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INELASTIC DEFORMATIONS OF WIDE BEAMS AND DEEP BEAMS

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Abstract

Current formulations proposed by Eurocode 8 part 3 for the inelastic deformations of existing reinforced concrete members are assessed aimed at finding out whether they are representative of beams with different cross-sectional aspect ratio, in particular for wide beams (WB) contrasted with conventional deep beams (DB). The current approach shows that WB present larger ultimate chord rotation but lower chord rotation ductility than DB despite the similar curvature ductilities, due to lower plastic hinge lengths in WB. Results of the large experimental database on the basis of current model are disaggregated for DB and WB. Predicted chord rotations appear to be significantly biased for both types, especially at ultimate; the actual model provides conservative values for DB and non-conservative values for WB, which suggest that plastic hinge length may be even greater for DB in comparison to WB. Hence, some different feasible modifications of both pure empirical and fundamental formulations for chord rotations are proposed, in order to reduce the bias and thus increasing the robustness of the model against cross-sectional shape variability.

Keywords: Wide beams, deep beams, chord rotation, plastic hinge length, Eurocode 8

1. Introduction

The use of wide beams (WB), i.e. beams in which width is larger than depth, instead of conventional deep beams (DB) in reinforced concrete frames is quite widespread in seismic regions of Mediterranean area [1]. In [2,3] it is shown that WBF may provide similar seismic global performances than DBF for modern performance-based seismic codes, whose provisions may overcome the poorer local ductility of wide beams rather than of deep beams; in fact, WB present larger ultimate chord rotation but lower chord rotation ductility than DB despite the similar curvature ductilities, due to lower plastic hinge lengths in WB. Hence, the availability of physical models aimed at a proper estimation of inelastic deformation of WB under cyclic loads appears to be a crucial issue.

For this aim, some codes for assessment and retrofitting of existing structures, as Eurocode 8 part 3 (EC8-3 in the following) [4], provide different expressions for yielding and ultimate chord rotation of members (θ_y and θ_u, respectively) within a lumped plasticity framework. These formulations are based on [5,6], which have been obtained as a regression of experimental results contained in a large database of 1540 tests. However, only 37 of those elements are WB. Hence, it is not clear whether those formulations can represent them appropriately, so any displacement-based consideration regarding performances of WB might be questionable.

The scope herein is to evaluate the reliability of the current deformation model adopted by EC8-3 regarding wide beams. The experimental results of the database underlying this approach are disaggregated into DB and WB, and current formulations are applied separately in order to evidence whether experimental-to-predicted ratios are significantly biased. Finally, some modifications for the current formulations are proposed aimed at reducing the bias and thus increasing their robustness against cross-sectional shape variations.

2. Disaggregation of experimental database into wide beams and deep beams

EC8-3 approach has adopted the formulations corresponding to members under cyclic loading, with proper seismic design and with potential slippage of longitudinal bars, proposed in [5,6] for deformations at yielding and ultimate, respectively. All those expressions are obtained as a regression of experimental results contained in a large database of about 1540 tests [7], and they can be understood as an evolution of the formulations proposed in [8], whose preliminary database is lower (1012 tests). Nevertheless, all the concerned specimens regarding this work belong to that preliminary bank: beams with full rectangular cross-section and ribbed bars, with neither lap-splices nor precompression or retrofitting, whose failure is governed by uniaxial flexion.

Only 266 of those specimens are classified as beams (i.e., no axial load and asymmetric reinforcement). However, in this work also symmetric-reinforced members are considered as beams, as design to DCH usually causes such arrangements, resulting in 948 mebers (314 beams and 634 columns). However, only 11 columns and 37 beams (representing 1% of the columns, 12% of the beams and 5% of the total amount of specimens) are tested in the parallel direction to the cross-section axe of minimum stiffness (members oriented as “wide” sections). Hence, the reliability of the models based on such databases for this minority is under discussion.

For this aim, models of Biskinis and Fardis [5,6], B&F in the following, and also the preliminary model of Panagiotakos and Fardis [8], P&F in the following, are applied separately to the sub-databases of DB and WB, in order to obtained disaggregated values of experimental-to-predicted ratios and thus assessing the possible bias of results within the two groups. Not all the experimental deformations are available: for DB, the number of specimens in which ϕ_y, ϕ_u (yielding and ultimate curvature, respectively), θ_y and θ_u are calculated is 163, 136, 257 and 240 out of 277, respectively; while for DB is 35, 36, 37 and 37 out of 37, respectively.

Sub-database of DB is composed by 277 specimen precedent from 24 different works in literature. 190 tests are monotonic while 87 are cyclic; 151 are able to show slippage of reinforcement while 126 do not; 106 show 90º-hooked closed stirrups while 171 show 90º hooks; 149 show stirrup arrangements able to furnish some confinement regardless of the closure of hooks, while 128 do not; 233 use hot-rolled ductile steel, 34 use tempcore steel and only 10 use cold-worked steel.

On the other hand, sub-database of WB is composed of only 37 specimen: 30 from [9]; four from [10], two from [11] and one from [12]. 36 tests are monotonic while only one is cyclic; three beams are able to show slippage of reinforcement while 34 do not; three beams show 135º-hooked closed stirrups while 34 show 90º hooks; five beams are able to furnish some confinement regardless of the closure of hooks, while 32 do not; five beams use hot-rolled ductile steel, eight use tempcore steel and 24 use cold-worked steel. Actually, the composition of the sub-database of WB is quite reduced and also unbalanced regarding the previous items, thus results of the disaggregated application of deformation models should be carefully considered.

All the graphics presented in the following show: (i) the median value of single experimental-to-predicted ratios, which is indicated as "Median exp/pred" and which corresponds to the slope of the plotted thick line; (ii) the 16th and 84th percentiles (associated to standard deviation in a normal distribution), corresponding to the slope of the dashed lines); and (ii) the coefficient of variation (CoV). In the case of WB, origin of each test is graphically showed as indicated in the legend of Fig. 1b. Also, it is indicated in each case which half of the graphic correspond to conservative results (i.e. overestimation at yielding and underestimation at ultimate).

