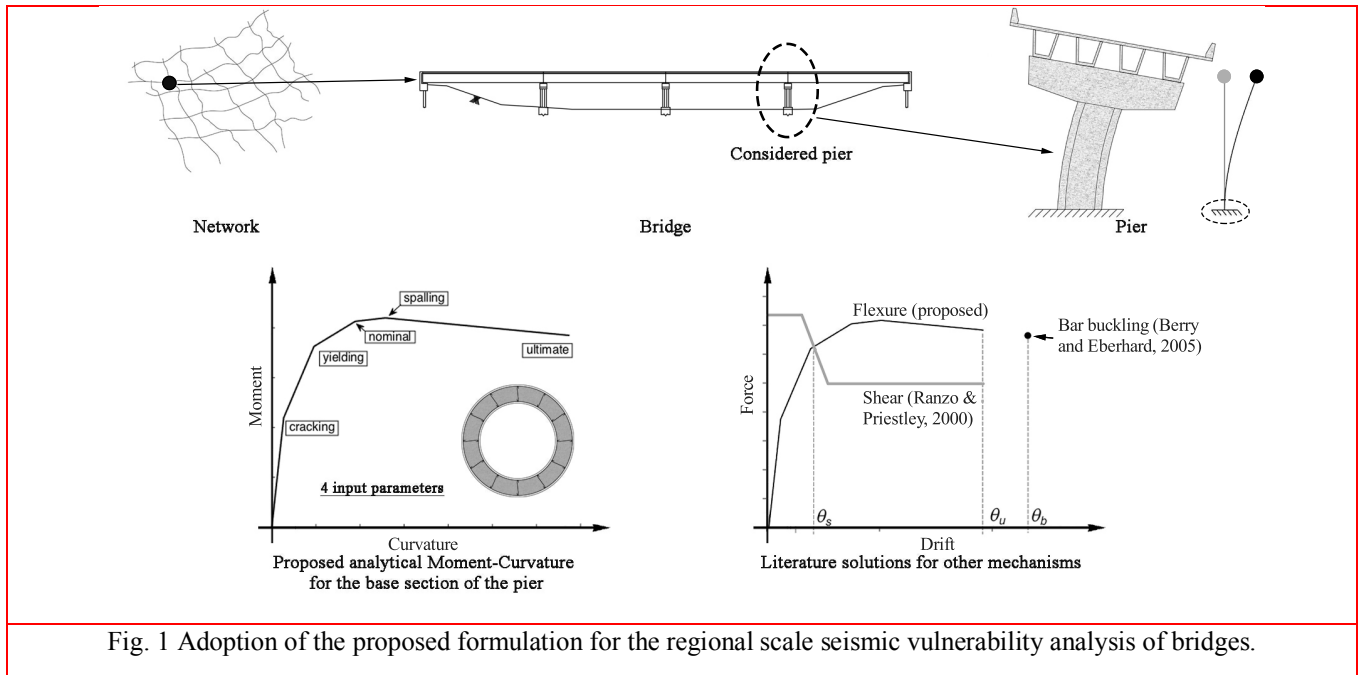


Fig. 1 Adoption of the proposed formulation for the regional scale seismic vulnerability analysis of bridges.

piers, if the deck remains elastic and the bearings do not fail (Fardis, 2007). In such conditions, the

vulnerability of the bridge can be assessed by studying the piers only, modelled as equivalent SDOF systems, in both the transverse and longitudinal directions. Depending on the direction of the analysis, it is therefore necessary to consider two distinct simplified models characterised by different parameters (Raffaele et al., 2014a,b,c), and considering the “effective mass” pertaining to each pier. The shear span of the piers is based on their fixity conditions. Therefore, the Force-Displacement flexural behaviour of a pier is defined by the Moment-Curvature diagram of a critical section, typically located at the base. For a detailed analysis, Moment-Curvature analysis is typically software-based, e.g. KSU_RC (Esmaeily and Peterman, 2007), Cumbia (Montejo and Kowalski, 2007), etc. Additional failure mechanisms such as shear, longitudinal bars buckling, lap-slice, second order effects are separately assessed.

However, for regional-scale analyses (Fig. 1) and the derivation of probabilistic fragility curves (Padgett et al., 2008, Zelaschi et al., 2015, Miano et al., 2015), it is useful to have a reliable but rapid solution for the Moment-Curvature diagram related to the RC bridge pier, which is the specific topic of this paper. In particular, a polynomial analytic solution is proposed to retrieve the Moment-Curvature diagram for RC hollow circular sections. This is obtained by means of fitting against hundreds of numerically-based sectional analyses. The result is an accurate, mechanically-based formulation which is rapid and computationally inexpensive at the same time. Alternatively, such a formulation can be used to verify and validate the

results of the numerical Moment-Curvature analyses in the context of detailed analyses on single structures. The assessment is completed by considering the additional mechanisms using analytical literature studies (shear failure, Ranzo and Priestley, 2000, longitudinal bars buckling, Berry and Eberhard, 2005, lap-splice, Priestley et al., 1996, second order effects, Priestley et al., 2007).

This simplified solution is deemed to be particularly accurate since it is based on refined stress-strain relationships for concrete and steel. The reliability of the proposed formulation is demonstrated by means of analytical vs numerical scatter plots and by the analysis of a bridge pier case study, comparing the results with refined FEM non-linear analysis.

It is worth mentioning that this work is part of a wider project in which other section shapes have been studied, such as the solid circular shape (Gentile et al., 2018), or are currently being studied, such as the rectangular section (Gentile et al., 2017).

2. Methodology and definition of the simplified formulation

This work is based on the definition of a database that comprises 720 hollow circular RC cross-sections, considering a wide range for the geometrical and mechanical parameters (Section 2.1), particularly appropriate to represent bridge piers cross sections. 4 dimensionless parameters are selected, through dimensional analysis, to completely define each case study. A numerically-based Moment-Curvature ($M-\varphi$) analysis is carried out for each entry of the database.

By individuating 6 “characteristic” points (Section 2.2), each numerical ($M-\varphi$) curve is represented by a simplified

piecewise linear curve (m - χ in dimensionless form), which is deemed to represent the flexural behaviour with sufficient accuracy, if compared to the complete numerical curve. A set of polynomial functions is fitted, by means of a least squares method linear regression, to represent the position of the characteristic points as a function of the selected dimensionless parameters, whose definition is given by Equations (6)-(9).

