SHEAR DATABASE FOR REINFORCED AND PRESTRESSED BEAMS MADE WITH FIBER REINFORCED CONCRETE

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Key words: Shear behavior, Beams, Fiber Reinforced Concrete, Building Codes

Abstract: A total number of 215 structural elements were used to prepare a complete database to analyze the shear behavior and the influence of each parameter on shear out of 363 elements of the experimental database. 148 elements were eliminated for various reasons. Thus, the following items were removed: those with different failure modes to shear, those beams which are not known in some detail, also the beams containing a mixture of more than one fiber type, those for which values of strength are not available and all those elements with ratios *a/d* smaller than 2.5, where the arching action is dominant [1].

The database is made up of elements from databases of the University of Brescia and of RILEM, in addition to all the shear tests carried out within the Brite/Euram project [2], beams tested by Dupont & Vandewalle [3], other beams [4] and the tests presented in the Ph.D. thesis of Cuenca [5]. The input parameters used were: the shear span-to-depth ratio (*a/d*); the effective depth (*d*); the concrete cylinder compressive stress (f_c); the residual flexural tensile strength (f_{R3}) corresponding to a crack mouth opening displacement CMOD=2.5 mm, according to EN 14651 [6]; the longitudinal reinforcement ratio (ρ_l); the average stress acting on the concrete cross-section for an axial force due to prestressing actions (σ_c); the amount of steel fibers (kg/m^3) and transverse reinforcement area per unit length ($A_{s\alpha}/s$). The output value was the safety margin (SM) obtained as V_{test}/V_{theo} (*the shear test value divided by the shear theoretical value*). The theoretical shear (V_{theo}) was calculated for each of the beams according to three calculation codes: the Spanish Standard EHE-08 [7], the RILEM approach [8] and the first complete draft of Model Code 2010 [9].

1 INTRODUCTION

After thorough review of the literature on structural elements with shear failure, and after carrying out several experimental programs[5] whose values were compared later with the theoretical values obtained with the three selected Design Codes to calculate shear in elements reinforced with fibers, it was found that it would be useful and also necessary to build a large database of elements failing in shear in order to have a large number of cases to allow a better evaluation of the resisting phenomena and the validity of the building Codes. For this reason, the present paper shows the analysis of that database.

The paper will explain how the data were selected and, also, how data were analyzed by separating it into four different clear cases:

Case 1 concrete beams without any shear reinforcement (neither fibers nor stirrups);

Case 2 beams with only stirrups (no fibers);

Case 3 beams with only fibers (no stirrups);

Case 4 beams with fibers and stirrups.

In each of these four cases the influence of the following parameters is analyzed: d, a/d, f_{cm}, f_{R3}, ρ, σ_c, and amount of fibers and stirrups.

2 DATA SELECTION

A total number of 215 structural elements were used to prepare a complete database to analyze the shear behavior and the influence of each parameter on shear, out of 363 elements of the experimental database. As it can be noticed, 148 elements were eliminated for various reasons. In particular, the following data were removed:

1. beams with different failure modes in shear;
2. beams which are not known in some detail;
3. beams containing a mixture of more than one fiber type;
4. beams where are not available any value of strength;
5. beams with a/d ratios smaller than 2.5, in which arching action is dominant [10], [11], [12], [13].

The present database was made by using data databases of the University of Brescia (Italy) and of RILEM, in addition to all the elements tested in shear in the Brite/Euram project [2], to beams tested by Dupont & Vandewalle [3], to other beams [4] as well as beams tested within the PhD thesis of Cuenca and presented in other papers ([5], [14], [15], [16], [4], [17], [18], [19], [20]).

The input parameters used were: the shear span-to-depth ratio (a/d); the effective depth (d); the concrete cylindrical compressive strength (f_c); the residual flexural tensile strength (f_{R3}) corresponding to a crack mouth opening displacement CMOD=2.5mm (according to the Standard EN 14651 [6]); the reinforcement ratio for longitudinal reinforcement (ρ_l); the average stress acting on the concrete cross-section for an axial force due to prestressing actions (σ_c); the amount of steel fibers (kg/m^3) and transverse reinforcement area per unit length ($A_{s\alpha}/s$).

The output value is the safety margin (SM) obtained as V_{test}/V_{theo}, ehere V_{theo} represents the shear strength determined according to the considered structural code.

A large shear database has been obtained, that covers a great interval of the main parameters influencing shear. Table 1 summarizes the ranges of the different values used in this shear database.

The theoretical shear (V_{theo}) was calculated according to three structural Codes: the Spanish Standard EHE08 [7], the RILEM approach [8] and the first draft of Model Code 2010 [9]. The shear formulations of these Codes are summarized in Table 2, on the other hand, limitations that Design Codes impose are in Table 3.

Table 1: Range of parameters in the complete database (N=215 elements)

Parameter	Min.	Max.
d (mm)	102	1440
a/d	2.50	4.69
f_{cm} (MPa)	17	96.34
f_{R3} (MPa)	0	10.60
Amount of fibers (kg/m^3)	0	240
ρ (%)	0.41	5.82
σ_c (MPa)	0	12
$A_{s\alpha}/s$ (cm^2/m)	0	4.90

EHE-08 [7] formulation considers fibers contribution separately from concrete, which is based in EC2 [21] while the contribution of the fibers is based on RILEM [8]. The MC2010 [9] considers Fiber Reinforced Concrete (FRC) as a composite material where fibers represent a distributed reinforcement; contribution that is modeled as a modifier of the longitudinal reinforcement ratio throughout a factor that includes the toughness properties of FRC [12].