2.1 Curvatures

Disaggregated results can only be compared to original ones if similar stress-strain models are used. Both B&F and P&F models assume parabola-rectangle envelope for concrete, without any tension resistance for cyclic loading; elastic-perfectly plastic behaviour of steel for lower strains at ultimate situation, and hardening otherwise. Stress values from the original database are adopted, while strain parameters correspond to Eurocode 2 [13] except for ultimate nominal strains and maximum-to-yielding strength ratios of steel. Steel ultimate strains for flexural behaviour are taken as a fraction of the nominal values, more reduced for cyclic loading [6]. Regarding model for confined concrete behaviour, P&F uses Mander approach [14], while B&F adopts a model similar to the current one proposed by EC8-3 but with a different evaluation of maximum stress [6]. Herein, the last model is adopted, thus formulations of P&F model for θ_u depending on ϕ cannot be assessed. Also, explicit M-ϕ relations are obtained, conversely to the original models, which carry out simplified procedures.

Experimental and predicted ϕ_y (through the fibre model) are compared in Fig. 1 for DB and WB. Very well fitting is shown. Curvatures adopted as $\phi_{y,exp}$ are indirect values obtained from experimental values of M_y in each case [5], instead of using the explicit values measured in the experimental tests, which are expected to show higher uncertainty due to several inherent problems of deformation measurement [8].

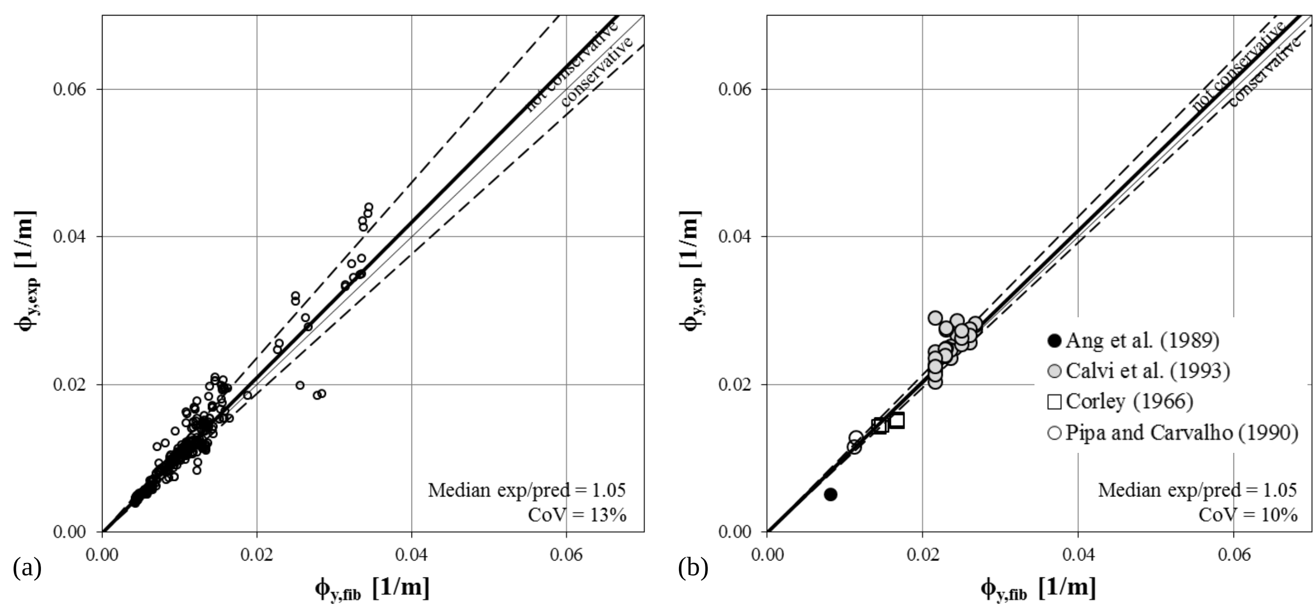

Fig. 1 – Comparison of experimental and predicted ϕ_y for DB (a) and WB (b)

Conversely, quite poorer fitting is shown for ϕ_u. If stirrups with 90º closed hooks are assumed to not provide any confinement at all, corresponding beams show very large underestimation of ϕ_u than the rest (see Fig. 2a). In fact, this assumption is intended to be feasible for design purposes, given that it furnishes conservative results.

However, the real influence of hooks detailing on stress-strain models is not clearly quantified; a modification of Mander's confinement model for columns with 90º closed hooks is proposed in [15]. If full confinement is assumed for beams with 90º closed hooks in which some confinement would be expected if 135º closed hooks were used (i.e., in beams with α>0), the error reduces largely (see Fig. 2b), even when only 56 out of 277 beams belong to this group. Regarding the application of fundamental approaches for the estimation of θ_u (based on ϕ values), the last assumption is adopted herein. For empirical approaches it is not relevant because the influence of confinement is significantly lower (see section 1) and also because, in the present database, beams with 90º closed hooks anyway show lower density of stirrups, thus they may perform almost as unconfined beams.

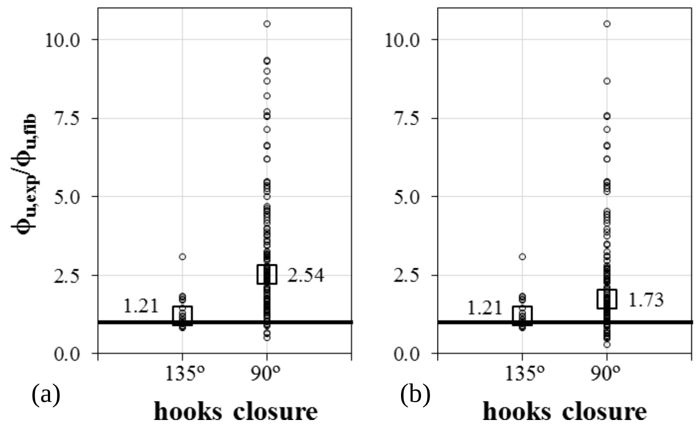

Fig. 2 – Experimental-to-predicted ratios of ϕ_u for DB, considering 90º-hook closed stirrups as ineffective (a) and completely effective (b) aimed at confining of concrete core