2.1 Description of the database

Given the number of the involved parameters in the definition of the flexural behaviour of RC hollow circular sections, a number of assumptions is adopted, along with the definition of four dimensionless groups. In general, the involved parameters are: external radius R , internal radius r , clear cover c , axial load N , concrete unconfined cylindrical compressive strength f_c , concrete tensile strength f_{ct} , concrete modulus of elasticity E_c , yielding strength of longitudinal and transverse reinforcement f_{ys} , f_{yh} , longitudinal and transverse moduli of elasticity of the steel E_s , E_h , respectively, longitudinal reinforcement bars pattern (n_l and d_l are the number of bars and their diameter), transverse reinforcement pattern (d_h and s are the diameter and the spacing).

For this work, the adopted assumptions are the following: concrete tensile strength f_t (for uniform tensile stress) is assumed to be dependent to the compressive one (f_c) according to Eq. (1), provided in the Italian code (NTC 2008). As suggested in the same code, Eq. (2) is adopted to calculate the tensile strength for flexure (f_{ct}). Such parameter affects only the first cracking in the Moment-Curvature, therefore this is not likely to limit the scope of the final formulations;

$f_t = 0.3f_c^{2/3}$	(1)
$f_{ct} = 1.2f_t$	(2)

- according to Eq. (3), the mechanical characteristics of longitudinal and transverse reinforcement steel are the same: yield stress (f_{ys} , f_{yh} respectively) and elastic modulus (E_s , E_h respectively);

$f_{yh} = f_{ys} \text{ and } E_h = E_s$	(3)
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- the longitudinal reinforcement consists of $n_l/2$ evenly distributed bars of equal diameter (d_l) along the internal and external circumferences. The total area of longitudinal steel is defined with Eq. (4);

$A_s = \frac{n_l(\pi d_l^2)}{4}$	(4)
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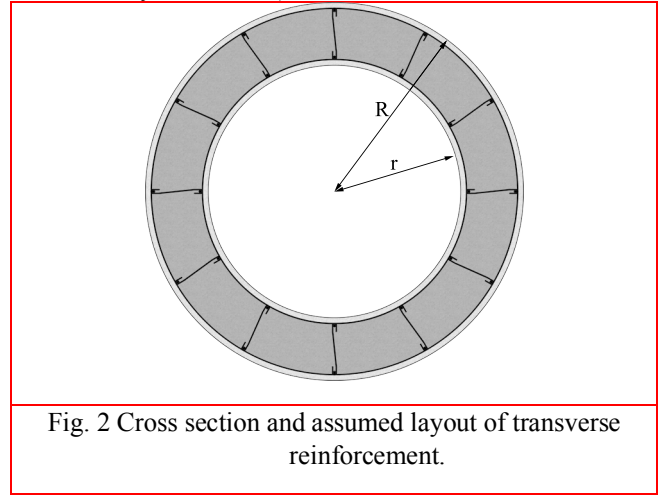
- the transverse reinforcement pattern, shown in Fig. 2, is composed by two perimetric stirrups and $n_l/2$ evenly distributed ties. Less-efficient patterns of the stirrups are deemed to be equivalent, in terms of confined concrete performance, to the above-mentioned one with a lower value of the stirrup size $A_{sp}^{(1)}$. For this reason,

the assumed transverse reinforcement pattern is not deemed to jeopardise the generality of the final polynomial formulations;

- the clear cover, c , is defined by Eq. (5);

$c = 0.02R$	(5)
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- the diameter is fixed to 1m. This was done considering that the relationship between the curvature at a given limit state and the diameter of the section is linear (e.g. Priestley et al., 2007).



Based on dimensional analysis, four dimensionless groups are defined with the remaining parameters, Equations (6)-(9): void ratio α , axial force ratio v , mechanical ratio of longitudinal reinforcement ω , volumetric ratio of transverse reinforcement ρ_{sp} . Therefore, any hollow circular section in the database can be completely defined with such parameters. Basically, a variation in ω can be interpreted as a variation in the longitudinal steel (A_s , f_y), the concrete compression strength f_c or the radii (R or r). Analogously, this applies for the remaining dimensionless groups, also used in similar works (e.g. Perus et al., 2006, 2007).

$\alpha = r/R$	(6)
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$v = \frac{N}{\pi(R^2 - r^2)f_c}$	(7)
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$\omega = \frac{A_s f_y}{\pi(R^2 - r^2)f_c}$	(8)
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$\rho_{sp} = \frac{A_{sp}^{(1)} [2\pi(R - c) + 2\pi(r + c) + n_l(R - r - 2c)]}{\pi[(R - c)^2 - (r + c)^2]s}$	(9)
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720 numerical analyses are conducted, considering all the possible combinations of the dimensionless parameters shown in Table 1. The range of the input parameters is fine-tuned to include the most probable configurations of RC hollow circular sections typically used in practical applications.

the (M- χ) diagram;

- The **Ultimate** point corresponds to the ultimate

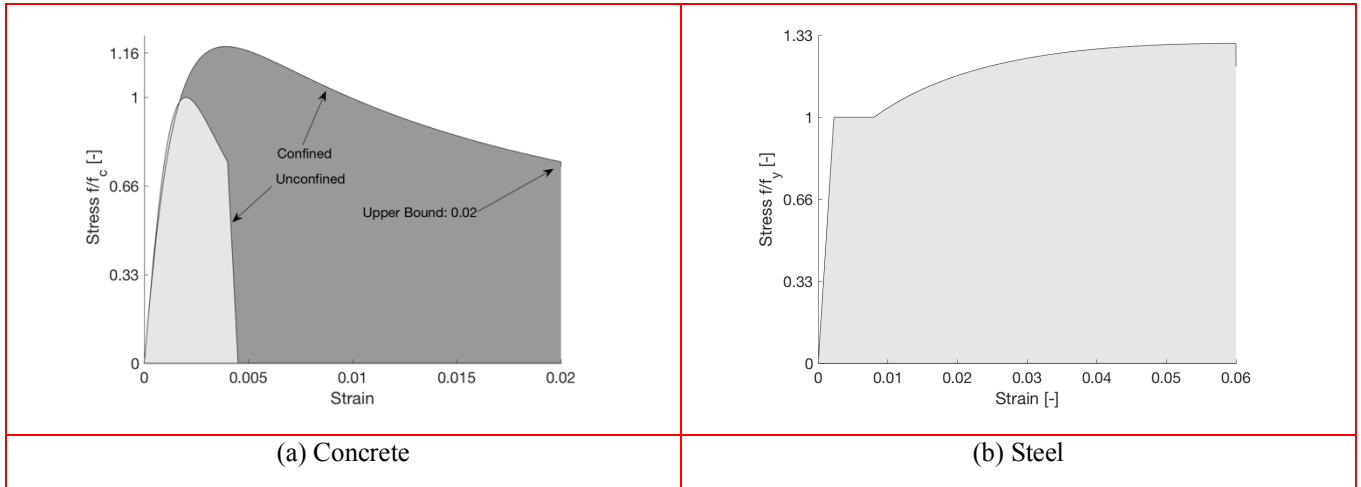


Fig. 4 Assumed stress-strain relationship for the materials.