Table 2: Current Codes shear formulas

<table>
<tr><th>Code</th><th>Theoretical Shear (V)</th><th colspan="2">Parameters</th></tr>
<tr><td></td><td>Concrete (V_{cu}) and fiber contribution (V_{fu}) to shear resistance</td><td>No TR</td><td>With TR</td></tr>
<tr><td>EHE-08</td><td>$V_{cu} = [(C_1/\gamma_c)\cdot\xi\cdot(100\cdot\rho_l\cdot f_{cv})^{1/3} + 0.15\cdot\sigma_{ck}]\cdot\beta\cdot b_o\cdot d$
$V_{fu} = k_f\cdot 0.7\cdot\xi\cdot 0.5\cdot 0.33\cdot(f_{R3k}/\gamma_c)\cdot b_o\cdot d$</td><td rowspan="2">$C_1=0.18$; $\beta=1$</td><td>$C_1=0.15$; $\beta=(*)$</td></tr>
<tr><td>EC-2 + RILEM</td><td>$V_{cu} = [(C_1/\gamma_c)\cdot\xi\cdot(100\cdot\rho_l\cdot f_{ck})^{1/3} + 0.15\cdot\sigma_{ck}]\cdot\beta\cdot b_o\cdot d$
$V_{fu} = k_f\cdot 0.7\cdot\xi\cdot 0.18\cdot(f_{R4k}/\gamma_c)\cdot b_o\cdot d$</td><td>$\beta=0$; $V_{cu}=0$</td></tr>
<tr><td rowspan="2">MC2010</td><td colspan="3">MC2010 (Without fibers):
$V_{cu} = k_v\cdot(\sqrt{f_{ck}}/\gamma_c)\cdot z\cdot b_o$ (Level III Approximation)</td></tr>
<tr><td colspan="2">MC2010 (With fibers):
$V_{cu} + V_{fu} = [(C_1/\gamma_c)\cdot\xi\cdot(100\cdot\rho_l\cdot C_2)^{1/3} + 0.15\cdot\sigma_{ck}]\cdot\beta\cdot b_o\cdot d$
$C_2=(1+7.5\cdot(f_{Ftuk}/f_{ctk}))\cdot f_{ck}$</td><td>$C_1=0.18$; $\beta=1$</td></tr>
</table>

Table 3: Parameters for the determination of the shear strength and their limitations

Common limitations for all Codes:
$\xi = 1+\sqrt{(200/d)} \leq 2.0$
$\rho_l = (A_s+A_p)/(b_o\cdot d) \leq 0.02$
Particular limitations of each Code:
$\sigma_{ck}=[(N_k+P_k)/(b_o\cdot d)]<0.30\cdot f_{ck} \leq 12$Mpa (EHE-08)
$\sigma_{ck}=[(N_k+P_k)/(b_o\cdot d)]<0.2\cdot f_{ck}$ (EC2 and MC2010 for FRC)
$k_f = 1+n\cdot(h_f/b_o)\cdot(h_f/d) \leq 1.5$ (EHE08 and RILEM)
$n=[(b_f-b_o)/h_f] \leq 3$ and $n \leq (3\cdot b_o/h_f)$ (EHE08 and RILEM)
$V_{cu,\,min} = [(0.075/\gamma_c)\cdot\xi^{3/2}\cdot fcv^{1/2} + 0.15\cdot\sigma_{ck}]\cdot b_o\cdot d$ (EHE-08)
$V_{cu,min}=[0.035\cdot\xi^{3/2}\cdot fcv^{1/2} + 0.15\cdot\sigma_{ck}]\cdot b_o\cdot d$ (EC2 & MC2010 for FRC)
$0.5 \leq \cot\theta \leq 2.0 \rightarrow 26.57^\circ \leq \theta \leq 63.43^\circ$ (EHE-08)
$1 \leq \cot\theta \leq 2.5 \rightarrow 22^\circ \leq \theta \leq 45^\circ$ (EC2)
β determination (EHE-08):
$\beta = (2\cdot\cot\theta - 1) / (2\cdot\cot\theta_e - 1)$; if $0.5 \leq \cot\theta < \cot\theta_e$
$\beta = (\cot\theta - 2) / (\cot\theta_e - 2)$; if $\cot\theta_e \leq \cot\theta \leq 2.0$
Parameters influencing V_{cu} (MC2010):
$\theta = 29^\circ + 7000\cdot\varepsilon_x$
$\varepsilon_x=[M_{Ed}/z + V_{Ed} + 0.5\cdot N_{Ed} - A_p\cdot f_{p0}] / [2\cdot(E_s\cdot A_s + E_p\cdot A_p)]$
$k_v=0.4\cdot 1300 / [(1+1500\cdot\varepsilon_x)\cdot(1000 + 0.7\cdot k_{dg}\cdot z)]$ if $\rho_w=0$
$k_v=0.4 / (1+1500\cdot\varepsilon_x)$ if $\rho_w \geq 0.08\cdot\sqrt{f_{ck}} / f_{yk}$

3 CASE 1: BEAMS WITHOUT SHEAR REINFORCEMENT

Table 4 and Table 5 summarize the ranges of the different parameters used in this case, referring to reinforced and prestressed beams, respectively.