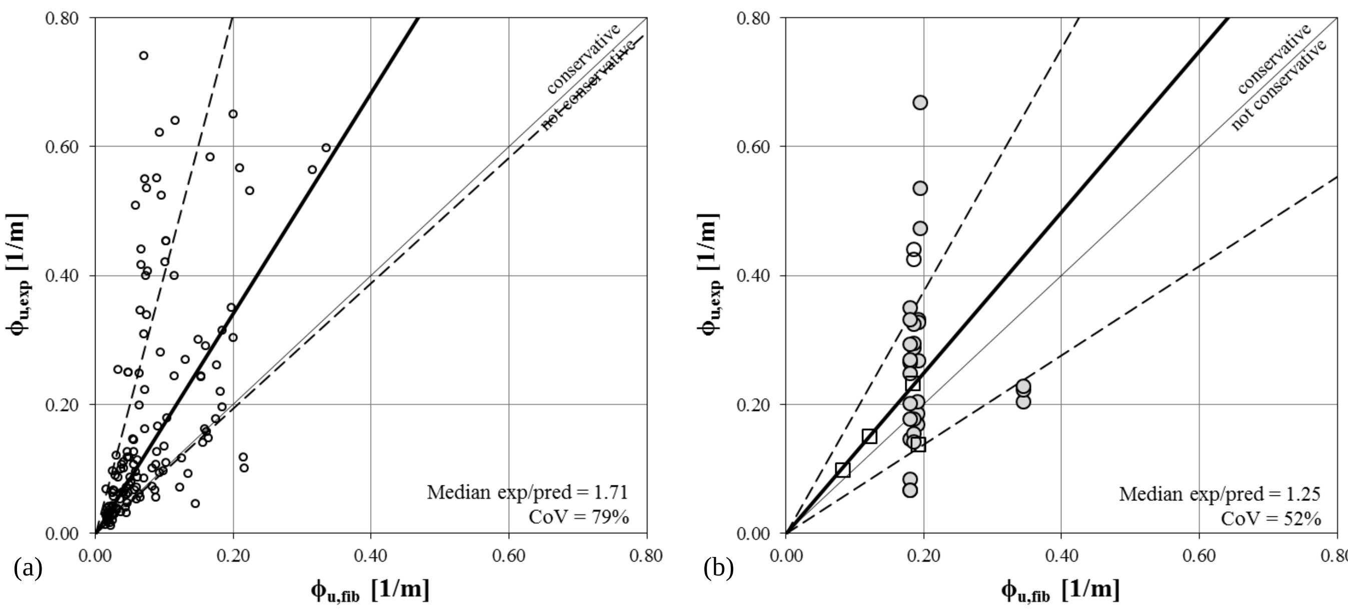

Fig. 3 – Comparison of experimental and predicted ϕ_u for DB (a) and WB (b), considering full confinement in beams with 90º-hook closed stirrups

In Fig. 3, experimental and predicted ϕ_u are compared. High underestimation and very large dispersion of results is shown especially for DB. It is worth noting that the adopted confinement model has been obtained as a regression of the whole original database, including columns. It should be necessary to apply the same procedure to the columns belonging to the database in order to know whether the generalised bias in beams is balanced by columns or not. In the last case, the difference of results may rely on the different approach on curvature calculation, even when similar models are adopted. It emphasises the higher sensitivity of fundamental procedures for θ respect to empirical ones regarding steel type or seismic detailing.

2.1 Chord rotations

Formulations proposed in [5,6,8] for θ are applied separately to the disaggregated sub-databases DB and WB. In Eqs. (1) to (8), all the expressions are presented in a homogenised form, where subscripts "*emp*" and "*fun*" denote empirical and fundamental, respectively. Zero-one parameters a_{old}, a_{cy}, a_{pl} and a_{sl} refer to 90º closed hooks, cyclic loading, plain bars and slippage, respectively; a_{st}, $\alpha_{st,mon}$, $\alpha_{st,cyc}$, α_{cy} refer to steel class, steel class in monotonic or cyclic tests, and type of loading, respectively; their values can be checked in the original works.

$$\theta_{y,P\&F} = \phi_y \frac{L_V}{3} + a_{sl} \frac{0.25\varepsilon_y d_{bL} f_y}{(d-d')\sqrt{f_c}} + 0.0025 \tag{1}$$

$$\theta_{y,B\&F} = \phi_y \left(\frac{L_V + a_v z}{3} + a_{sl} \cdot 0.125 d_{bL} \frac{f_y}{\sqrt{f_c}} \right) + 0.0014 \left(1 + 1.5 \frac{h_b}{L_V} \right) \tag{2}$$

$$\theta_{u,P\&F,emp1} = 0.01 \alpha_{st} \alpha_{cyc} \left(1 + \frac{a_{sl}}{2.3} \right) \left(\frac{\max\{0.01;\omega'\}}{\max\{0.01;\omega\}} f_c \right)^{0.275} \left(\frac{L_V}{h_b} \right)^{0.45} \cdot 1.1^{100\alpha\omega_w} \cdot 1.3^{100\rho_d} \tag{3}$$

$$\theta_{u,P\&F,emp2} = \begin{cases} 0.01\alpha_{st,mon} \left(1 + \frac{a_{sl}}{8} \right) \left(\frac{\max\{0.01;\omega'\}}{\max\{0.01;\omega\}} \frac{L_V}{h_b} f_c \right)^{0.425} & \text{(monotonic)} \\ 0.01\alpha_{st,cyc} \left(1 + \frac{a_{sl}}{2} \right) \cdot f_c^{\,0.175} \left(\frac{L_V}{h_b} \right)^{0.4} \cdot 1.1^{100\alpha\omega_w} \cdot 1.3^{100\rho_d} & \text{(cyclic)} \end{cases} \tag{4}$$

$$\begin{aligned} \theta_{u,B\&F,emp1} = {} & a_{st} \left[1 - \frac{a_{old} a_{cy}}{6} \left(1 + 0.25 a_{pl} \right) \right] \left(1 - 0.43 a_{cy} \right) \left(1 + \frac{a_{sl}}{2} \right) \left(\frac{\max\{0.01;\omega'\}}{\max\{0.01;\omega\}} f_c \right)^{0.225} \cdot \\ & \cdot \left(\min\left\{ \frac{L_V}{h_b}; 9 \right\} \right)^{0.35} \cdot 25^{\alpha\omega_w} \cdot 1.25^{100\rho_d} \end{aligned} \tag{5}$$

$$\begin{aligned} \theta_{u,B\&F,emp2} = {} & \theta_{y,B\&F} + a_{st}^{pl} \left[1 - \frac{a_{old} a_{cy}}{6} \left(1 - 0.05 a_{pl} \right) \right] \left(1 - 0.52 a_{cy} \right) \left(1 + \frac{5}{8} a_{sl} \right) \left(\frac{\max\{0.01;\omega'\}}{\max\{0.01;\omega\}} \right)^{0.3} \cdot \\ & \cdot f_c^{\,0.2} \left(\min\left\{ \frac{L_V}{h_b}; 9 \right\} \right)^{0.35} \cdot 25^{\alpha\omega_w} \cdot 1.275^{100\rho_d} \end{aligned} \tag{6}$$

$$\theta_{u,B\&F,fun} = \theta_{y,B\&F} + \left(\phi_u - \phi_y \right) L_{pl,B\&F} \left(1 - \frac{L_{pl,B\&F}}{2L_V} \right) + a_{sl} \left(9.5 - 4a_{cy} \right) d_{bL} \phi_u \tag{7}$$

$$L_{pl,B\&F} = \begin{cases} 0.04 \min\{L_V; 9h_b\} + 1.1 h_b & \text{(monotonic)} \\ 0.0\widehat{6} \min\{L_V; 9h_b\} + 0.2 h_b & \text{(cyclic, seismic design)} \end{cases} \tag{8}$$

