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ORIGINAL RESEARCH PAPER

Capacity models for shear strength of exterior joints in RC frames: experimental assessment and recalibration

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Abstract Several theoretical models are currently available in the scientific literature for evaluating the shear capacity of both exterior and interior beam-to-column joints in reinforced concrete (RC) frames. A reasonably wide set of those models, based on either analytical or empirical formulations, has been summarised within a companion work. The present paper firstly presents a wide database which collects results obtained in about two-hundred experimental tests carried out on RC joints. Those results are employed for assessing the above mentioned capacity models by considering a set of experimental data much wider than those usually utilised in the original formulation of such models. Accuracy and reliability of the various models are measured by quantifying some statistical parameters actually describing the relationship between the experimental evidence and the prediction of the various capacity models under consideration. Three relevant classes of joints (namely unreinforced, under reinforced and code-compliant) are considered with the aim of emphasising that the various models perform in a rather different way when applied to those different classes. Finally, a possible recalibration of the various models is proposed with the objective of enhancing their predictive capacity with respect to both the database as a whole and the three classes of RC joints mentioned above.

Keywords Reinforced concrete · Joints · Shear strength · Capacity models · Seismic behaviour · Experimental database

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1 Introduction

Although the first experimental studies on beam-to-column joints in reinforced concrete (RC) frames date back to more than forty years ago (Hanson and Connor 1967), research about those structural components has only recently intensified. A comprehensive overview of capacity models currently available in the scientific literature for RC joints has been proposed in a companion paper (Lima et al. 2012).

As a matter of principle, the structural response of those components is influenced by a wide set of geometric and mechanical parameters. The analytical expressions of shear capacity models for RC joints generally involve a variable subset of those parameters. Thus, a systematic uncertainty affects each one of those models, as they generally do not consider all relevant parameters and adopt simplified analytical expressions for simulating the influence of those ones actually belonging to the above mentioned subset. Moreover, the aleatoric nature of a large number of those parameters leads to a significant randomness predicting shear capacity through those models. Design-oriented analytical models are always affected by both uncertainty and randomness (Cornell et al. 2002), and the resulting influence on the accuracy and reliability of their theoretical prediction can be quantified through a probabilistic analysis aimed at quantifying suitable error and dispersion indices by observing the scatter of the theoretical prediction and an appropriate number of experimental results. However, the number of parameters considered in models available in the scientific literature is generally too small for simulating the effects of all geometric and mechanical quantities actually affecting the behaviour of RC joints. Moreover, such capacity models usually cover only a limited range of variation of those parameters and some of the possible technical solutions (in terms of geometry and reinforcement in both longitudinal and transverse direction) of practical interest.

The present paper deals with assessing ten of those models chosen among the most well-established and widely known ones currently available in the scientific literature (Lima et al. 2012). A wide number of experimental results obtained in tests carried out on exterior beam-to-column joints has been collected by the authors in a wide database which is presented in Sect. 2. Those experimental results are employed in Sect. 3 for assessing the mentioned capacity models and evaluating the relevant error and dispersion measures needed for assessing and quantifying the predictive capacity of the models under consideration. Since all models are partly or fully based on calibrations against a set of experimental observations, they exhibit a different level of accuracy, depending on the various types of joints which they are applied to. Thus, three relevant classes of joints (namely unreinforced, under reinforced and code-compliant) are considered with the aim of emphasising that the various models perform in a rather different way when applied for evaluating shear capacity of RC joints belonging to those different classes.

Finally, a possible recalibration of those models on the wide number of experimental results collected in the database is proposed in Sect. 4.

2 Experimental database

The capacity models briefly outlined in a companion paper (Lima et al. 2012), and further investigated in the present one, are generally based on different assumptions about the basic mechanisms actually controlling shear strength in RC joints (Paulay and Priestley 1992). Moreover, they are often calibrated on experimental results and their accuracy can be hugely affected by both nature and number of those results. Consequently, such models need to be assessed by considering a set of experimental results as large as possible, and wider than the are actually employed in their original calibration.

A database collecting the results obtained in 224 experimental tests carried out on exterior RC joints and available in the scientific literature has been assembled for this purpose. Those tests have been carried out in different years and countries; consequently, a wide variety of materials, structural details and testing protocols are considered. For the sake of brevity, the complete geometric and mechanical properties of the RC joints collected in the database are omitted herein and can be found in the original works mentioned in Table 1. The experimental tests listed in Table 1 include exterior subassemblies tested under either monotonic (M) or cyclic (C) loading. Figure 1 describes the database in terms of both loading protocols and observed failure modes. In principle, the following five types of failure mechanisms can be recognised by the experimental reports:

- Joint failure (J): the joint fails without the development of a plastic hinge at the end of the beam;
- Beam failure (B): a plastic hinge fully develops in the beam with no damage within the joint;
- Beam-Joint failure (BJ): the joint failure occurs after that a plastic hinge starts developing within the beam;
- Column-Joint failure (CJ): the joint fails after that plastic hinges start developing in columns;
- Unknown failure (U), if authors did not report any information about the observed failure mode.

The tests characterised by beam failure have been neglected in the following sections, as they are intended at assessing a series of models for shear capacity of RC joints and such a capacity is not fully attained in those tests. Moreover, the tests characterised by an unknown failure mode are not taken into account. Consequently, 176 experimental tests have been actually considered for assessing the capacity models outlined in the companion paper (Lima et al. 2012).

2.1 The experimental value of the shear strength

The authors of experimental tests on beam-to-column joints generally provide information about the relevant geometric and mechanical parameters of the various specimens. Moreover, relevant data describing the observed mechanical response in terms of both forces and displacements are generally available. However, as a matter of fact, the experimental value of the shear strength V_{jh}^{exp} of the various RC joints can be derived by those data, at least in the case of ultimate condition controlled by joint failure (namely, for failure modes mentioned as "J", "BJ", "CJ" in the end of the previous subsection).