Table 4: Range of parameters in the shear database of reinforced beams made without shear reinforcement (N=37 elements)

Parameter	Min.	Max.	Average	CoV (%)
d (mm)	197	1440	395.38	65.59
a/d	2.50	4.69	3.19	21.61
f_{cm} (MPa)	20	85.57	36.90	34.50
f_{R3} (MPa)	--	--	--	--
Amount of fibers (kg/m^3)	--	--	--	--
ρ (%)	0.99	3.72	1.76	47.47
σ_c (MPa)	--	--	--	--
$A_{s\alpha}/s$ (cm^2/m)	--	--	--	--

Table 5: Range of parameters in the shear database of prestressed beams made without shear reinforcement (N=6 elements)

Parameter	Min.	Max.	Average	CoV (%)
d (mm)	226.47	550	282.16	42.46
a/d	3.27	4.30	380	11.72
f_{cm} (MPa)	43.80	54.20	50.25	9.30
f_{R3} (MPa)	--	--	--	--
Amount of fibers (kg/m^3)	--	--	--	--
ρ (%)	0.41	3.03	1.06	87.28
σ_c (MPa)	2.87	10.18	4.77	54.24
$A_{s\alpha}/s$ (cm^2/m)	--	--	--	--

3.1 Influence of the *a/d* ratio

In Figure 1, Safety Margins (SMs) are represented for each beam of Case 1. Each column represents one beam of this subset and on each column there are three points corresponding to its SM according to Codes EHE08, MC2010 and RILEM. Beams are sorted in ascending order according to their value of *a/d* (*right vertical axis*), so that the height of each column indicates the value of *a/d* of each beam (*as can be read on the right vertical axis*). On the other hand, SM values of each beam can be obtained through the left vertical axis. Also, reinforced beams are represented by light grey columns (left side of the graph), while dark grey columns are prestressed beams (right side of the graph). Moreover, the upper side of the graph (green shaded) represents the area in which Codes are conservative (SM> 1), whereas the lower side area (red shaded) refers to SM <1. For example, the first beam, starting from the left is a reinforced beam because the column is in light grey; the height of the column indicates that the beam has *a/d* ratio of 2.5. In turn, if one focus on the 3 points on the column, then SM values are obtained referring to the left vertical axis.

With this graph it has been possible to observe that for *a/d*>3.5, the MC2010 was the most conservative (Figure 1).

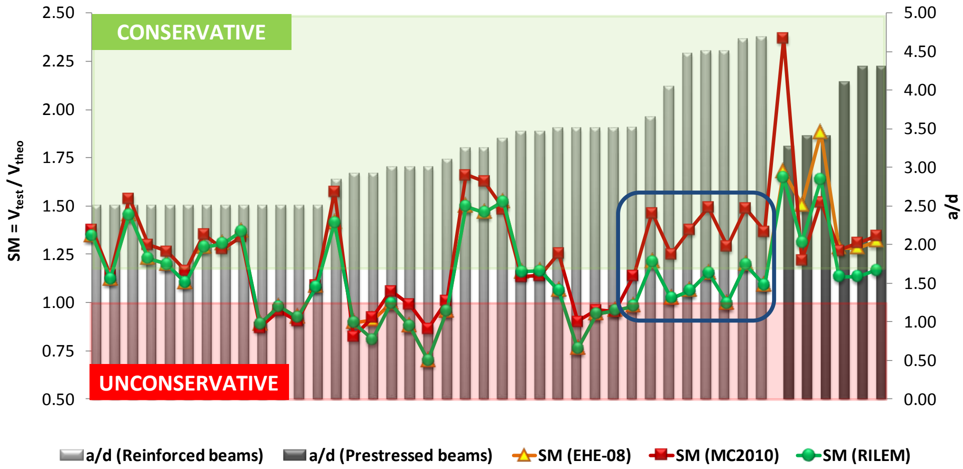

Figure 1: SM represented versus a/d for beams without any reinforcement.

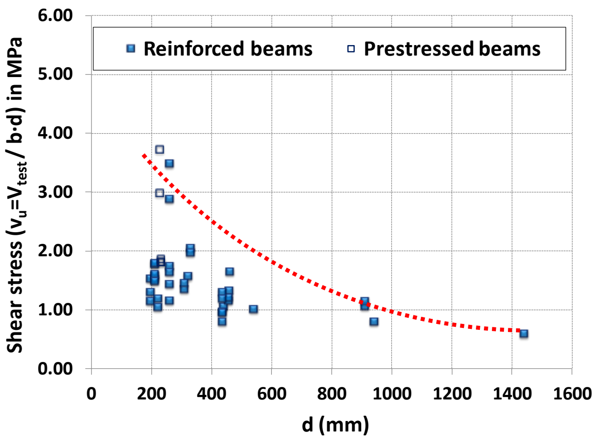

Figure 2: Size effect in beams without shear reinforcement (neither fibers nor stirrups).

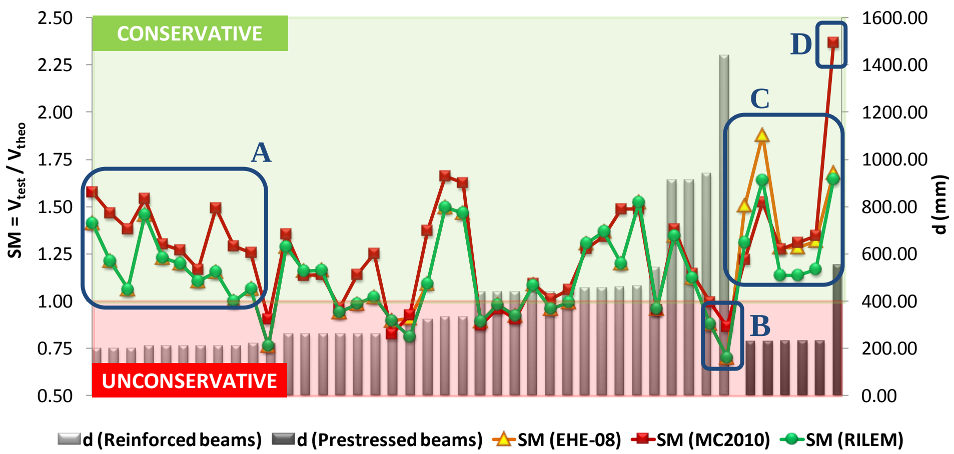

Figure 3: Beams without shear reinforcement (neither fibers nor stirrups). SM versus d (mm)

3.2 Influence of effective depth *d*.Size effect

If experimental shear stress (v_u=$V_{test}/b{\cdot}d$) is represented versus effective depth (*d*), a clear tendency (*size effect*) is observed, as expected; in fact, shear stress decreased when effective depth increase (Figure 2).