Median values and dispersion of all the cases are shown in Table 1. Both approaches P&F and B&F slightly underestimate θ_y both for DB and WB, which is not conservative; conversely, they underestimate θ_u for DB (which is conservative) and overestimate θ_u for WB (non-conservative). Empirical approaches show better fitting that fundamental one: in the first case, median experimental-to-predicted ratios are always within ±20% respect to perfect fitting, while in the second case it can reach 100%, due to the high uncertainty regarding the calculation of curvatures. In general, P&F model show better fitting than B&F, as the original database from which it comes out as a regression is more similar to the sub-databases used herein (e.g. it does not include sections different from rectangular shape). However, the present work focuses mainly in B&F because it is in the base of current EC8-3 formulations. Except for fundamental approach, dispersion levels in all the cases are rather similar than those observed in the original works.

Table 1 – Fitting of different expressions for θ respect to experimental disaggregated data

Experimental-to-predicted ratio		Expression for prediction	DB		WB	
			Median	CoV	Median	CoV
$\theta_{y,exp}$ /	/ $\theta_{y,P\&F}$	Eq. (1a)	1.02	35%	1.06	21%
	/ $\theta_{y,B\&F}$	Eq. (1b)	1.07	34%	1.14	21%
$\theta_{u,exp}$ /	/ $\theta_{u,P\&F,emp1}$	Eq. (2)	1.14	47%	0.88	40%
	/ $\theta_{u,P\&F,emp2}$	Eq. (3)	1.00	52%	0.95	44%
	/ $\theta_{u,B\&F,emp1}$	Eq. (4)	1.19	46%	0.84	38%
	/ $\theta_{u,B\&F,emp2}$	Eq. (5)	1.21	47%	0.90	37%
	/ $\theta_{u,B\&F,fun}$	Eqs. (6) and (7)	2.06	68%	0.88	46%

In Fig. 4, experimental and predicted θ_y for B&F model are compared. Larger underestimation but lower dispersion is shown for WB rather than for DB. Median experimental-to-predicted ratio for the all the beams (DB+WB) is 1.11 if WB values are weighted in order to provide similar contribution to the median despise their lower number of tests, 1.08 otherwise. No particular bias is shown for the different sub-groups (i.e. depending of steel class, type of loading, possibility of slippage or hooks closure angle).

Regarding θ_u, in Fig. 5 experimental and predicted values for B&F model are compared. Almost exactly symmetric bias is shown for DB and WB: median experimental-to-predicted ratios for both cases are inverse (1.19 for DB and 0.84 for WB); better fitting is shown by P&F second model (1.00 and 0.95, respectively). If both sub-databases are merged, weighted median values of 0.94 are obtained, which is not conservative. The bias is more important for the sub-groups that likely represent current seismic-designed buildings: hot-rolled ductile steel, cyclic loading, slippage of longitudinal reinforcement and seismic detailing of stirrup hooks (see Fig. 6). In fact, EC8-3 assumes by default the formulations corresponding to cyclic loading and slippage.

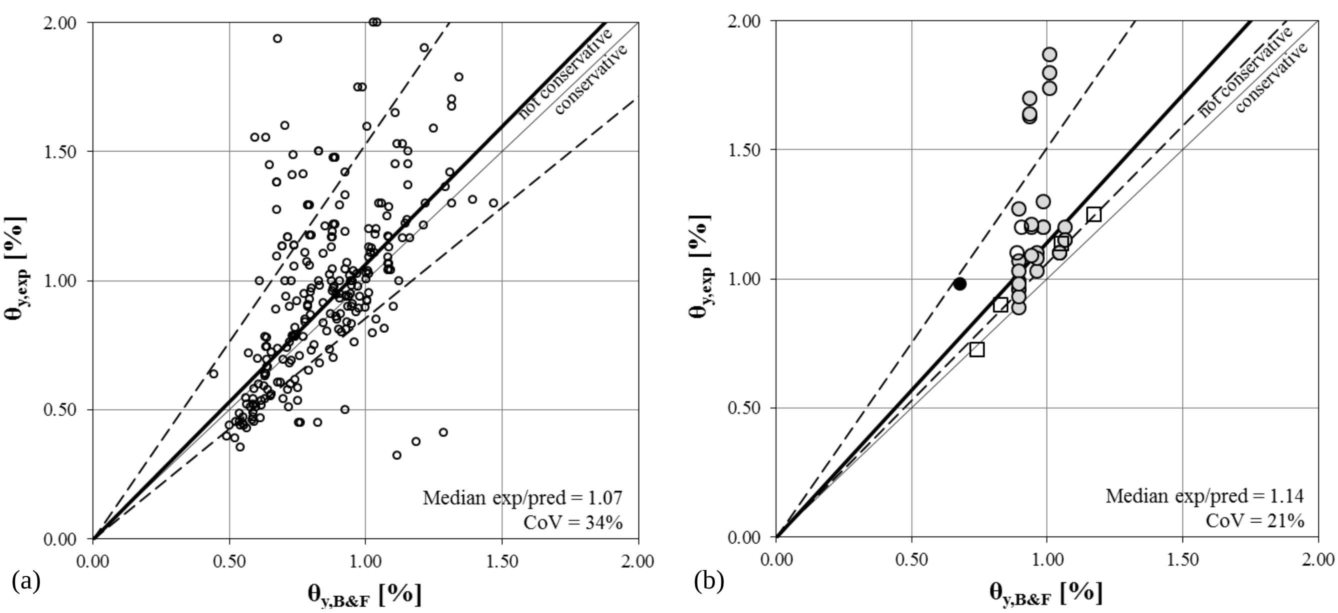

Fig. 4 – Comparison of experimental and predicted θ_y according to [5] for DB (a) and WB (b)