Table 1 Input values for the construction of the database.

Input parameter	Interval		Number of samples
	Min	Max	
α	0.6	0.8	3
ν	0	0.9	10
ω	0.05	0.4	4
ρ_{sp}	0	0.04	6

2.2 Chosen characteristic points

Six characteristic points are selected for each Moment-Curvature diagram in the database. Those are deemed to be sufficient to represent the flexural behaviour of the cross-section by means of a piecewise linearisation (Fig. 3). Below is given the list of the mechanically-based definition of the characteristic points:

- **Cracking** is the point for which the strain in the furthest core concrete fibre is equal to $\varepsilon_{ct} = f_{ct}/E_c$;
- **First Yielding** is related to the tensile yield of the first rebar, or a compressive strain in the furthest core concrete fibre equal to $\varepsilon_c = 0.002$, whichever occurs first (Priestley et al., 2007);
- **Concrete Peak** is associated to the strain corresponding to the peak stress for the furthest compressed fibre in the confined core of the section;
- **Nominal**. This corresponds to a compressive strain equal to $\varepsilon_c = 0.004$ in the furthest core concrete compression fibre or equal to $\varepsilon_s = 0.015$ in the furthest tension rebar, whichever occurs first (Priestley et al., 2007);
- **Spalling** is the point on the (M- χ) diagram for which the strain of the unconfined concrete in the cover is equal to its ultimate strain (0.0045). Typically, this is associated to a degrading branch in

compressive strain for confined concrete (according to Mander et al, 1988) or the ultimate tensile strain for steel (assumed to be 0.06, according to NZSEE 2017).

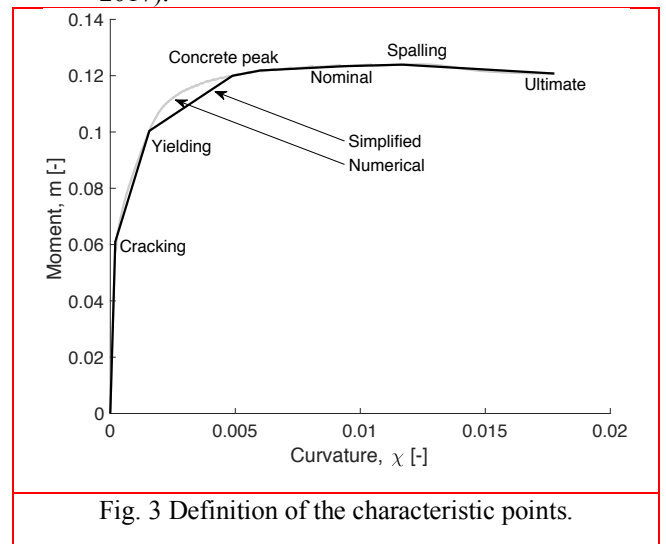


Fig. 3 Definition of the characteristic points.

2.2 Assumptions for the numerical analyses

A *Moment-Curvature* analysis is conducted for each entry of the database, considering all the combinations of the selected input parameters ($3 \times 10 \times 4 \times 6 = 720$ combinations). The software KSU-RC (Esmaily and Peterman, 2007) is adopted for the Moment-Curvature analyses, which is based on a fibre discretisation of the cross-section.

Concrete is modelled according to (Mander et al., 1988), considering both the confined and unconfined behaviour (Fig. 4.a). It is worth mentioning that the confined concrete ultimate strain is calculated according to Mander et al., 1988, adopting 0.02 as an upper bound value.

The behaviour of steel (Fig. 4.b) is modelled according to Esmaily and Peterman, 2007. The curve is linear up to

yielding, with a plateau up to 10 times the yielding strain (Sadowski et al., 2017) and followed by a parabolic shape up to the ultimate strain, which corresponds to the peak and is equal to 0.06 to implicitly consider low cycle fatigue failure (NZSEE 2017). The peak stress is assumed to be 1.3 times the yield stress. These parameters are tuned to represent a commercial steel with a nominal yield stress ranging between 400 and 500 MPa, e.g. the Italian B450C (NTC 2008) and the New Zealand grade 500 (NZSEE 2017). It is worth mentioning that the adopted stress-strain relationship is in close agreement with the widely utilised curve proposed in King et al., 1986, as shown in Gentile et al., 2018.

3. Analysis of the trends and accuracy of the polynomials

3.1 Post processing and curve fitting

Each Moment-Curvature diagram in the database is firstly expressed in dimensionless form according to Equations (10) and (11). Therefore, a purpose-specific Matlab routine is used to “extract” the characteristic points, both in terms of moment and curvature. Fig. 5 shows, as an example, the trend of the characteristic moments and curvatures as a function of the dimensionless axial force, ν , a fixed value of both the void ratio (α) and the longitudinal reinforcement (ω) and the minimum and maximum value of the transverse reinforcement (ρ_{sp}) ratios (represented by the thickness of the line). Appendix A shows the synthetic plots considering the entire database. In such plots (Fig. 9-Fig. 10), void ratio (α) and the mechanical ratio of the longitudinal reinforcement (ω) is fixed, each characteristic point has a different line colour (e.g. green is for yielding), and the line width increases with the increase of the volumetric ratio of transverse reinforcement (the dashed line is for unconfined).