It can be also observed that, when $d > 900$mm (*specifically d=1440mm in this case*), all Codes are unsafe (Figure 3). On the other hand, for $d < 900$mm, all Codes give similar values.

Figure 3 also shows that all Codes are conservative for $d < 200$mm, although MC2010 underestimates the effect of the effective depth (*d*) in this range (see square A, in Figure 3). Codes are unconservative for reinforced beams with $d > 900$mm (see square B, in Figure 3). Prestressed beams are always conservative for all Codes (see square C, in Figure 3). Finally it is noted that, for one of the prestressed beams, the MC2010 gives higher SM, it appears that the MC2010 underestimates the effect of prestressing, as discussed below (see square D, in Figure 3).

3.3 Influence of the amount of longitudinal reinforcement, ρ_l

In prestressed beams without any shear reinforcement, SM increase when increase ρ_l for $\rho_l \leq 2$ %. When $\rho_l >> 2$ %, SM for MC2010 beams increases quickly (Figure 4).

3.4 Influence of the stress due to the prestressing actions, σ_c

Prestressed beams are always safe according to all Codes considered herein (Figure 5).

4 CASE 2: BEAMS WITH STIRRUPS

With respect to the *a/d* ratio, safety margins (SM) do not show any trend within the range studied ($2.5 \leq a/d \leq 3.5$).

In the range ($400 < d < 900$mm) it is observed that SM increases with increasing values of the effective depth (*d*).

For beams with f_c>70MPa, SM are unconservative; however, since there are two reinforced beams with f_c >70MPa, these values are not sufficient to ensure this tendency.

Referring to the amount of longitudinal reinforcement (ρ_l) and its influence on SM, no trends are detected; it is only observed an increasing shear stress with the increase of ρ_l.

No clear trends are obtained on the influence of the transverse reinforcement area ($A_{s\alpha}/s$) on the shear stress or SM.

5 CASE 3: BEAMS WITH FIBERS

Table 6 and Table 7 summarize the ranges of the different parameters used in beams only reinforced with fibers, referring to reinforced and prestressed beams, respectively.

Table 6: Range of parameters in the shear database of beams reinforced only with fibers (N=102)

Parameter	Min.	Max.	Average	CoV (%)
d (mm)	102	1440	360.80	59.59
a/d	2.50	4.69	3.24	18.60
f_{cm} (MPa)	17.00	96.34	38.86	41.32
f_{R3} (MPa)	1.22	10.60	3.65	49.24
Amount of fibers (kg/m^3)	15	240	63.31	66.33
ρ (%)	0.99	3.72	2.23	39.80
σ_c (MPa)	--	--	--	--
$A_{s\alpha}$/s (cm2/m)	--	--	--	--

Table 7: Range of parameters in shear database of prestressed beams with only fibers (N=26)

Parameter	Min.	Max.	Average	CoV (%)
d (mm)	226.47	738.89	440.93	48.79
a/d	2.84	4.40	3.40	11.15
f_{cm} (MPa)	35.90	77.00	55.38	22.78
f_{R3} (MPa)	2.83	8.61	4.95	39.19
Amount of fibers (kg/m^3)	50	70	55	12.61
ρ (%)	0.41	5.82	2.23	92.52
σ_c (MPa)	2.87	12.00	7.16	50.05
$A_{s\alpha}$/s (cm^2/m)	--	--	--	--

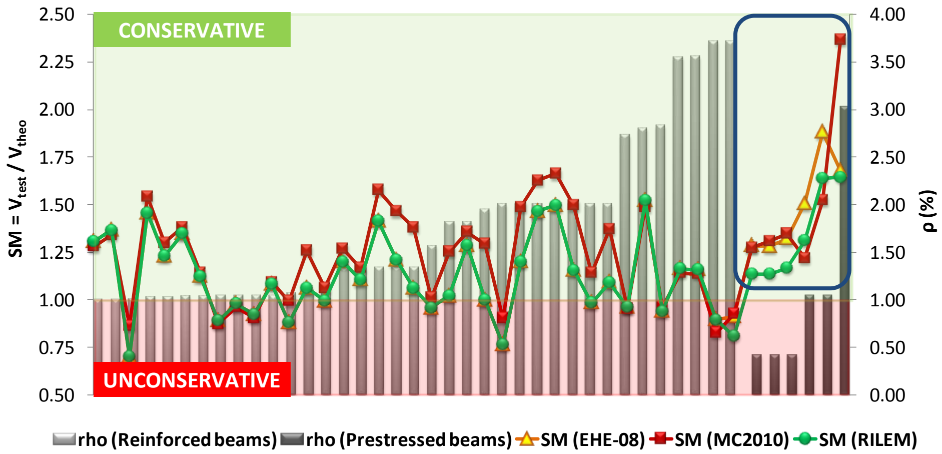

Figure 4: Beams without shear reinforcement. SM represented versus ρ (%)