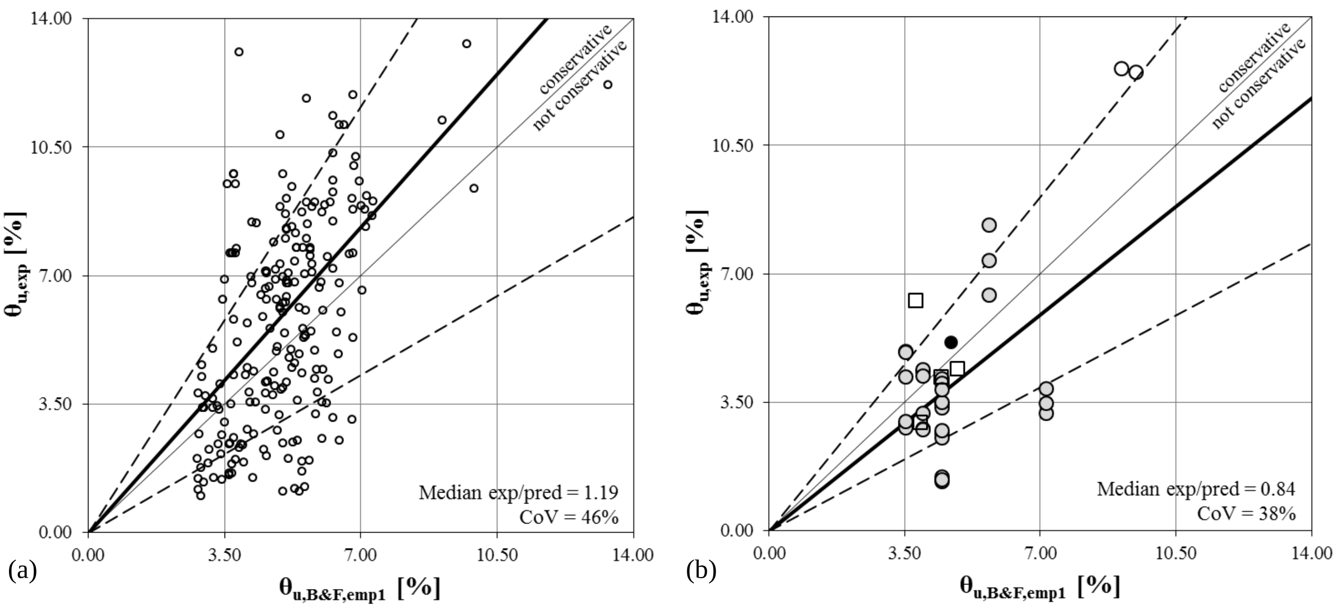

Fig. 5 – Comparison of experimental and predicted θ_u according to the empirical formulation in [6] for DB (a) and WB (b)

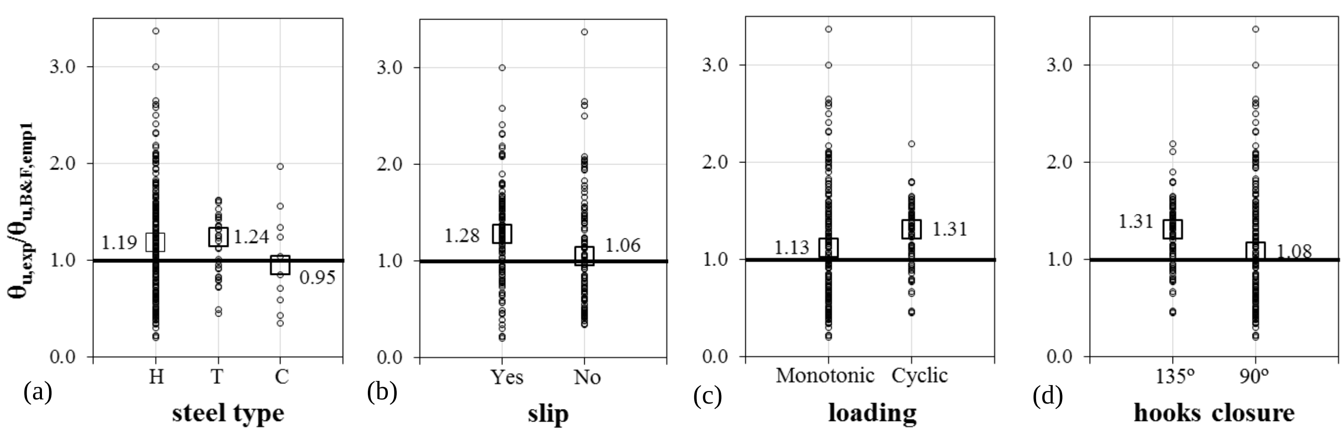

Fig. 6 – Experimental-to-predicted ratios of θ_u according to the empirical formulation in [6] for DB, disaggregated for different cases (H: hot-rolled; T: tempcore; C: cold worked)

The B&F fundamental approach (see Fig. 7) shows rather similar overestimation of θ_u for WB (median values of 0.88) but the underestimation for DB is huge (2.06), even when curvatures corresponding to perfect confinement also for 90º closed hooks are assumed. In order to evaluate the relevance of the uncertainty associated to the approach used for the calculation of ϕ_u on the huge bias observed in fundamental method, values of θ_u corresponding to experimental values of ϕ_u , instead of using calculated values by means of a fiber model, are shown in Fig. 8. According to the high bias shown in Fig. 3a, results are very different for DB: in this case there is overestimation, while for WB the difference when compared with Fig. 7 is lower. Those results highlight the low reliability of fundamental approach aimed at the scope of the present work, because of (i) the high variability of results induced by the method used for calculating curvatures; and (ii) the use of a set of formulations for a reduced fraction of elements of the database (only beams).

Doubtless, reliability of the results obtained in this section may be under discussion, considering the limited number of tests belonging to sub-database WB and also their reduced variability of cases. However, in almost all the cases the median experimental-to-predicted ratios for the merge of both sub-databases DB and WB are roughly near to 1.0, which means that those few results of WB provide kind of balance to DB ones, whose reliability is higher. Also, lower bias is observed to WB rather than for DB.