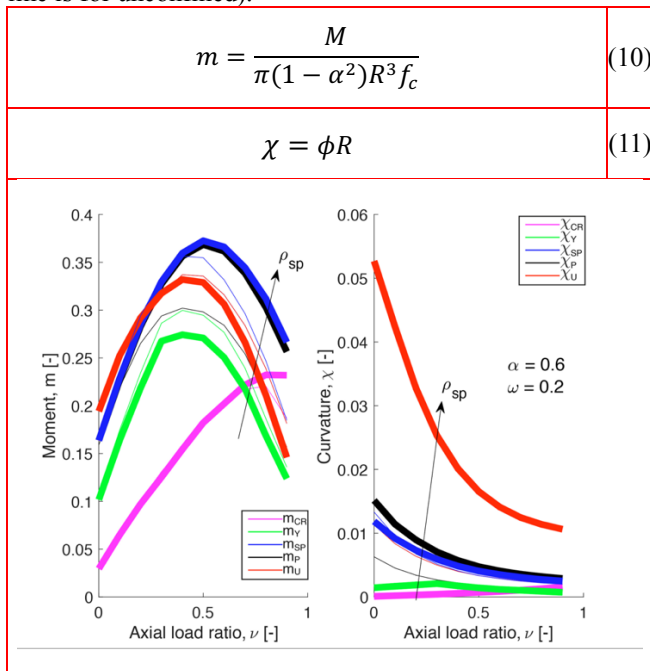


Fig. 5 Trends for the ultimate moment and curvature: section void ratio $\alpha=0.6$, longitudinal reinforcement ratio $\omega=0.2$.

A set of polynomial functions is fitted using a least square method linear regression, using the extracted characteristic moments and curvatures in the database. The input variables for these polynomials are the 4 dimensionless input parameters defined in Section 2.1. This process led to 12 polynomials, in the form of Eq. (12) and (13), which allow to analytically construct the Moment-Curvature diagram of hollow circular sections characterised by mechanical and geometrical parameters within the scope of this database.

The study of the main trends (Fig. 9-Fig. 10) allowed to

$$\begin{aligned}
 m_{char} = & a_0 + a_1\alpha + a_2\nu + a_3\omega + a_4\rho_{sp} + a_5\alpha^2 \\
 & + a_6\nu^2 + a_7\omega\nu + a_8\omega^2 \\
 & + a_9\nu\rho_{sp} + a_{10}\omega\rho_{sp} + a_{11}\alpha\nu \\
 & + a_{12}\alpha\omega + a_{13}\alpha\rho_{sp} + a_{14}\alpha^2\nu \\
 & + a_{15}\alpha\nu^2 + a_{16}\alpha\omega^2 + a_{17}\alpha^2\omega \\
 & + a_{18}\alpha\rho_{sp}^2 + a_{19}\alpha\nu\omega + a_{20}\alpha\omega\rho \\
 & + a_{21}\alpha\nu\rho_{sp} + a_{22}\nu^3 + a_{23}\nu^2\omega \\
 & + a_{24}\nu\omega^2 + a_{25}\nu\rho_{sp}^2 + a_{26}\nu^2\rho_{sp} \\
 & + a_{27}\nu\omega\rho_{sp} + a_{28}\omega\rho_{sp}^2 \\
 & + a_{29}\omega^2\rho_{sp} + a_{30}\rho_{sp}^2
 \end{aligned} \quad (12)$$

$$\begin{aligned}
 \chi_{char} = & a_0 + a_1\alpha + a_2\nu + a_3\omega + a_4\rho_{sp} + a_5\alpha^2 \\
 & + a_6\nu^2 + a_7\omega\nu + a_8\omega^2 \\
 & + a_9\nu\rho_{sp} + a_{10}\omega\rho_{sp} + a_{11}\alpha\nu \\
 & + a_{12}\alpha\omega + a_{13}\alpha\rho_{sp} + a_{14}\alpha^2\nu \\
 & + a_{15}\alpha\nu^2 + a_{16}\alpha^2\omega + a_{17}\alpha\nu\omega \\
 & + a_{18}\alpha\nu\rho_{sp} + a_{19}\nu^3 + a_{20}\nu^3\rho_{sp} \\
 & + a_{21}\nu^2\omega + a_{22}\nu\omega^2 + a_{23}\nu^2\rho_{sp} \\
 & + a_{24}\nu\omega\rho_{sp} + a_{25}\omega^2\rho_{sp} + a_{26}\rho_{sp}^2
 \end{aligned} \quad (13)$$

select the degree of the polynomials with respect to the 4 selected input parameters. The *adjusted* - R^2 value is greater than 95% for all the polynomials. Although this is not a statistical analysis, the terms with a *p* - value smaller than 5% are eliminated.

3.2 Ultimate curvature correction factor

A constant value equal to $f_c = 31.83\text{MPa}$ is considered in the database. Therefore, an additional process is adopted to consider the variability of the ultimate curvature with respect to this parameter. Confined concrete ultimate strain depends on the unconfined concrete compressive strength,

according to Mander et al., (1986). Given the ratio of transverse reinforcement, the relationship between confined concrete ultimate strain and unconfined concrete compressive strength is parabolic and is shown in Fig. 6. A similar pattern is to be expected for the ultimate curvature, that directly depends on the ultimate strain.

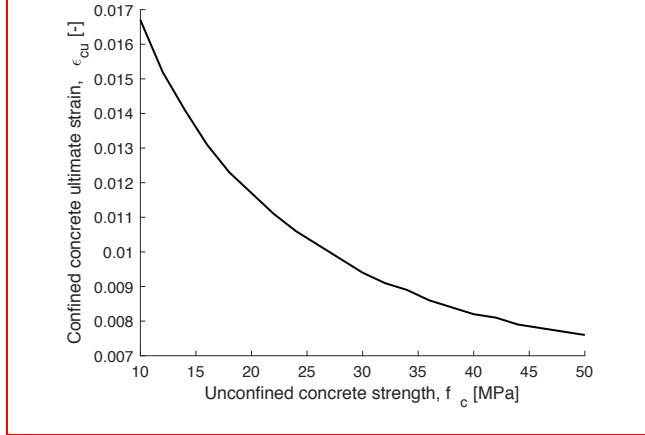


Fig. 3 Relationship between unconfined concrete strength and confined concrete ultimate strain for a given value of the transverse reinforcement ratio ($\rho_{sp}=0.01$).