Consequently, the following values of the experimental shear strength V_{jh}^{exp} are evaluated depending on the ultimate force P_u^{exp} through simple equilibrium conditions. The analytical expression of such equilibrium conditions depends on the actual layout adopted in the experimental tests. The tests considered in the present database are generally realised by adopting two alternative experimental layouts:

- an "horizontal configuration" (Fig. 2), in which the column is pinned at both ends and the load (or the imposed displacement) is applied at the free end of the beam;
- a "vertical configuration" (Fig. 3), in which the load (or the imposed displacement) is applied at the top of the column and the beam end can only have horizontal displacements.

Table 1 The Experimental database collecting 224 exterior joints

Authors	Number of Specimens	Loading type
Alva (2004)	1	C
Bindhu and Jaya (2008)	4	C
Chalioris et al. (2008)	20	C
Chun et al. (2007)	7	C
Clyde et al. (2000)	4	C
Ehsani and Alameddine (1991)	11	C
Ehsani and Wight (1985a)	4	C
Genesan et al. (2007)	1	C
Hamil (2000)	16	C
Hegger et al. (2003)	8	M
Hwang et al. (2005)	9	C
Karayannis et al. (2008)	10	C
Karayannis and Sirkelis (2008)	4	C
Kusuhara and Shiohara (2008)	3	C
Liu (2006)	3	C
Pampanin et al. (2002)	1	C
Parker and Bullman (1997)	12	M
Tsonos (1999)	2	C
Tsonos et al. (1992)	8	C
Wong and Kuang (2008)	7	C
Alva et al. (2007)	4	C
Calvi et al. (2001)	1	C
Chun and Kim (2004)	4	C
Chutarat and Aboutaha (2003)	4	C
Durrani and Zerbe (1987)	4	C
Ehsani et al. (1987)	5	C
Ehsani and Wight (1985b)	6	C
Gencoglu and Eren (2002)	2	C
Hakuto et al. (2000)	2	C
Hwang et al. (2004)	6	C
Idayani (2007)	3	M
Karayannis and Sirkelis (2005)	2	C
Kuang and Wong (2006)	4	C
Lee and Ko (2007)	5	C
Masi et al. (2009)	10	C
Pantelides et al. (2002)	6	C
Scott (1996)	15	M
Tsonos (2007)	4	C
Wallace et al. (1998)	2	C

C cyclic loading, *M* monotonic loading

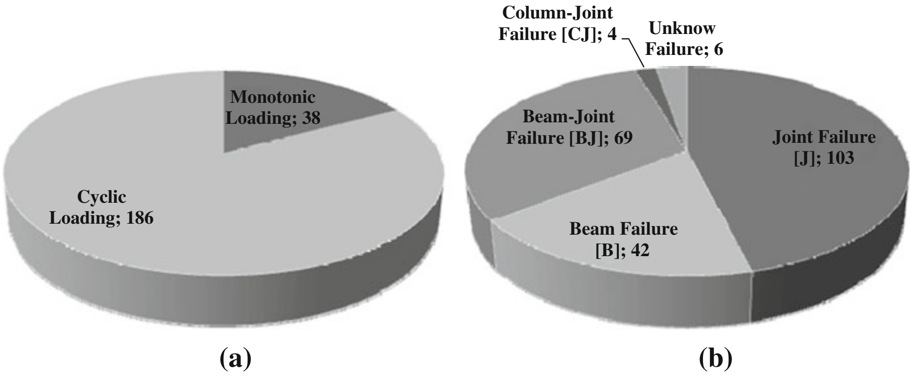


Fig. 1 Main features of the experimental results collected in the database. **a** loading protocol, **b** observed failure mode

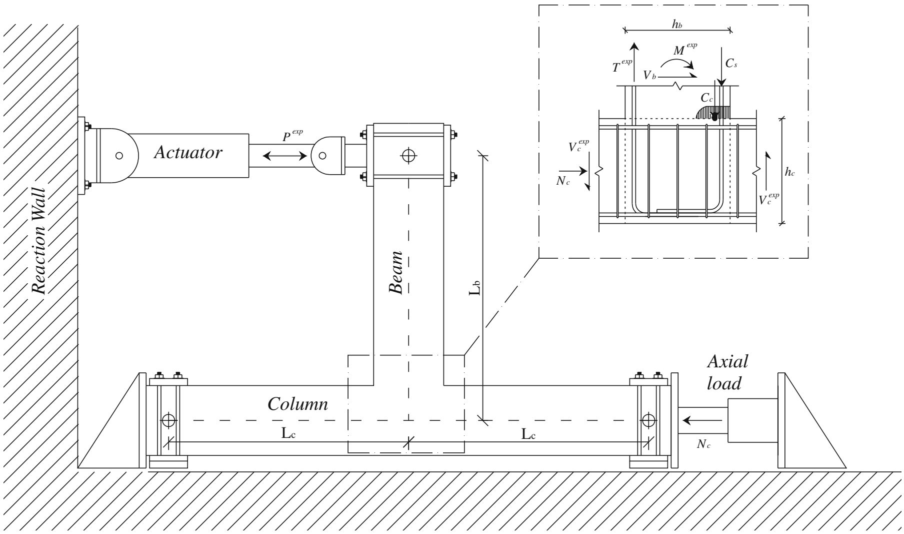


Fig. 2 Horizontal test configuration for exterior joints

The experimental value of shear strength V_{jh}^{exp} is evaluated as follows:

$$V_{jh}^{exp} = T^{exp} - V_{c}^{exp} \tag{1}$$

in which V_c^{exp} is the ultimate shear action applied at the top of the column and T^{exp} is the tensile force attained by beam rebars. If joint failure occurs before yielding in beam ($M^{exp} < M_y$), the force T^{exp} is simply evaluated as follows:

$$T^{exp} = \frac{M^{exp}}{M_y} \cdot A_{sb,sup} \cdot f_{yb} \tag{2}$$

If the beam reinforcement is yielded, but the ultimate flexural strength M_u is not achieved ($M_y \leq M^{exp} < M_u$), the tensile force T^{exp} developed in the bars in tension is evaluated through a linear interpolation between M_y and M_u:

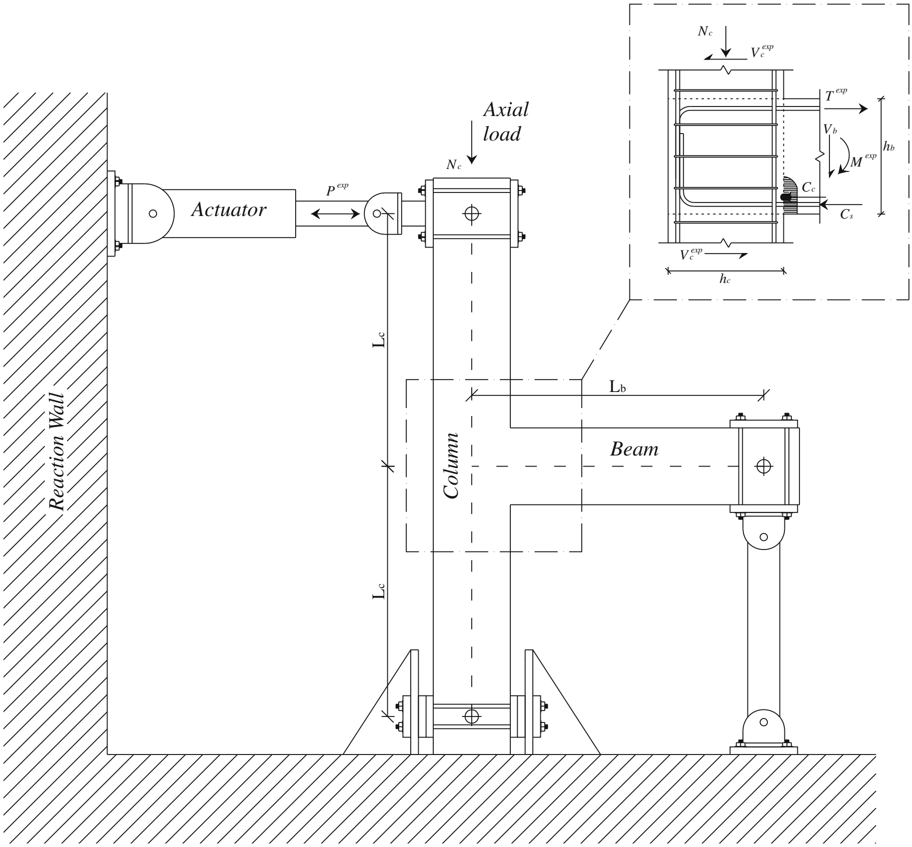


Fig. 3 Vertical test configuration for exterior joints

$$T^{exp} = A_{sb,sup} \cdot f_{yb} \left[1 + \frac{M^{exp} - M_y}{M_u - M_y} \cdot (\lambda - 1) \right] \tag{3}$$

Finally, if the beam fails before the joint failure ($M^{exp} = M_u$) the top reinforcement attains the maximum tension:

$$T^{exp} = A_{sb,sup} \cdot f_{yb} \cdot \lambda. \tag{4}$$

The resulting moment M^{exp} on the joint can be evaluated by equilibrium as a function of the force P^{exp} at the free end of the beam; the force P^{exp} in the case of horizontal test configuration (Fig. 2) is directly known by the test report. On the contrary, in the cases of vertical configuration (Fig. 3), P^{exp} can be evaluated by equilibrium starting from the shear force applied on the top column V_c^{exp}. Then, the bending moment M^{exp} acting on the joint is:

$$M^{exp} = P^{exp} \cdot L_b \tag{5}$$

in which the breadth of the panel zone ($h_c/2$) has been neglected, for taking into account the translation of bending moments due to the cracking effects (EN 1992-1 2005).

In this paper, the yielding and ultimate moments have been evaluated by assuming a bilinear elastic-plastic behaviour with ultimate strain $\varepsilon_{us} = 0.075$ for steel rebars and the parabola-rectangle constitutive law for concrete, assuming $\varepsilon_{cu} = 0.0035$ as ultimate strain.

2.2 Classification

A subset of 176 experimental results, out of the 224 collected in the above mentioned database, is considered in the following section, as they refer to failure modes controlled by the shear capacity of joints. Those data will be employed in the next section for assessing accuracy and reliability of the capacity models outlined in Lima et al. (2012). Since those models are partly or fully obtained through empirical calibrations on experimental data, it is reasonable to expect that their predictions are as accurate as they are applied to joints similar to the ones considered in their original calibration. Consequently, it is relevant for this study to assess the various models by considering not only the database as a whole, but possible relevant subsets of data corresponding to particular classes of joints.

Several possible classifications can be considered for RC joints. However, in the present study, the following three classes have been defined on the basis of the amount of transversal reinforcement actually present within the joint panel:

– EC8-compliant joints (EN 1998-3 2005);
– under-reinforced joints;
– unreinforced joints.

The first class collects the joints with an amount of transversal stirrups A_{sjh} which complies with EC8 provisions for RC frames in seismic areas:

$$A_{sjh} \geq A_{sjh,EC8} = \left[\frac{\left(\frac{V_{jh,E}}{b_j \cdot h_{jc}} \right)^2}{(f_{ctd} + v_d \cdot f_{cd})} - f_{ctd} \right] \cdot \frac{b_j \cdot h_{jb}}{f_{yj}} \tag{6}$$

The complete definition of the parameters in Eq. (6) is omitted herein for the sake of brevity and can be found in EN 1998-3 (2005). In particular, the shear stress in Eq. (6) $V_{jh,E}$ should be evaluated as follows:

$$V_{jh,E} = 1 \cdot 2 \cdot A_{sb,sup} \cdot f_{yb} - V_c^{exp} \tag{7}$$

where V_c^{exp} is the shear stress in the top column, which is related to the ultimate load P_u^{exp} and depends on the test layout. All joints whose amount of stirrups A_{sjh} is

$$0 < A_{sjh} < A_{sjh,EC8} \tag{8}$$

are considered as "under-reinforced", while no stirrups are present within "unreinforced" joints ($A_{sjh} = 0$).