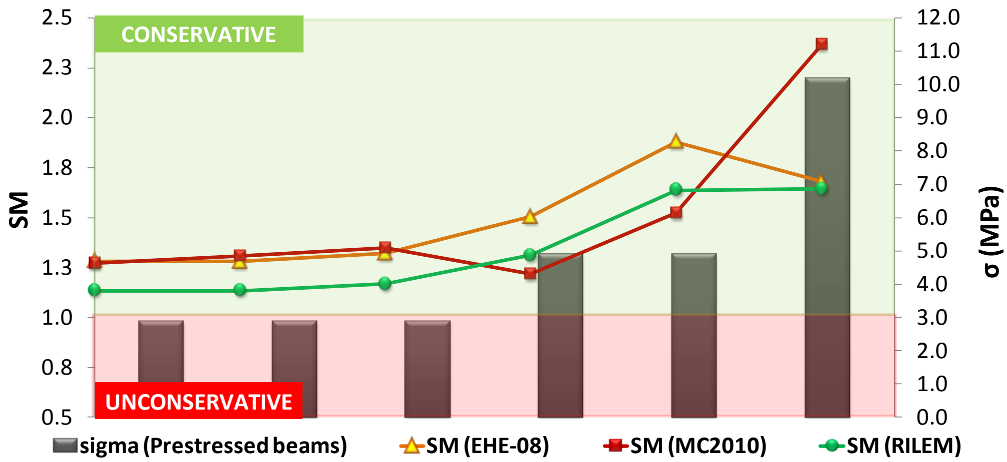

Figure 5: SMs represented versus σ_c (MPa) for beams without shear reinforcement

5.1. Influence of the residual tensile strength (CMOD=2.5mm), f_{R3}

Reinforced beams with f_{R3}>5 MPa presented low SM.

Shear stresses increases when f_{R3} also increases for both, reinforced and prestressed beams. It can be observed that the slopes are different between reinforced and prestressed beams, due to the effect of prestressing which also produce higher shear stresses (Figure 6).

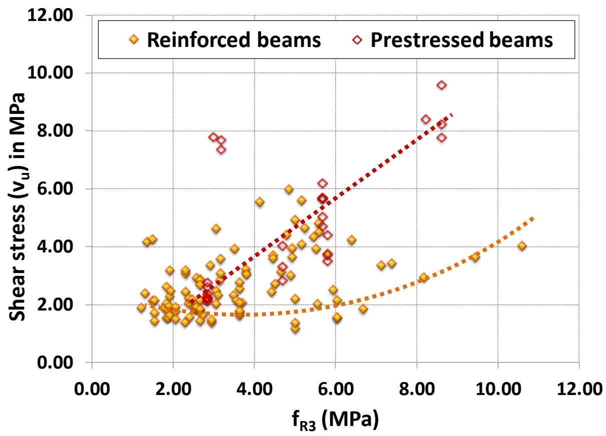

Figure 6: Experimental shear stress versus f_{R3} for beams reinforced only with fibers

5.2. Influence of longitudinal reinforcement

In Figure 7, experimental shear stresses are plotted versus the longitudinal reinforcement percentage. As it can be observed, no trend is detected in reinforced beams while, in prestressed beams the shear stress increases with ρ_l.

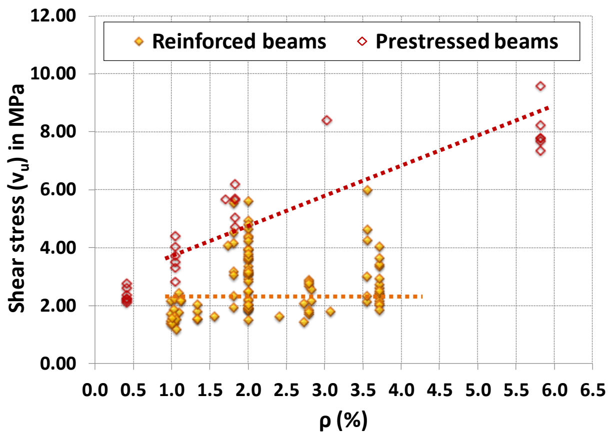

Figure 7: Experimental shear stress versus ρ_l (%) for beams reinforced only with fibers

In Figure 8, SM of all studied Codes (EHE, MC2010 and RILEM) are plotted versus ρ_l for all beams.

Some reinforced beams (see square A in Figure 8) show high SMs; the reason is that these beams have a real value of ρ_l greater than 2% (the exact value is unknown), but the data come from elements of the database of other Authors. Therefore, the calculations are using a value lower than the actual ρ_l, resulting in a lower predicted value.

In RC, when $\rho_l \geq 3\%$, SMs for all Codes reduce (square B in Figure 8), when ρ_l increases. In prestressed beams, when ρ_l increases, SM also increases; however, when $\rho_l \geq 5\%$, MC2010 underestimates the effect of prestressing (square C in Figure 8).

5.3. Influence of prestressing

In general, it is observed that RILEM & EHE are most balanced for all levels of f_c and σ_c whereas MC2010 is more conservative for high levels of f_c and σ_c.

The first prestressed elements correspond to hollow core slabs (square A in Figure 9). One beam (dashed line square in Figure 9) has a clearly lower value of SM than its analogous beam (square B in Figure 9), this is because the beam has a flange width (b_f =260mm) much lower than its analogous (b_f =400-600 mm). Therefore, RILEM & EHE codes, which take into account the contribution of the flange width in beams reinforced with fibers, are overestimating the contribution of a flange which is very small. In beams with flanges of considerable size (b_f > 400mm), MC2010 gives higher SM values than the other two codes, which means that determines a lower shear theoretical value since it neglects the contribution of flanges to shear (flanges factor, k_f, was not applied, Table 2).

5.4. Influence of the amount of fibers

Reinforced and prestressed beams with fibers are always safe (SM>1) for all Codes, according to this database, when the amount of fibers is greater than 125 kg/m^3 (Figure 10).