This effect is taken into account with a correction factor for the ultimate curvature, calibrated through a sensitivity analysis with respect to f_c . A smaller database of RC sections is defined in which the parameters α , ν , ω and ρ_{sp} are constant while f_c is variable. The dimensionless ultimate dimensionless curvature $\chi_u(f_c)$ is calculated for each of them by means of a numerical Moment-Curvature analysis and the post processing. On the other hand, the calibrated polynomial for the ultimate curvature, Eq. (13), is used to predict the same value, named $\chi_u(31.83)$. The ‘‘Correction Factor (CF)’’, Eq. (14), is therefore fitted against the ratios of the above-mentioned parameters. This is used to include the variability of the ultimate curvature with the concrete strength, according to Eq. (15), by multiplying the value predicted with the ultimate curvature polynomial (depending on α , ν , ω , ρ_{sp}) to correction factor (which depends on f_c).

$$CF = \frac{\chi_u(f_c)}{\chi_u(31.83)} = 0.000276f_c^2 - 0.032f_c + 1.7453 \quad (14)$$

$$\chi_u(f_c) = CF\chi_u(31.83) \quad (15)$$

3.3 Reliability of the polynomials

A specific procedure is adopted to validate the proposed simplified polynomials for the construction of ($M - \varphi$) diagrams. A set of 14 RC hollow circular sections (‘‘test cases’’), not included in the original database, is defined considering configurations appropriate for RC bridge piers. According to the same procedure used for the database, the test cases are analysed to obtain the characteristic moments and curvatures. The geometrical and mechanical characteristics of the test dataset is shown in Table 6, in

Appendix A. The same parameters are predicted using the proposed polynomial solution, also considering the ultimate curvature correction factor.

For each test case, the error for the 14 polynomials is calculated with Eq. (16) and a global error (ERR_{glob}) is calculated using Eq. (17). The results (Table 2) show that the error is smaller than 11% except for the ultimate curvature for which it is equal to 16.8%. Finally, the general trends for the polynomials are shown in the analytical (predicted) vs numerical (‘‘measured’’) plots in Fig. 7, considering both the original database and the test series. This demonstrates the accuracy of the proposed model, considering the relatively low registered scatter regardless of the considered characteristic polynomial.

$$Err = 100 \left| \frac{analytical - numerical}{numerical} \right| \quad (16)$$

$$Err_{glob} = \frac{\sum_{i=1}^{14} Err_i}{14} \quad (17)$$

4. Application to a case study bridge pier

A numerical validation of the proposed polynomial formulation is presented herein. An RC bridge pier case study with hollow circular cross-section is analysed. The geometrical and mechanical parameters belonging to the piers are listed in Table 3. It should be recognised that the length and the axial load on the simplified SDOF representing the pier depend, in general, on the fixity conditions of the bridge and the ‘‘effective mass’’ pertaining to the pier itself.

The proposed polynomials, Equations (12) and (13), are used to predict the flexural behaviour of the base section of the pier. Equations (10) and (11) are used to transform the result in dimensional form. This is shown in Fig. 8.a, where the curve is compared to the numerical solution obtained with SAP2000 v18 section designer (Computers and structures, 2016). A particularly good match is shown, with a slight underestimation of the ultimate moment and curvature (3.9% and 6.0%, respectively).

The Force-Displacement ($F - \delta$) curve (Fig. 8.b) is calculated according to Equations (18) and (19), in which φ is the curvature, φ_Y is the yield curvature, M is the moment, L is the length of the pier and L_p ($= 0.67m$) is the plastic hinge length, calculated according to Priestley and Park, (1987). On the other hand, the pier is modelled using 8 ‘‘beam’’ elements in the FEM software SAP2000 v18. 600 fibres are used to discretise the cross-section using the ‘‘Fiber P M2 M3 hinge’’ property in the software. The constitutive relationships shown in Fig. 4 are used for the materials. A displacement-control Pushover analysis is conducted applying a horizontal force at the top of the pier.

Table 2. Percentage global error for the test dataset.

	χ_{CR}	χ_{Yc}	χ_Y	χ_P	χ_N	χ_{SP}	χ_U	m_{CR}	m_{Yc}	m_Y	m_P	m_N	m_{SP}	m_U
ERR_{glob}	2.3	10.9	6.2	1.2	8.8	6.3	16.8	1.5	2.1	3.6	3.2	3.0	2.6	7.3