Figure 4 shows how the 176 experimental data considered in the following sections are distributed in terms of both failure mode and reinforcement class.

3 Assessment of a set of capacity models available in the scientific literature

The present section focuses on assessing the ten capacity models for RC joints outlined in a companion paper (Lima et al. 2012). In particular, each one of the 176 values of shear strength V_{jh}^{exp} collected within the experimental database is compared with the corresponding theoretical prediction V_{jh}, determined by applying the above mentioned models.

Figures 5, 6, 7, 8, 9, 10, 11, 12, 13, 14 report the points of coordinates (V_{jh}^{exp}, V_{jh}) for the ten models considered in the present study. Those models can be deemed as accurate as the bunch of points reported within the above mentioned figures is close to the bisector

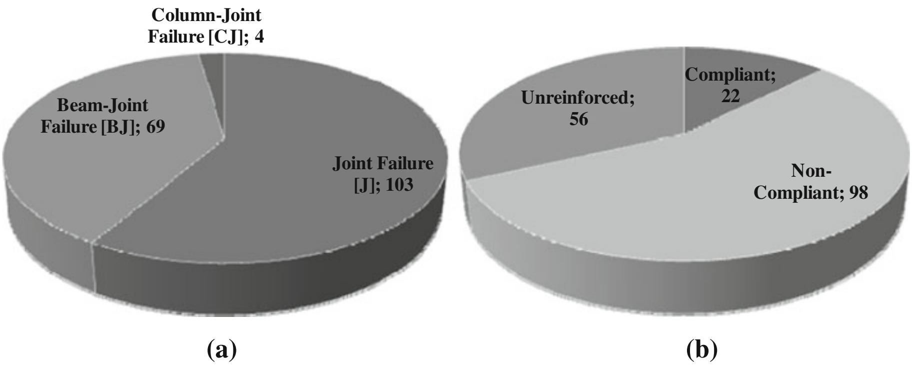


Fig. 4 Main features of the experimental results collected in the reduced database and employed for assessing the capacity models for RC shear strength. **a** loading protocol, **b** observed failure mode

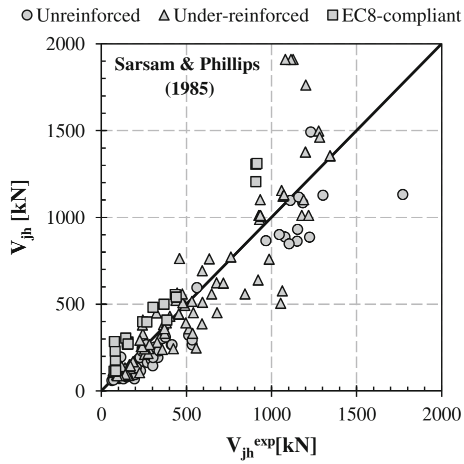


Fig. 5 Theoretical–experimental comparison: Sarsam and Phillips (1985)

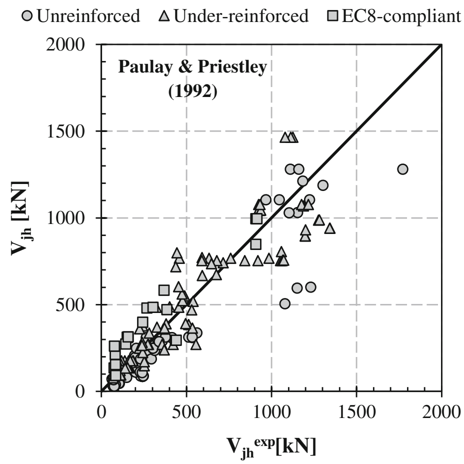


Fig. 6 Theoretical–experimental comparison: Paulay and Priestley (1992)

Fig. 7 Theoretical–experimental comparison: Scott et al. (1994)

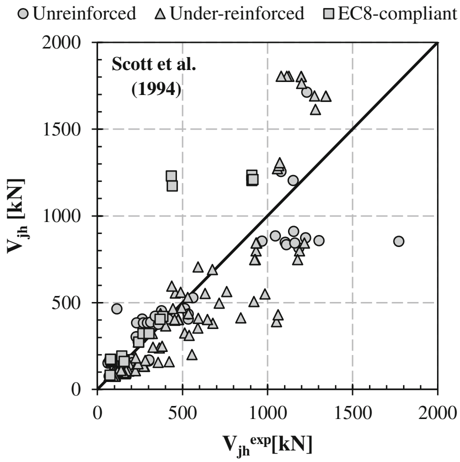


Fig. 8 Theoretical–experimental comparison: Parker and Bullman (1997)

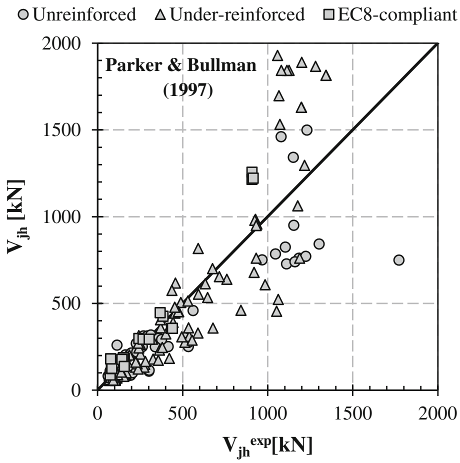


Fig. 9 Theoretical–experimental comparison: Vollum and Newman (1999)