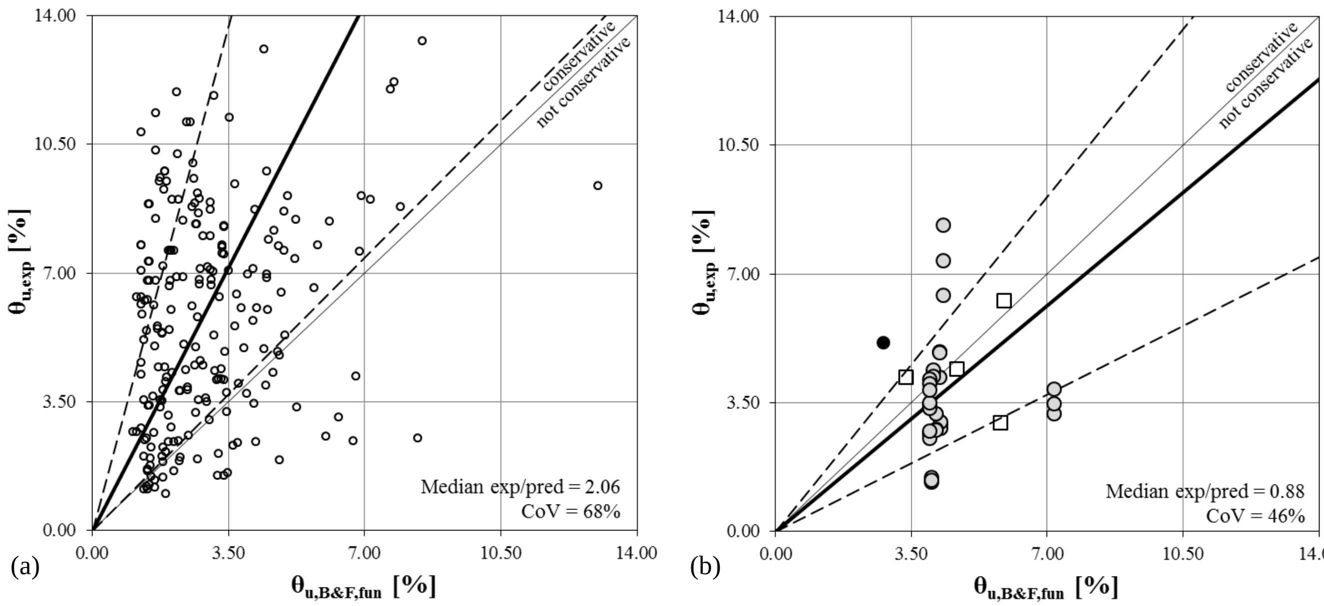

Fig. 7 – Comparison of experimental and predicted θ_u according to the fundamental formulation in Biskinis and Fardis (2010b) for DB (a) and WB (b), considering calculated values of ϕ_u

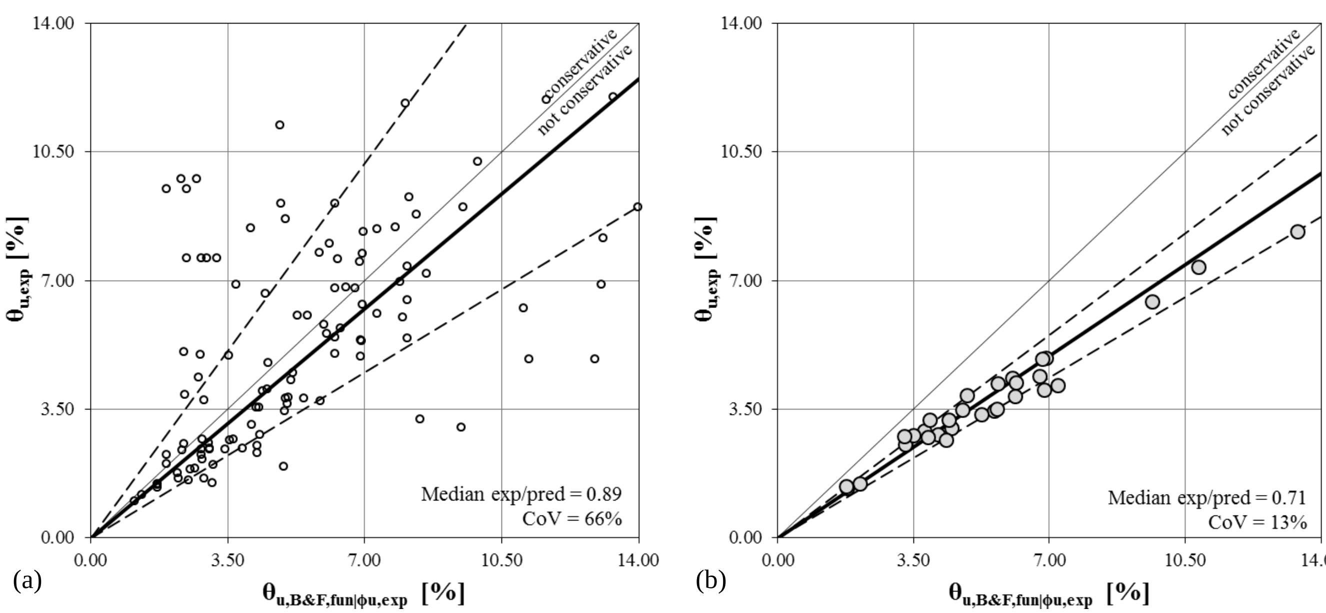

Fig. 8 – Comparison of experimental and predicted θ_u according to the fundamental formulation in Biskinis and Fardis (2010b) for DB (a) and WB (b), considering experimental values of ϕ_u

3. Proposal of modified expressions

In the previous section, the application of formulations on the base of the current procedure in EC8-3 separately to DB and WB shows that experimental θ_u is lower than predicted for WB and higher than predicted for DB, while experimental θ_y is slightly higher than predicted mainly for WB. In this section, some modifications for the formulations of Biskinis and Fardis [4,5] are proposed, in order to reduce the bias and thus increasing the robustness of the deformation model against cross-sectional shape variations. This proposal should be understood purely as an available simple alternative for the assessment of buildings with WB, or to be used for compared analysis of WB and DB, for instance. The current approach in EC8-3 makes no explicit distinction between columns and beams aimed at the estimation of θ. Hence, any alternative set of formulations able to account for cross-sectional aspect ratio should be also checked for columns, which is not possible to be carried out with the existing database because cross-sectional orientation is always similar in most cases.

The proposals are intended as slight modifications within the main structure of the formulations, which is not altered. In some cases, independent contribution factors are added, while in other cases new parameters are placed inside other contributions. In all the cases, modifications are carried out on the part of the body of formulations which is pure empirical, because the theoretical-based "skeleton" cannot be modified. Hence, the choice of variables and their relative weight become mainly an issue of "best-fitting" rather than a pure mechanically-justified decision; in fact, same principle is under the definition of the empirical body of formulations [4-7]. Such a procedure is carried out only on empirical formulations, given that the strong biased results observed in fundamental approach mostly depend on the uncertainty of the calculation of curvatures rather than in the sensitivity of L_{pl} regarding cross-sectional aspect ratio.