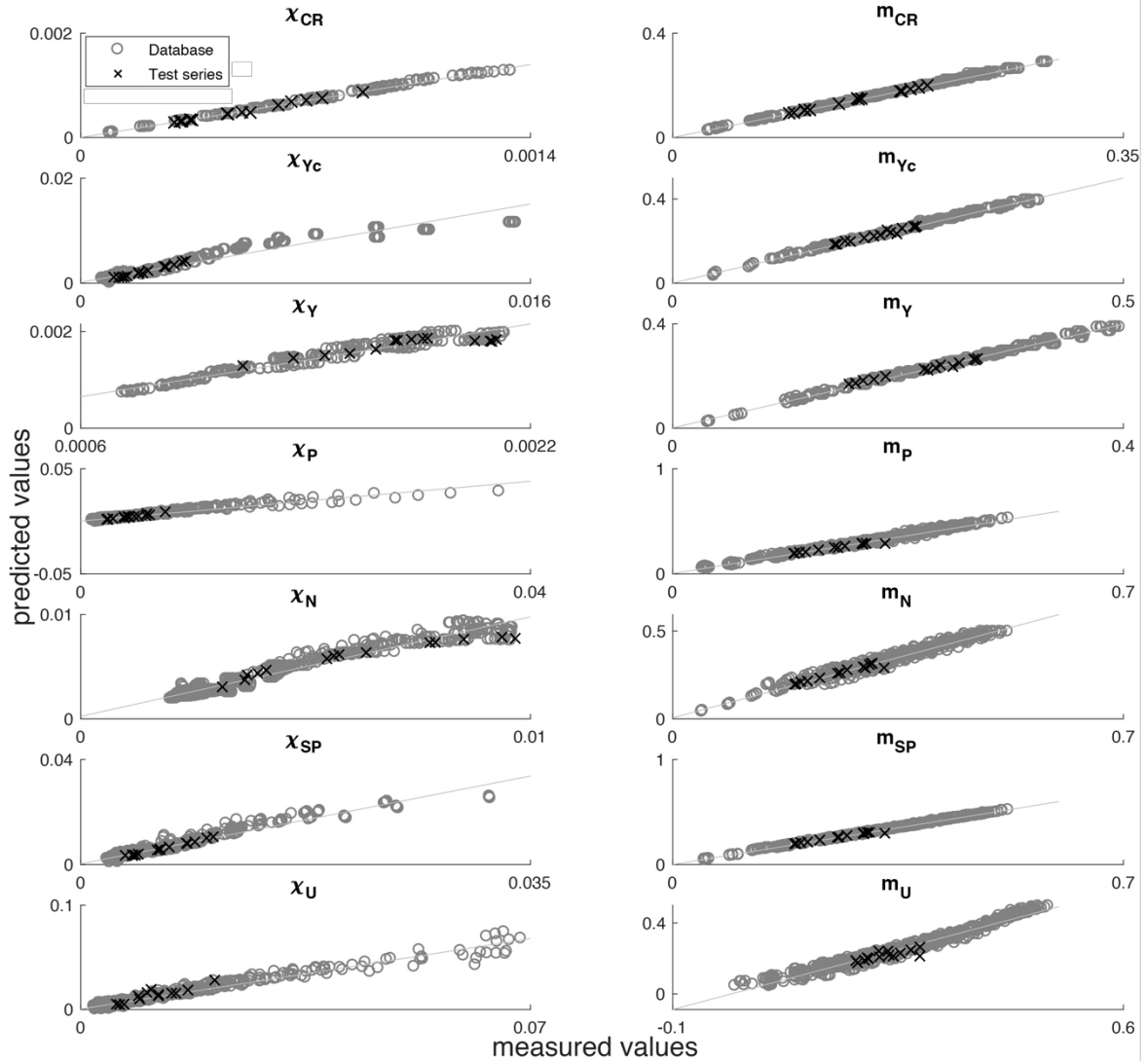


Fig. 7 Predicted vs “measured” (numerical) plots for the characteristic polynomials.

Table 3 Geometrical and mechanical characteristics of the case study.

L	R	r	c	n_l	d_l	d_h	s	f_c	f_{ys}	N	α	ν	ω	ρ_{sp}
[m]	[m]	[m]	[m]	[-]	[mm]	[-]	[mm]	[MPa]	[MPa]	[MN]	[-]	[-]	[-]	[-]
8	2.2	1.6	0.05	40	20	12	100	20	430	10	0.727	0.279	0.151	0.006

The numerically-based flexural capacity curve is compared to the analytical one (Fig. 8.b) showing that the two approaches are matching. A 1.6% and 6.1% overestimation is respectively registered for the force and the displacement at the peak, while for the ultimate force and displacement, a 4.0% and 4.3% underestimation is respectively measured.

Fig. 8.b shows the shear degradation curve calculated according to Ranzo and Priestley, 2000 and the bar buckling displacement, calculated according to Berry and Eberhard, 2005. The predicted failure mode for the pier is bar buckling, since the shear degradation curve is not intersecting the flexural one, and the bar buckling displacement is smaller than the ultimate flexural one.

$$\delta = \begin{cases} \frac{\varphi L^2}{3} & \text{if } \varphi \leq \varphi_Y \\ \frac{\varphi_Y L^2}{3} + (\varphi - \varphi_Y)L_p(L - 0.5L_p) & \text{if } \varphi > \varphi_Y \end{cases} \quad (18)$$

$$F = \frac{M}{L} \quad (19)$$

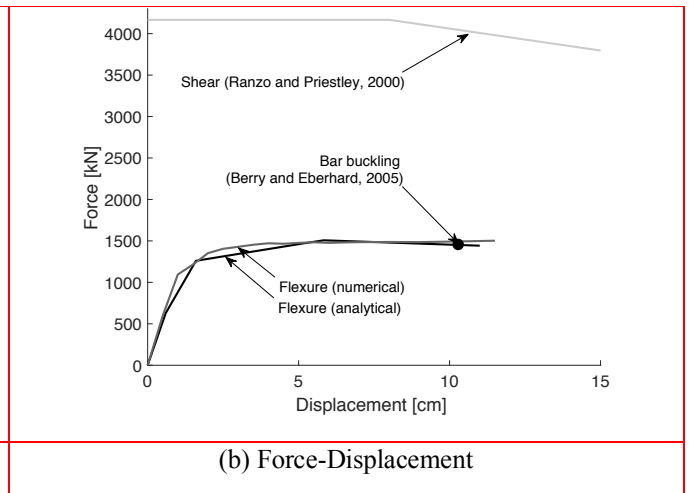
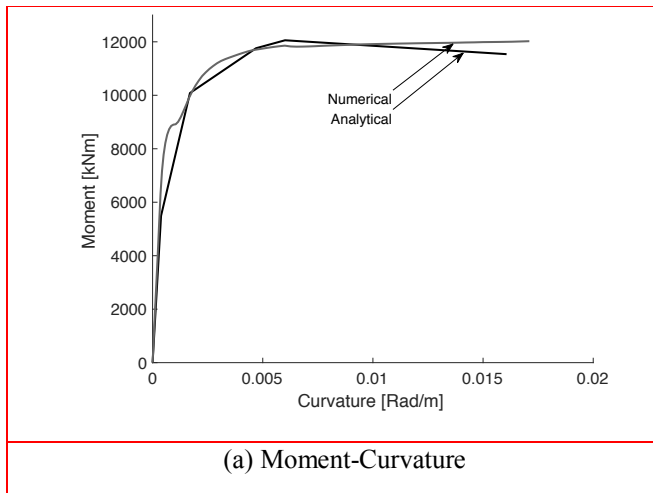


Fig. 8 Practical application: comparison between analytical and numerical solutions.

5. Final remarks

In this paper, a polynomial solution for the characterisation of the flexural behaviour of RC hollow circular cross-sections is proposed, with particular reference to bridge piers. The *Moment-Curvature* diagram is calculated by defining the position of 6 characteristic points, related to mechanically-based performance points (e.g. cover spalling). Calibrated polynomials allow to accomplish this goal. Those are dependent on 4 parameters: section void ratio, dimensionless axial force, mechanical ratio of longitudinal reinforcement, volumetric ratio of transverse reinforcement. The polynomial functions are fitted against a database of 720 fibre-based numerical *Moment-Curvature* diagrams which considers wide ranges for the defining parameters. An RC bridge pier case study is assessed using the proposed formulation and the results are

compared to a refined non-linear FEM model showing good match.