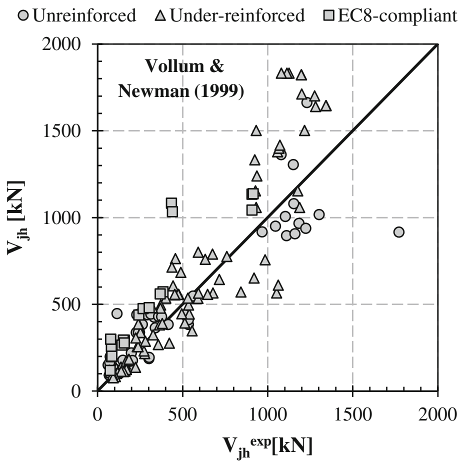


Fig. 10 Theoretical–experimental comparison: Bakir and Boduroglu (2002)

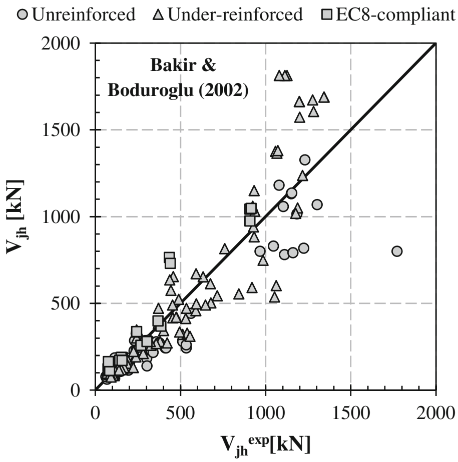


Fig. 11 Theoretical–experimental comparison: Parra-Montesinos and Wight (2002)

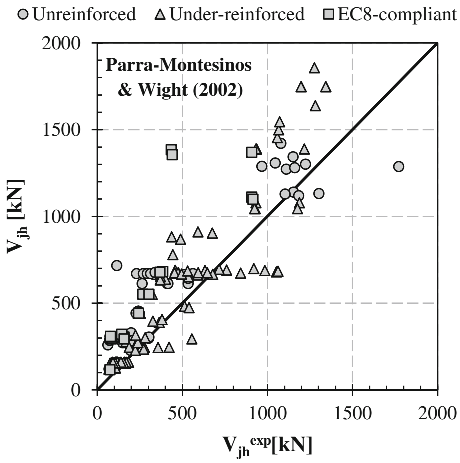
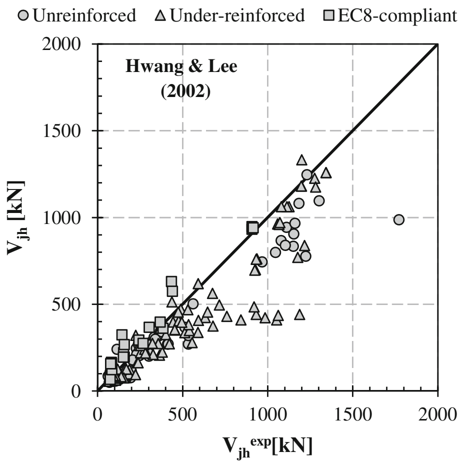


Fig. 12 Theoretical–experimental comparison: Hwang and Lee (2002)



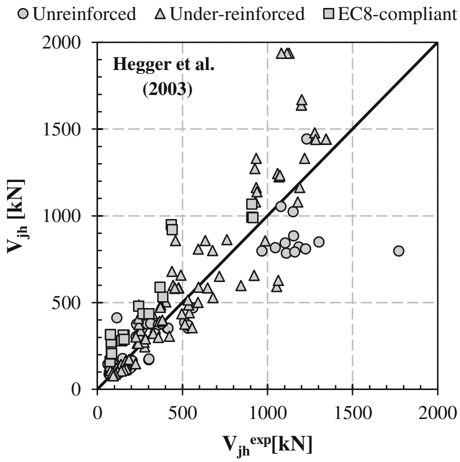


Fig. 13 Theoretical–experimental comparison: Hegger et al. (2003)

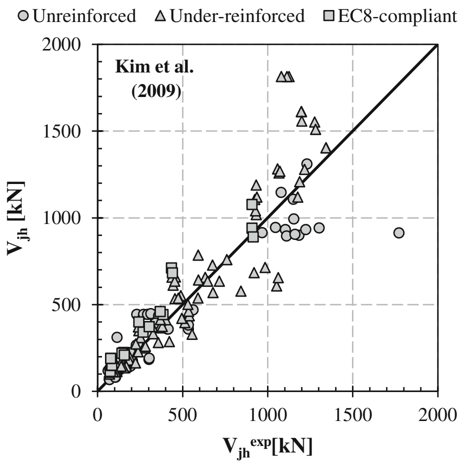


Fig. 14 Theoretical–experimental comparison: Kim et al. (2009)

segment. Moreover, they result in either conservative (i.e. $V_{jh} \leq V_{jh}^{exp}$) or non-conservative (i.e. $V_{jh} \geq V_{jh}^{exp}$) predictions as the points tend to be manly below or above such a segment, respectively.

Figure 5 shows the comparison between the experimental values of shear strength V_{jh}^{exp} and the corresponding theoretical prediction V_{jh} evaluated by applying the model by Sarsam and Phillips (1985). In the case of unreinforced joints, this model generally underestimates shear strength, as a huge number of points lies below the bisector segment. The model has a good predictive capacity in the case of under-reinforced joints, while it is often non-conservative for EC8-compliant ones (Fig. 5). Based on these comments the model tends to overestimate the stirrups contribution to the shear strength V_{jh} of RC joints.

Figure 6 shows the comparison between the theoretical prediction V_{jh} obtained by applying the model by Paulay and Priestley (1992) and the corresponding experimental values V_{jh}^{exp}. The former are in good agreement with the latter, as the points representing both unreinforced and under-reinforced joints are bunched together around the bisector segment. On the contrary, predictions of shear strength for EC8-compliant joints are often non-conservative.