However, some premises according to previous results could be followed aimed at the definition of the modification parameters. Firstly, they must be referred to the geometry of the seccion (h_b and/or b_w), which are also the only responsible of different performances of DB and WB regarding curvatures (see section 1). In order to be coherent with the disaggregation of the original database that allowed determining the bias (see section 2), maybe the most feasible factor to be used would be the cross-sectional aspect ratio (h_b/b_w), which is on the base of the definition of DB and WB depending on a corner value of 1.0. Still, all the expressions already contain terms depending on h_b, thus different attempts aimed at avoiding such duplicity are carried out.

Regarding θ_u, influence of aspect ratio can be intended as being divided into two contributions, as it influences both ϕ and L_{pl} (see section 1). In empirical approach both implicit contributions are concentrated mainly in the factor $h_b^{-0.35}$ and to a lesser extent on the confinement factor $25^{\alpha\cdot\omega w}$; the last one is not modified in the proposal. Firstly, the form of expressions is chosen. Four different forms for the modified empirical formulations for θ_u are proposed; they are shown in Eqs. (9) to (12), in which parameters C_1 and C_2 must be sought aimed at best fitting with experimental data. Aimed at easing the awareness of the differences between formulations, some of their members are condensed respect to the original expression in Eq. (5): $a=a_{st}[1–a_{old}\cdot a_{cy}(1+0.25a_{pl})/6](1–0.43a_{cy})(1+a_{sl}/2)$;$k_\alpha=25^{\alpha\cdot\omega w}$; $k_\rho=1.25^{100\rho d}$; $k_\omega=(\max\{0.01;\omega\}/\max\{0.01;\omega'\}\cdot f_c)^{0.225}$.

$$\theta_{u,emp1,\mathrm{mod}1} = a \cdot k_\omega \cdot k_\alpha \cdot k_{\rho d}\left(\min\left\{\frac{L_V}{h_b};9\right\}\right)^{0.35}\left(\frac{h_b}{b_w}\right)^{C_1} \tag{9}$$

$$\theta_{u,emp1,\mathrm{mod}2} = a \cdot k_\alpha \cdot k_{\rho d} \cdot k_\omega\left(\min\left\{\frac{L_V}{h_b};9\right\}\right)^{0.35}\left(\frac{C_2}{b_w}\right)^{C_1} \tag{10}$$

$$\theta_{u,emp1,\mathrm{mod}3} = a \cdot k_\alpha \cdot k_{\rho d} \cdot k_\omega\left(\min\left\{\frac{L_V}{\sqrt{b_w h_b}};9\right\}\right)^{C_1} \tag{11}$$

$$\theta_{u,emp1,\mathrm{mod}4} = a \cdot k_\alpha \cdot k_{\rho d} \cdot k_\omega\left(\min\left\{\frac{L_V}{\sqrt[3]{b_w h_b^{2}}};9\right\}\right)^{C_1} \tag{12}$$

The first proposal is to multiply the original formulation by a power of aspect ratio (Eq. (9)), which increases θ_u of DB and decreases θ_u of WB. In order to avoid the duplicity of terms depending on h_b, a second option, based on a factor only depending on b_w, is proposed (Eq. (10)). However, this option needs to be defined a "corner value" for b_w in order to define the threshold for the increase or decrease of θ_u, which is actually kind of a definition of DB and WB regarding only b_w, being in some cases insufficient. On the other hand, the third and fourth options are essentially based on the combined influence of h_b and b_w on relative ultimate curvatures (see section 1). In the third option (Eq. (11)), original denominator h_b is replaced by the geometric mean of h_b and b_w (in order to keep the dimensionless character of the shear span ratio). In the fourth option (Eq. (12)), similar approach is proposed but more importance is given to h_b.

Then, parameter C_1 and eventually C_2 in each expression must be searched. When there is only one parameter, it is trivially selected in order to provide best fitting to experimental data (i.e. median experimental-to-predicted ratio equal to 1.0). Conversely, when there are two variables, an optimisation of C_2 is searched for each value of C_1 and the solution with lower CoV is selected.

Proposed parameters for all the formulations are shown in Table 2. Rather satisfactory solutions are found: similar dispersion level than in the original formulations are shown. Perfect fitting (i.e. median experimental-to-predicted ratio equal to 1.0 also for the disaggregated sub-databases DB and WB) is shown for the second option of modified θ_u (Fig. 9). In the rest of expressions, bias of results is rather symmetric and, almost all, much more reduced than in the original ones: mean ratios are approximately within ±5% respect to perfect fitting, except for the fourth option for modified θ_u in DB (+14%). Regarding bias corresponding to different disaggregations of sub-databases (steel type, slippage, loading type and hooks closure, see Table 3), the two first proposals for modified empirical θ_u also show rather good balance, but quite large bias is shown by third and fourth proposal.

Table 2 – Selected values of parameters providing best fitting of proposed modified expressions for θ with merge experimental database

Modified expression	Equation	Proposed parameters		Experimental-to-predicted ratios					
				All cases		DB		WB	
		C_1	C_2	Median	CoV	Median	CoV	Median	CoV
$\theta_{u,emp1,mod1}$		0.20	-	1.00	43%	1.04	48%	0.98	38%
$\theta_{u,emp1,mod2}$		0.40	262mm	1.00	45%	1.00	47%	1.00	43%
$\theta_{u,emp1,mod3}$		0.35	-	1.00	43%	1.06	47%	0.96	38%
$\theta_{u,emp1,mod4}$		0.33	-	1.00	43%	1.14	47%	0.95	38%

Table 3 – Disaggregated experimental-to-predicted ratios for proposed modified expressions on different sub-groups of DB

Modified expression	Median experimental-to-predicted ratios								
	Steel type			Slippage		Loading		Hooks	
	Hot-rolled	Tempcore	Cold	Yes	No	Monotonic	Cyclic	135º	90º
$\theta_{u,emp1,mod1}$	1.03	1.15	0.83	1.15	0.89	0.93	1.18	1.17	0.92
$\theta_{u,emp1,mod2}$	0.99	1.08	0.79	1.13	0.89	0.91	1.19	1.18	0.90
$\theta_{u,emp1,mod3}$	1.05	1.16	0.84	1.17	0.92	0.95	1.19	1.19	0.94
$\theta_{u,emp1,mod4}$	1.13	1.22	0.91	1.23	1.00	1.02	1.26	1.25	1.01

$$\theta_{u,EC8,emp,\mathrm{mod}1} = 0.016\left(\frac{\max\{0.01;\omega'\}}{\max\{0.01;\omega\}} f_c\right)^{0.225}\left(\frac{L_V}{h_b}\right)^{0.35}\left(\frac{h_b}{b_w}\right)^{0.2} \cdot 25^{\alpha\omega_w} \cdot 1.25^{100\rho_d} \quad (13)$$

$$\theta_{u,EC8,emp,\mathrm{mod}2} = 0.016\left(\frac{\max\{0.01;\omega'\}}{\max\{0.01;\omega\}} f_c\right)^{0.225}\left(\frac{L_V}{h_b}\right)^{0.35}\left(\frac{262mm}{b_w}\right)^{0.4} \cdot 25^{\alpha\omega_w} \cdot 1.25^{100\rho_d} \quad (14)$$