The scope of the proposed polynomial formulation is the regional scale seismic assessment of multi-span bridges with RC hollow circular piers, based on a mechanical approach, instead of the commonly-used empirical methods based on calibrated indices. While allowing accuracy, this simple method allows to considerably reduce the computational effort for large number of analyses, since it's implementable in computer-based electronic spreadsheets. This work is part of a wider project, which considers solid circular sections and aims to study other significant section shapes in the future.

Acknowledgments

The research described in this paper was partially supported by the Project ReLUIS-DPC 2014-2018, "Linea C.A." – R.U. Politecnico di Bari (G.Uva) and the FRA 2016 project (Politecnico di Bari, D.Raffaele).

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Table 5 Coefficients for the characteristic moments' polynomials.

	m_{CR}	m_{Yc}	m_Y	m_P	m_N	m_{SP}	m_U
a_0	0	-0.05162	0	0	0	0.01086	-0.03793
a_1	0.03641	0.07601	-0.00048	0.04947	0.00752	0.00746	0.13634
a_2	0.29570	0.70080	0.62819	0.77438	0.65123	0.63068	0.94759
a_3	-0.06961	0.85305	0.28707	0.37322	0.53203	0.48417	0.39816
a_4	0	0	0	-0.47093	0	-0.20504	-1.64580
a_5	0.00961	0	0	0	0	0	0
a_6	0.06314	-0.84345	-0.76992	-0.86343	-0.50120	-0.46745	-1.01360
a_7	-0.28139	-2.17370	-0.78166	-0.33059	-0.98446	-0.87757	0
a_8	0	-0.26679	0	0	0	0	0
a_9	0	0	0	3.14400	0	0	-1.30400
a_{10}	0	0	0	2.40340	0	1.01470	1.81250
a_{11}	-0.03164	0.54353	0.58912	0.08871	0.54266	0.48321	-0.16470
a_{12}	0.30832	0	0.32189	0.37160	0.35507	0.37849	0.32994
a_{13}	0	0	0	0	0	0	-2.84780
a_{14}	0.22038	0	0	0	0	0	0
a_{15}	-0.05963	-0.73016	-0.59711	0	-0.63900	-0.64649	0
a_{16}	-0.24137	0	0	0	0	0	0
a_{17}	0.22056	0.61765	0	0	0	0	0
a_{18}	0	0	0	0	0	1.46230	0
a_{19}	-0.26485	0.19504	0.05334	0	-0.10267	-0.16599	0
a_{20}	0	0	0	0	0	0	0
a_{21}	0.38260	1.50240	0.81451	0	0.85366	0.83621	0
a_{22}	0	0.33802	0	0	0	0	0
a_{23}	0	0	0	0	0	2.98750	0
a_{24}	0	0	0	0	0	-2.70990	0
a_{25}	0	0	0	0	0	0	0
a_{26}	0	0	0	0	0	0	90.28600

Table 6 Geometric and mechanical characteristics for the test dataset.

D	r	c	n_l	d_l	d_h	s	f_c	f_{ys}	N	α	ν	ω	ρ_{sp}
[m]	[m]	[m]	[-]	[mm]	[mm]	[mm]	[MPa]	[MPa]	[MN]	[-]	[-]	[-]	[-]
1.35	0.85	0.06	30	26	10	100	45	370	20	0.630	0.129	0.038	0.008
1.30	0.80	0.06	40	24	8	60	24	350	21	0.615	0.265	0.080	0.009
1.45	0.97	0.05	42	28	10	50	30	380	32	0.669	0.292	0.090	0.017
1.23	0.75	0.05	44	22	12	80	28	400	25	0.612	0.310	0.081	0.018
1.40	0.90	0.04	36	24	16	120	25	450	55	0.643	0.609	0.081	0.016
1.50	1.00	0.04	38	26	10	90	39	500	25	0.667	0.163	0.066	0.008
1.60	1.10	0.04	46	30	14	70	32	480	21	0.688	0.159	0.115	0.022
1.75	1.25	0.04	40	32	12	50	29	360	45	0.714	0.329	0.085	0.020
1.90	1.40	0.07	46	26	8	60	26	390	63	0.737	0.471	0.071	0.008
2.00	1.50	0.07	44	24	10	65	32	450	31	0.750	0.176	0.051	0.012
1.80	1.40	0.04	36	30	12	75	31	490	53	0.778	0.425	0.100	0.015
1.55	0.95	0.05	50	22	10	80	40	380	60	0.613	0.318	0.038	0.010
1.85	1.35	0.06	46	30	14	60	25	450	75	0.730	0.597	0.116	0.025
2.05	1.55	0.04	42	26	12	80	28	420	64	0.756	0.408	0.059	0.012