The comparison shown in Fig. 7 between the experimental values V_{jh}^{exp} and the corresponding predictions evaluated through the model by Scott et al. (1994) demonstrates that it is not uniformly accurate. In particular, the model is rather accurate in the case of joints (either reinforced or not) characterised by relatively low values of shear strength, while it often results in non-conservative predictions in the case of reinforced joints (either EC8-compliant or not) with relatively high values of V_{jh}^{exp}. This non uniform level of accuracy for joints with relatively different values of shear strength is a clear consequence of the range of variation of the parameters considered by the Authors in the original calibration.

According to the results reported in Fig. 8, the model by Parker and Bullman (1997) generally underestimates shear strength for unreinforced joints leading to a conservative (though affected by a huge dispersion) prediction of their behaviour. Moreover, a lot of points are distributed around the bisector segment, even though the model tends to overestimate shear capacity in reinforced joints characterised by relatively high strength. However, the model is in good agreement with the experimental results obtained on EC8-compliant joints, while its predictions are less accurate for under-reinforced ones.

Figure 9 deals with the model by Vollum and Newman (1999). It shows that the model performs quite well for both unreinforced and under-reinforced joints, while non-conservative predictions can be observed for EC8-compliant ones.

Figure 10 refers to the model by Bakir and Boduroglu (2002) whose predictions result in good agreement with the experimental values. A slightly conservative trend is obtained for unreinforced joints, while shear strength predictions for under-reinforced and EC8-compliant joints are very accurate and affected by low dispersion.

Figure 11 examines the predictive capacity of the model by Parra-Montesinos and Wight (2002). As a matter of fact, it generally tends to overestimate shear strength, as the bunch of points is mainly grouped around the bisector segment. Moreover, the dispersion is very high and no relevant differences emerge in terms of predictive capacity for the three classes of joints defined in the present study.

Figure 12 deals with the model by Hwang and Lee (2002) whose predictions tends on average to underestimate the actual values of shear strength, as a huge number of points lies below the bisector segment. However, a substantial equivalence between the theoretical shear strength V_{jh} and the experimental evidence V_{jh}^{exp} can be observed for EC8-compliant joints, as a result of the original calibration of the model carried out for covering the case of reinforced RC joints in seismic areas.

Figure 13 reports the results obtained by applying the model by Hegger et al. (2003), whose performance is rather different in terms of predictive capacity of both unreinforced or reinforced joints. In particular, the model generally underestimates shear strength in unreinforced joints, especially in the case of relatively high strength. On the contrary, the theoretical prediction of shear strength for under-reinforced joints is much more accurate. However, the model is quite non-conservative (namely, it tends to overestimates shear strength) by considering EC8-compliant joints. Thus, Fig. 13 points out that the model under consideration tends to overestimate the steel stirrup contribution and underestimate the concrete one.

Figure 14 compares the model by Kim et al. (2009) and the corresponding experimental results. The graph shows a good correlation between theoretical predictions and experimental values for unreinforced, under-reinforced and EC8-compliant joints. A slightly non-conservative trend can be observed for EC8-compliant joints, as the theoretical prediction is often higher than the corresponding experimental values.

Finally, as a general comment, it can be observed that all models tend to overestimate the contribution of steel stirrups to shear strength in reinforced (either under-reinforced or EC8-compliant) joints. In fact, they lack in simulating that the beneficial effect of stirrups decreases by increasing the amount of horizontal reinforcement. Among the others, the model by Bakir and Boduroglu (2002) actually looks after this phenomenon by introducing a well calibrated reduction factor for the contribution of the horizontal reinforcement depending on the amount of steel stirrups (Lima et al. 2012).

3.1 Error measures and other relevant quantities

Some quantitative parameters can be introduced for "measuring" the accuracy of capacity models in predicting shear strength of RC joints. The so-called average quadratic error Δ is a simple parameter defined as follows:

$$\Delta = \sqrt{\frac{\sum_{i=1}^{n}\left[V_{jh,i}^{exp} - V_{jh,i}\right]^2}{n}} \tag{9}$$

where n is the total number of experimental results considered in the experimental-to-theoretical comparison. As a matter of principle, the lower the value of Δ, the more accurate is the model.

Moreover, the coefficient of determination R^2 gives a measure of the linear correlation which characterises the experimental results and is defined as follows:

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(V_{jh,i}^{exp} - \overline{V_{jh}^{exp}}\right)\cdot\left(V_{jh,i} - \overline{V_{jh}}\right)\right]^2}{\sum_{i=1}^{n}\left(V_{jh,i}^{exp} - \overline{V_{jh}^{exp}}\right)^2\cdot\sum_{i=1}^{n}\left(V_{jh,i} - \overline{V_{jh}}\right)^2} \tag{10}$$

where $\overline{V_{jh}^{exp}}$ and $\overline{V_{jh}}$ are the average values of experimental and theoretical shear strength, respectively.

However, neither Δ nor R^2 can discriminate whether a model tends to over- or underestimate shear capacity. Thus, the distribution of the ratio x_i between experimental V_{jh}^{exp} and theoretical V_{jh} values has been studied:

$$x_i = \frac{V_{jh,i}^{exp}}{V_{jh,i}} \tag{11}$$

and its relevant statistical parameters (i.e., mean value μ and standard deviation σ) have been quantified.

Finally, the following reliability factor β_C has been determined as the standard deviation of the natural logarithm of the ratios x_i (Pinto et al. 2004):

$$\beta_C = \sigma\left(\ln x_i\right). \tag{12}$$

This parameter can be directly employed for performing simplified reliability analyses covering the uncertainties which affect the models adopted for describing shear capacity of RC joints (Cornell et al. 2002).

Table 2 reports some of the above mentioned parameters (i.e., the average quadratic error Δ, the coefficient of determination R^2, the reliability index β_C and the average of V_{jh}^{exp}/V_{jh} ratios) evaluated on the experimental results collected into the database as a whole. The numerical results show that the models by Hwang and Lee (2002) and Kim et al. (2009) lead to the higher correlation. Moreover, the latter is characterised by the lower value of β_C. The model by Paulay and Priestley (1992) results in the lower average error.