5.5. Codes for beams with only fibers

Table 8 and Table 9 show that, for the beams reinforced with fibers, MC2010 presents the greater CoV (%) but, it is the safest Code, with the highest value of 5th percentile. Codes are safer for prestressed beams.

Table 8: Summary of statistics of RC beams with fibers

	Reinforced beams (Beams with fibers)		
	EHE-08	**MC2010**	**RILEM**
Minimum	0.62	0.73	0.59
Maximum	1.87	2.36	1.79
Average	1.17	1.25	1.13
Standard deviation	0.26	0.32	0.26
CoV (%)	**22.32**	**25.81**	**23.07**
5th percentile (%)	**0.80**	**0.84**	**0.77**
95th percentile (%)	1.69	1.87	1.63

6 CASE 4: BEAMS WITH FIBERS AND STIRRUPS

Table 10 summarizes the ranges of the different parameters used in beams transversally reinforced with stirrups and fibers. Influence on SM due to parameters: a/d, d, f_{cm} and $A_{sα}/s$ were not detected in this analysis.

Table 9: Summary of statistics of prestressed beams only with fibers

	Prestressed beams (Beams with fibers)		
	EHE-08	**MC2010**	**RILEM**
Minimum	0.93	1.05	0.83
Maximum	**1.70**	**2.19**	**1.73**
Average	1.29	1.57	1.20
Standard deviation	**0.21**	**0.32**	**0.24**
CoV (%)	15.92	20.23	20.20
5th percentile (%)	**1.04**	**1.20**	**0.93**
95th percentile (%)	1.64	2.10	1.66

Table 10: Range of parameters in the shear database of reinforced beams with only fibers (N=19 elements)

Parameter	Min.	Max.	Average	CoV (%)
d (mm)	210	650	293.68	34.65
a/d	3.10	4.50	3.53	10.06
f_{cm} (MPa)	38.00	50.67	45.33	9.91
f_{R3} (MPa)	1.22	8.54	3.19	56.33
Fibre (kg/m^3)	15	60	39.95	42.52
ρ (%)	1.56	3.56	2.99	26.41

σ_c (MPa)	--	--	--	--
$A_{s\alpha}/s$ (cm^2/m)	1.40	3.53	2.18	34.50

6.1. Influence of the residual tensile strength

Figure 11 shows the SM of all Codes versus the residual flexure tensile strength (f_{R3}); it can be observed that, for reinforced beams, the most conservative Code is EHE while, for prestressed beams, the RILEM was the safest; MC2010 maintained the same SM levels for reinforced and prestressed beams.

6.2. Influence of the longitud. reinforcement

In Figure 12 it can be observed that reinforced beams with $\rho_l \leq 2\%$ and f_{R3}<1.5MPa were all in the side of unsafety (SM<1). Reinforced beams with ρ_l =3.5% had similar levels of SM for all Codes. The MC2010 was the most balanced in both: reinforced and prestressed.

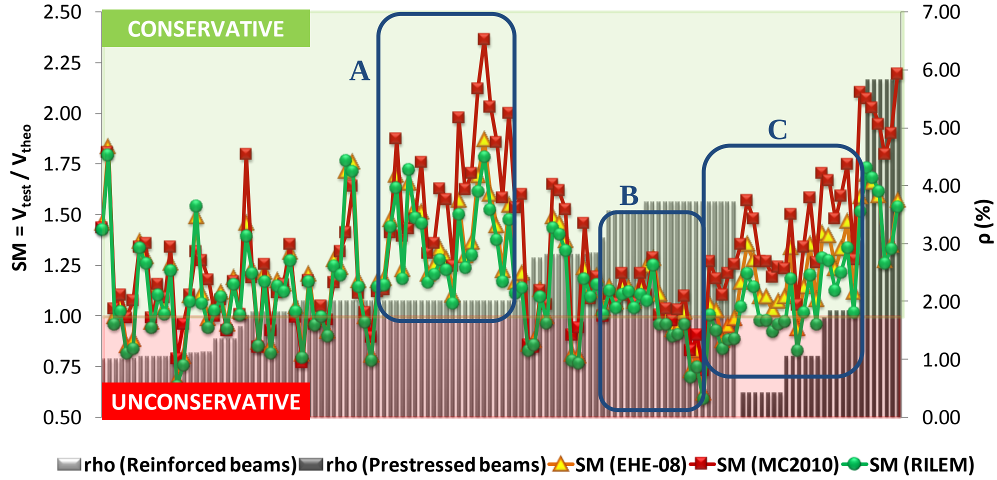

Figure 8: Beams transversally reinforced with fibers. SM represented versus ρ_l (%)

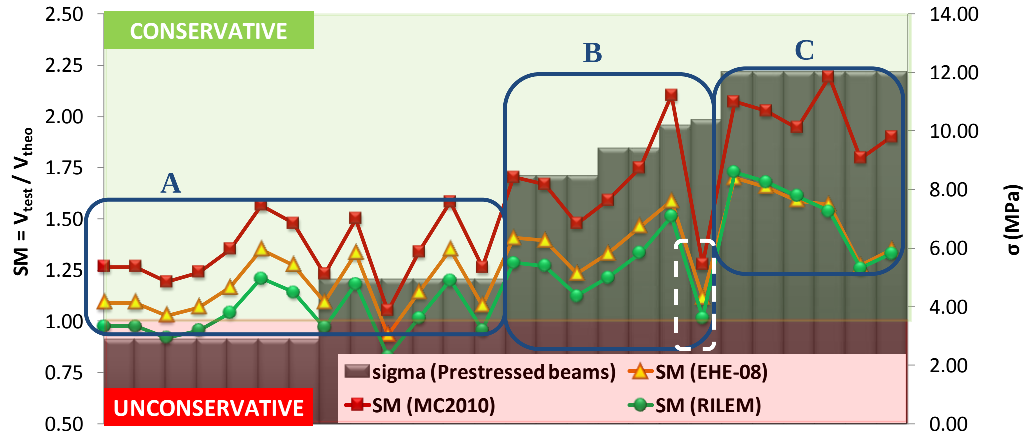

Figure 9: Beams transversally reinforced with fibers. SM represented versus σc and fc (MPa)