Finally, some of those proposals are applied to the EC8-3 formulations, because they correspond to a particular case of those ones. Modified expressions for EC8-3 corresponding to the first (Eq. (13)) and second (Eq. (14)) proposals for θ_u are adopted, considering that they show better fitting than the rest. It is worth noting that, in the second proposal, the value of C_2=262mm represents kind of a “corner” value for b_w aimed at separating between DB and WB. In fact, such value is obtained for best fitting with the sub-database of DB, which contains a high amount of specimen scaled (255 out of 272 with b_w<262mm). However, in real (full-scale) construction practice such a corner value appears to be quite low: DB with b_w=300mm are widely used [16]. Hence, first proposal (Eq. (13)) may be more robust than the second one, in which cross-section geometry measures are always rated to L_V.

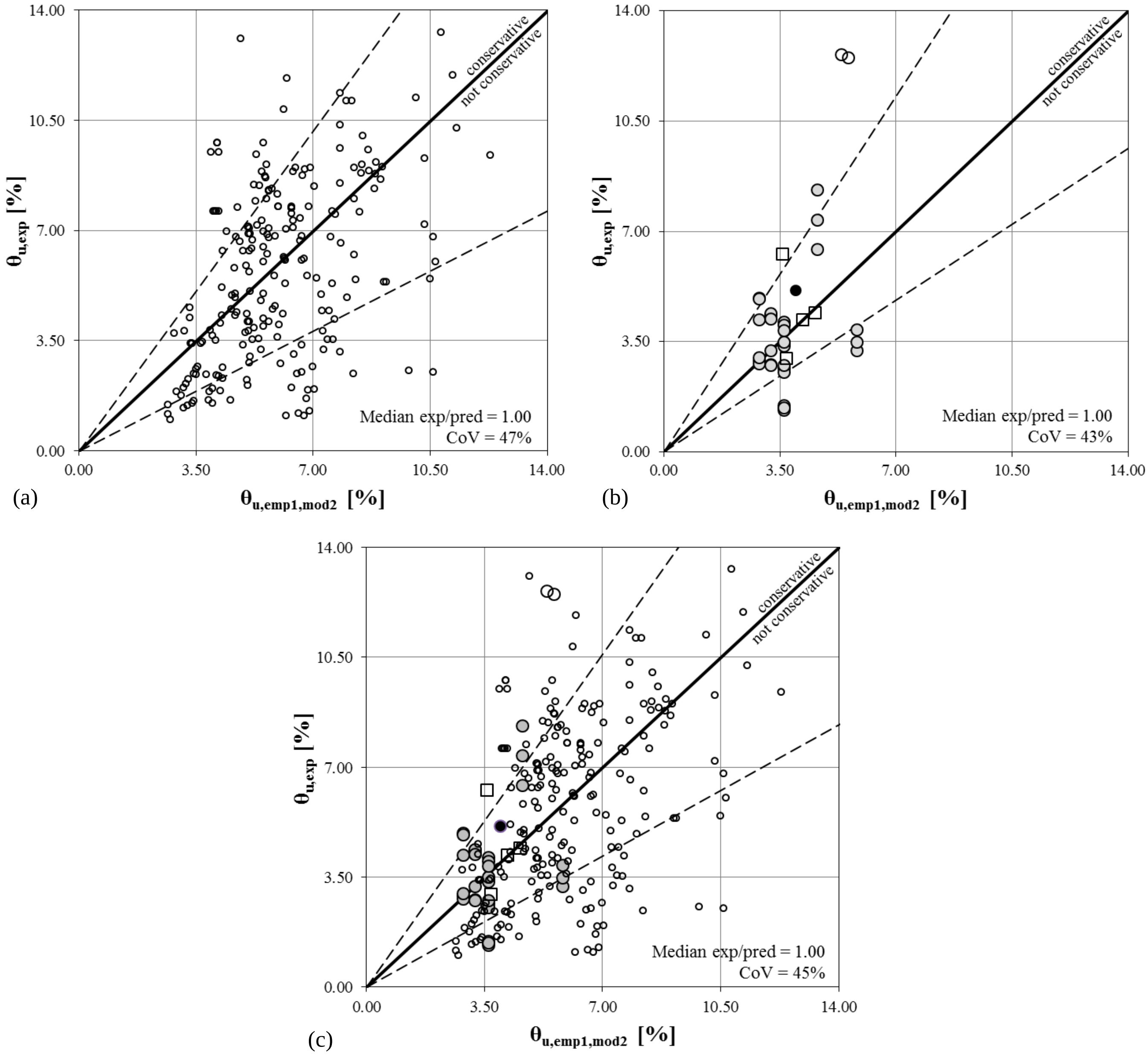

Fig. 9 – Comparison of experimental and predicted θ_u according to the second proposed modification to the empirical formulation in [6] for DB (a), for WB (b) and for the weighted merge of both sub-databases (c)

5. Conclusions

Current formulations proposed by Eurocode 8 part 3 (EC8-3) for the inelastic deformations of existing RC members are assessed aimed at finding out whether they are representative of beams with different cross-sectional aspect ratio, in particular for wide beams (WB) contrasted with conventional deep beams (DB).

Parametric results show that confined WB present larger ultimate chord rotation but lower chord rotation ductility than DB despite the similar curvature ductilities, due to lower plastic hinge lengths in WB. Then, the experimental results of the database underlying EC8-3 approach are disaggregated into DB and WB, and current formulations are applied separately to both groups. Predicted chord rotations appear to be significantly biased for both types, especially at ultimate; the actual model provides conservative values for DB and non-conservative values for WB.

Hence, some different feasible modifications of both pure empirical and fundamental formulations for chord rotations are proposed, in order to reduce the bias and thus increasing the robustness of the model against cross-sectional shape variability. Factors including cross-sectional geometry are added to the original formulations, and parameters aimed at best fitting with experimental data are searched, resulting in rather satisfactory solutions with show similar dispersion than the original approach.

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