Table 3 reports the same parameters listed in Table 2, though determined for the three subclasses of joints defined in terms of amount of stirrups in the joint panel. Regarding unreinforced joints, the models by Sarsam and Phillips (1985) and Hwang and Lee (2002) lead

Table 2 Average quadratic errors, correlation factors and reliability capacity factors

Model	Database as a whole			
	Δ[kN]	R^2	β_C	μ
Sarsam and Phillips (1985)	183.80	0.820	0.385	1.106
Paulay and Priestley (1992)	165.72	0.829	0.433	1.166
Scott et al. (1994)	236.30	0.724	0.417	1.133
Parker and Bullman (1997)	247.64	0.749	0.389	1.230
Vollum and Newman (1999)	222.23	0.797	0.385	0.898
Bakir and Boduroglu (2002)	191.76	0.815	0.310	1.085
Parra-Montesinos and Wight (2002)	288.76	0.781	0.413	0.738
Hwang and Lee (2002)	177.13	0.857	0.352	1.280
Hegger et al. (2003)	212.76	0.766	0.401	0.940
Kim et al. (2009)	172.25	0.837	0.293	0.939

to the highest correlation. Moreover, the model by Kim et al. (2009) leads to the highest correlation for the case of under-reinforced joints. Furthermore, for EC8-compliant ones, the model by Sarsam and Phillips (1985) leads to the higher correlation, while the model by Hwang and Lee (2002) results in the lower average error. In terms of reliability measure, the model by Kim et al. (2009) outperforms for under-reinforced joints, while the model by Bakir and Boduroglu (2002) is slightly more reliable for EC8-compliant one.

4 Recalibration of the available capacity models

A series of key statistical parameters have been reported in Tables 2 and 3 for outlining the results of the assessment procedure described in the previous section.

The models under consideration are often characterised by rather high coefficient of determination: Table 3 shows several values of R^2 rather close to the unit. For instance, both models by Sarsam and Phillips (1985) and Hwang and Lee (2002) lead to very high values of R^2 (0.929 and 0.949, respectively, as one can see in the second column of Table 3) for unreinforced joints. This means that their predictions are in very good correlation with experimental results. In fact, Figs. 5 and 12 shows that the corresponding points (those represented by circles) are bunched up an ideal segment which is in both cases below the bisector one. In other words, although the two mentioned models are in good correlation they tend to underestimate the experimental values of shear strength, as Table 3 confirms in terms of experimental-to-theoretical ratio, whose average value μ is in both cases higher than the unit (namely, 1.369 and 1.293, respectively). Thus, the predictive capacity of both models can be easily enhanced by means of a possible recalibration simply based on a linear scaling of the relationship V_{jh} proposed by the various models

$$V_{jh,rec,i} = \overline{\alpha} \cdot V_{jh,i} \tag{13}$$

through a factor $\overline{\alpha}$ selected by performing the following least square procedure:

Table 3 Average quadratic errors, correlation factors and reliability capacity factors

Model	Unreinforced				Under-reinforced				EC8-Compliant			
	Δ[kN]	R^2	β_C	μ	Δ[kN]	R^2	β_C	x_{av}	Δ[kN]	R^2	β_C	μ
Sarsam and Phillips (1985)	152.81	0.924	0.278	1.369	199.93	0.824	0.306	1.067	181.05	0.966	0.326	0.614
Paulay and Priestley (1992)	182.11	0.871	0.386	1.606	161.41	0.829	0.286	1.018	138.36	0.860	0.439	0.706
Scott et al. (1994)	201.28	0.789	0.414	1.027	248.64	0.768	0.354	1.287	261.13	0.808	0.336	0.718
Parker and Bullman (1997)	226.57	0.767	0.382	1.287	277.54	0.805	0.368	1.290	129.72	0.953	0.288	0.815
Vollum and Newman (1999)	181.40	0.822	0.400	0.931	236.99	0.856	0.290	0.960	247.25	0.842	0.344	0.533
Bakir and Boduroglu (2002)	186.77	0.857	0.297	1.224	208.12	0.852	0.281	1.075	111.55	0.934	0.249	0.777
Parra-Montesinos and Wight (2002)	251.09	0.824	0.441	0.662	291.88	0.819	0.299	0.841	256.47	0.727	0.382	0.474
Hwang and Lee (2002)	170.11	0.929	0.315	1.293	195.69	0.837	0.291	1.389	82.23	0.961	0.281	0.762
Hegger et al. (2003)	205.02	0.829	0.416	1.064	216.57	0.847	0.286	0.960	214.99	0.861	0.370	0.537
Kim et al. (2009)	166.13	0.882	0.327	1.014	186.04	0.871	0.235	0.954	133.66	0.946	0.253	0.683

Table 4 Recalibration factors and average quadratic errors of the recalibrated models

Model	Database as a whole			Unreinforced			Under-reinforced			EC8-Compliant		
	α	Δ[kN]	μ	α	Δ[kN]	μ	α	Δ[kN]	μ	α	Δ[kN]	μ
Sarsam and Phillips (1985)	0.924	177.28	1.197	1.168	124.40	1.172	0.880	180.74	1.213	0.698	56.73	0.880
Paulay and Priestley (1992)	1.027	164.97	1.135	1.130	168.23	1.421	1.009	161.39	1.009	0.827	112.73	0.853
Scott et al. (1994)	0.887	224.74	1.277	1.081	196.21	0.950	0.864	229.42	1.489	0.623	122.25	1.153
Parker and Bullman (1997)	0.854	227.18	1.441	1.163	210.65	1.106	0.785	221.30	1.644	0.776	61.59	1.050
Vollum and Newman (1999)	0.822	182.09	1.091	1.013	181.23	0.919	0.786	163.60	1.222	0.637	115.22	0.836
Bakir and Boduroglu (2002)	0.912	183.17	1.190	1.177	162.75	1.040	0.847	174.68	1.270	0.820	70.18	0.948
Parra-Montesinos and Wight (2002)	0.727	185.73	1.015	0.787	191.08	0.841	0.729	176.63	1.153	0.534	143.25	0.887
Hwang and Lee (2002)	1.178	152.17	1.086	1.257	113.69	1.029	1.187	168.96	1.171	0.885	64.24	0.861
Hegger et al. (2003)	0.872	194.64	1.078	1.193	180.26	0.892	0.816	163.68	1.176	0.681	118.27	0.788
Kim et al. (2009)	0.910	161.79	1.032	1.129	150.71	0.898	0.851	149.76	1.121	0.822	74.93	0.832