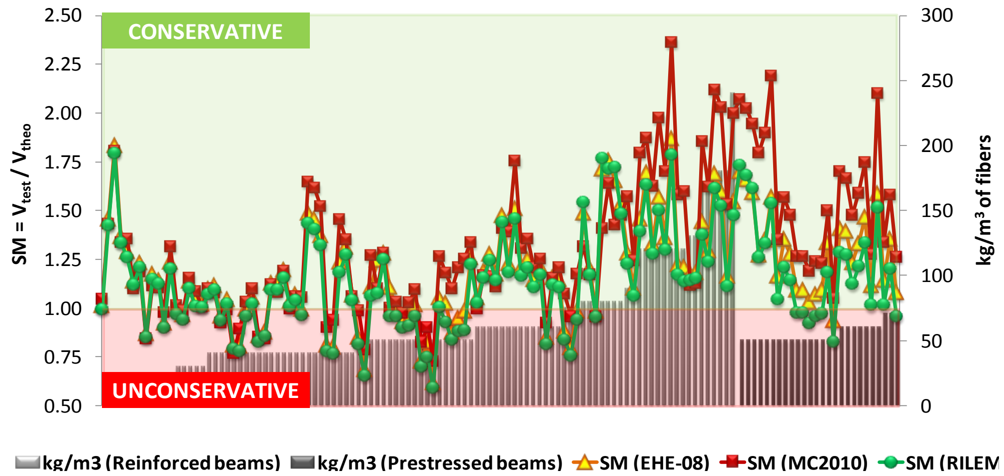

Figure 10: Beams transversally reinforced with fibers. SM represented versus fibre content (kg/m³)

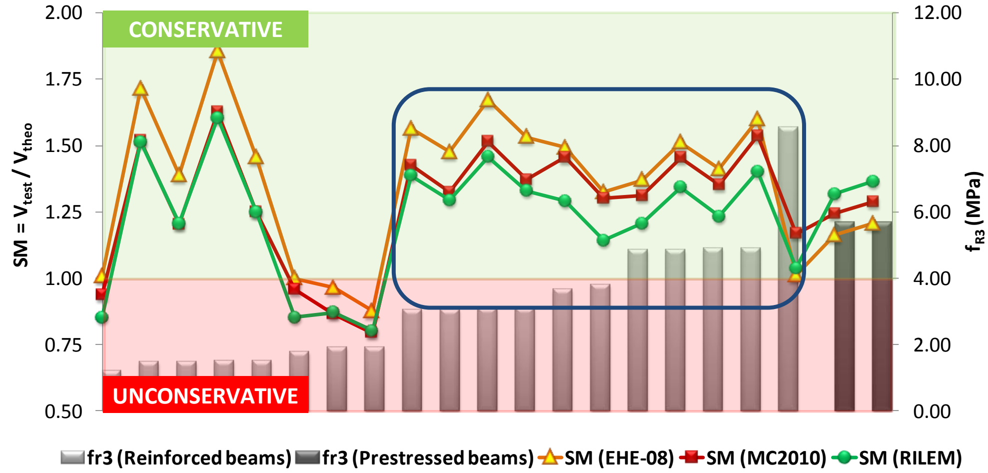

Figure 11: Beams transversally reinforced with fibers + stirrups. SM represented versus f_{R3} (MPa)

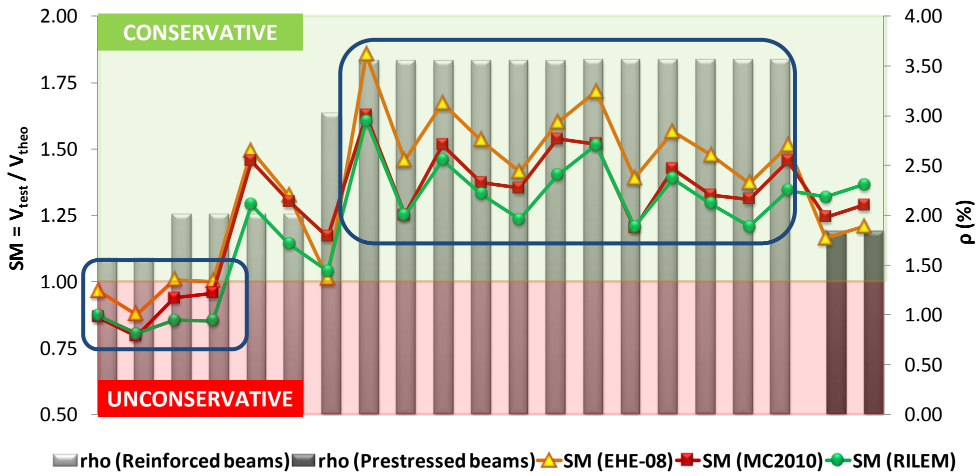

Figure 12: Beams transversally reinforced with fibers + stirrups. SM represented versus ρ_l (%)

6.3. Influence of prestressing

In beams reinforced with fibers and stirrups there were only two prestressed beams, so they were not enough to formulate strong conclusions, but it seemed that, when both reinforcements were present (fibers and stirrups), SM for prestressed beams was higher.