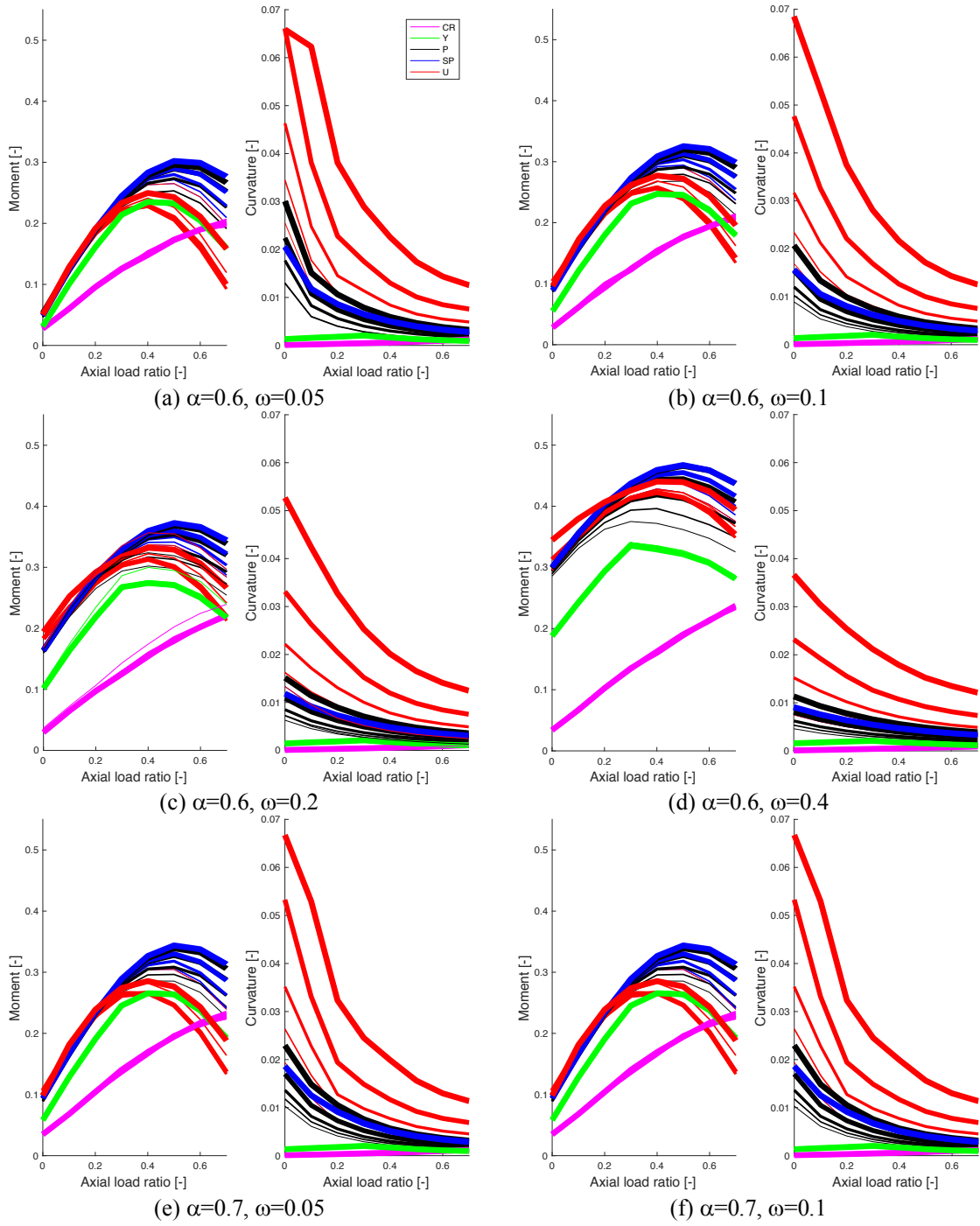


Fig. 9 Main trends for the characteristic moments and curvatures.

Simplified analytical Moment-Curvature relationship for hollow circular RC cross-sections

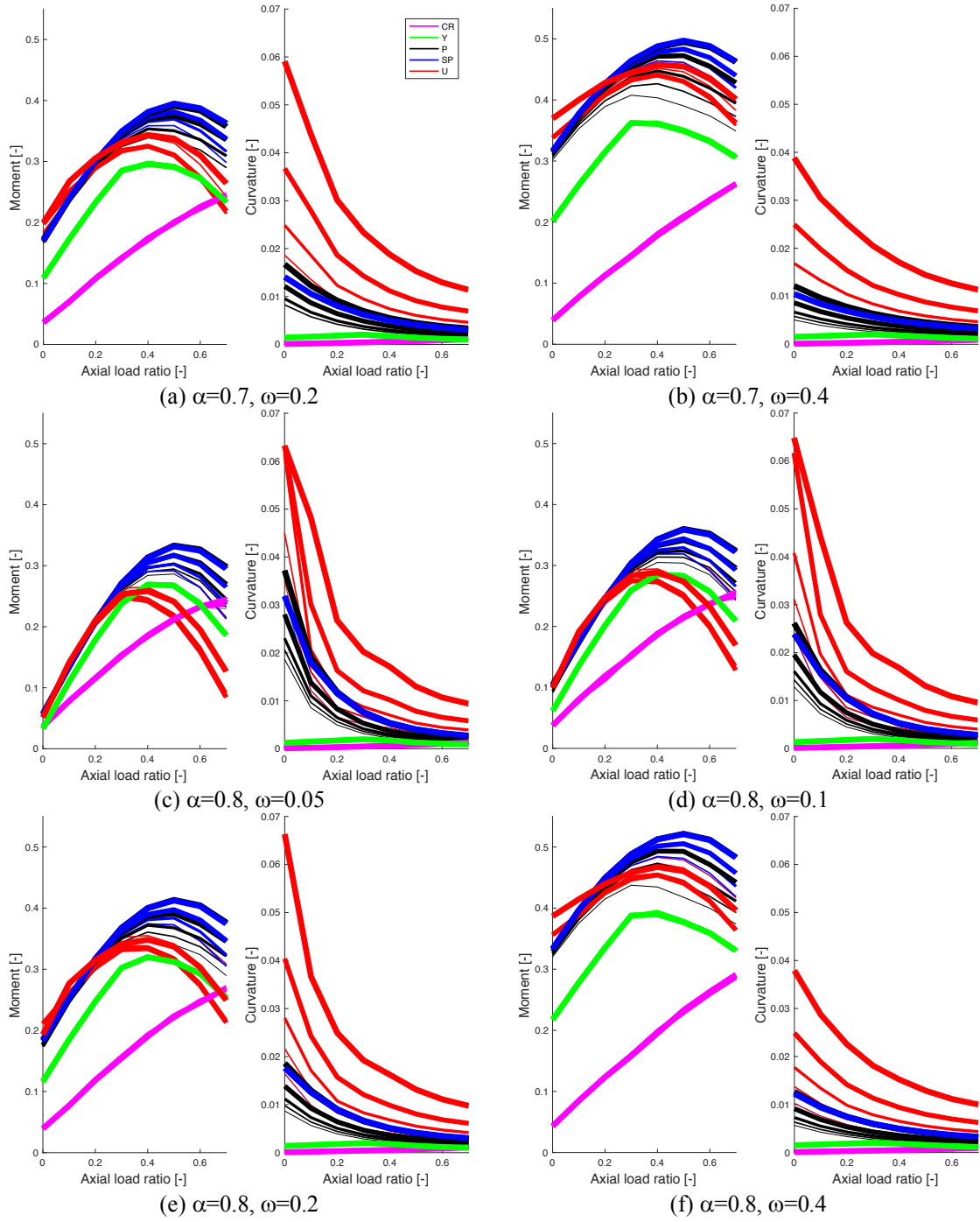


Fig. 10 Main trends for the characteristic moments and curvatures.