7 SUGGESTIONS FOR DESIGN CODES

After analyzing a large database consisting of 215 structural elements failing in shear, and determined the expected shear strength according to three different Design Codes, it was possible to evidence the role of the simple parameters and, among these, the ones that could be better evaluated.

The analyses performed on the database allowed observing that existing building Codes can be significantly improved and that every time new concrete matrices with enhanced mechanical properties are developed, the existing Codes may be no longer suitable.

In the present work, some suggestions for improving existing Codes are made. In particular:

- codes are not reliable for calculating shear strength when *a/d* < 2.5, since the arch action is very pronounced and shear strength provided by Codes is markedly conservative. For proper calculation of these cases, other methods should be used as the method of struts and ties.
- The larger the crack width at Ultimate Limit State (ULS) becomes, the stronger the size-effect will be. Furthermore, it should be considered that the size factor is influence by the FRC toughness [15]. The latter is a mechanical property that better characterize the material behavior.
- After analyzing the database, it was found that, for small elements without stirrups (eg. d= 200mm), Codes provides conservatives SMs, and that, for larger elements without stirrups, Codes overestimates shear strength.
- For small beam depths will interest to decrease the SM by increasing the theoretical shear; for that, size effect factor (ξ) must be increased. In contrast, for great depths, SM will be increased by reducing the theoretical shear by diminishing the size effect factor (ξ). Therefore, the size effect rules proposed by Codes should be connected accordingly.
- It has been observed that Codes overestimate the shear strength of beams made of HSC (f_c>70MPa). Therefore, structural codes should provide rules that better take into account the shear strength, when f_c>70MPa, as does the EHE when limits the compressive strength ($f_c \leq 60$MPa) and the MC2010 for elements without fibers [$(f_{ck})^{1/2} \leq 8$MPa]. In fact, the Model Code [11] ensures that its limitation in f_{ck} is provided due to the larger observed variability in shear strength of higher strength concrete, particularly for members without stirrups. However, concrete compressive strength also influences the FRC toughness.
- Beside fracture parameter f_{R3}, parameter f_{R1} should be considered for shear strength, since it depends also on the smaller cracks. A parameter that better represents the shear strength in FRC could be represented by the average value $f_{Rm}=(f_{R1}+f_{R3})/2$ in some particular cases, as in small beams.
- Codes are highly conservative for prestressed beams, better and more appropriate rules for considering the compressive stress in the beams should be proposed.

8 CONCLUDING REMARKS

After analyzing a shear database consisting of 215 structural elements, it was detected the influence of each parameter influencing shear.

In the following, Codes will be compared with the experimental results available in the considered database, under the assumption that the partial safety factors are equal to the unit; therefore, the comparisons will not refer to the safety because, in this case, this safety factor have to be considered.

8.1 Influence of effective depth, *d*

For small effective depths (d~200mm), the considered Codes were always conservative for all cases except for beams with only stirrups.

For larger values of d ($\geq$ 900mm), Codes overestimate the shear strength of beams without any shear reinforcement; however, in beams with stirrups, Codes are conservative. In beams with only fibers as shear reinforcement, Codes overestimate the shear strength experimentally determined in some experimental sets.

It should be underlined that both stirrups and fibers mitigate the size effect in shear.

8.2 Influence of the *a/d* ratio

For the range $2.5 \leq a/d \leq 3.5$, particular trends are not observed, independently of the reinforcement type (fibers and/or stirrups).

8.3 Influence of concrete compres. strength

In all beams with higher concrete compressive strength (f_c > 70 MPa), Codes generally overestimate the shear strength. However, it should be observed that in the database, HSC beams reinforced with both stirrups and fibers were not available.

8.4 Influence of residual tensile strength

For FRC beams without stirrups, the SMs are generally higher than the unit, with a high scatter. The scatter is smaller in beams with both fibers and stirrups, but a lower number of results are available in the database.

However, it was evidenced that the shear should not rely solely on the value of f_{R3} for all types of FRC (with any type of fiber and any concrete compressive strength), since residual strength for smaller crack opening (f_{R1}) also influences the shear strength. Hence parameters f_{R1} and f_{R3} should be linked to correctly estimate the theoretical shear value, as evidenced in [5] when an alternative parameter $f_{Rm} = (f_{R1} + f_{R3})/2$ was proposed.

Furthermore, in large beams, a crack opening corresponding to f_{R3}, is not reached and a residual strength value related to f_{R1} should be considered.

Reinforced beams with more than 125 kg/m^3 of fibers, evidenced SM>1. In beams with combined reinforcement, for amounts of fibers greater than 40kg/m^3, SM was always higher than 1.

8.5 Influence of the amount of longitudinal reinforcement, ρ_l

The considered codes tends to overestimate shear strength for higher longitudinal reinforcement ratios (ρ_l > 3.5%). This trend was observed in all cases with the exception of beams with a combination of stirrups and fibers; however, in these beams, when ρ_l < 2% and f_{R3} < 1.5 MPa, Codes overestimate the experimental results.

In all prestressed beams, for all Codes, the Safety Margin increases for increasing values of longitudinal reinforcement, ρ_l.

8.6 Influence of prestressing

Codes were always conservative for prestressed beams with high SM; only in beams with both fibers and stirrups, prestressed beams had SM levels of the same order of beams without prestressing.

For beams without any shear reinforcement, SM of the prestressed beams had a clear dependence on the prestressing stress; in fact, the Safety Margin increases with σ. This trend was also present in beams with fibers but a higher scatter was observed; the latter cannot ensure that the safety margin increases with σ.

In beams with fibers, MC2010 underestimated the effect of prestressing, giving rise to higher SM. All Codes were conservative up to σ = 10MPa.

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