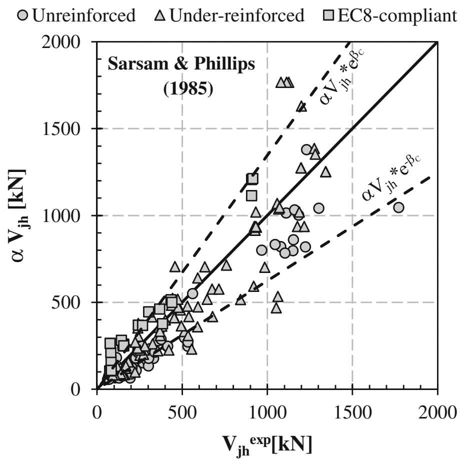


Fig. 15 Assessment of the recalibrated models: Sarsam and Phillips (1985)

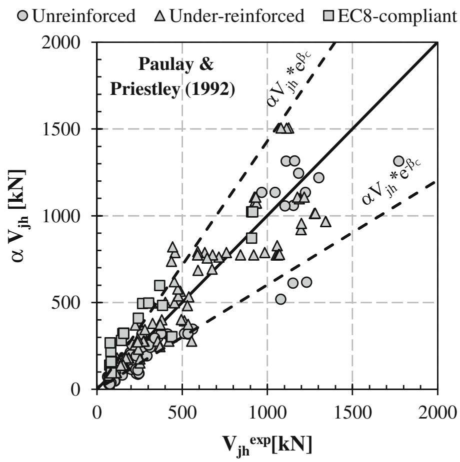


Fig. 16 Assessment of the recalibrated models: Paulay and Priestley (1992)

$$\overline{\alpha} = \arg\min_{\alpha} \left[\sqrt{\frac{\sum_{i=1}^{n} \left(\alpha \cdot V_{jh,i} - V_{jh,i}^{exp}\right)^2}{n}} \right] = \arg\min_{\alpha} \left[\Delta\left(\alpha\right)\right] \quad (14)$$

As a matter of principle, $\overline{\alpha} \leq 1$ means that the original model generally leads non-conservative predictions (or, in other words, it overestimates shear strength), and vice versa.

Table 4 shows the results in terms of $\overline{\alpha}$ and Δ for the various models after recalibration. It is worth to note that linear scaling [Eq. (14)] does not affect neither the correlation factor R^2 nor the reliability index β_C: thus, they are not reported in Table 4, but can be read in Table 3 for all models and joint classes.

Figures 15, 16, 17, 18, 19, 20, 21 show the comparisons between the experimental values of the shear strength V_{jh}^{exp} (on the x-axis) and the corresponding theoretical predictions V_{jh} (on the y-axis) derived by applying the recalibrated models. The same figures also report the

Fig. 17 Assessment of the recalibrated models: Bakir and Boduroglu (2002)

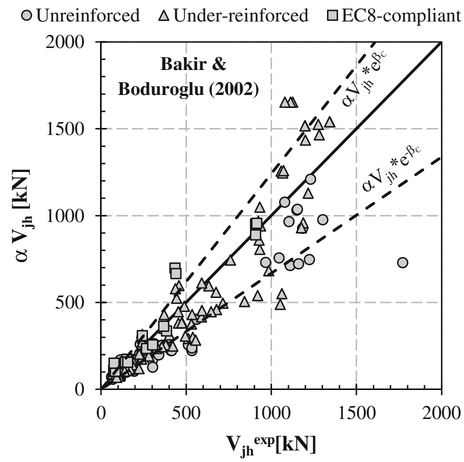


Fig. 18 Assessment of the recalibrated models: Hwang and Lee (2002)

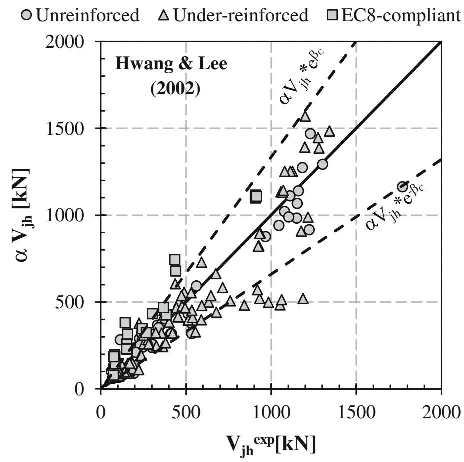
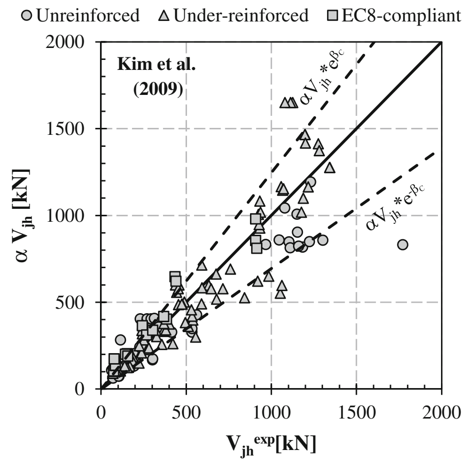
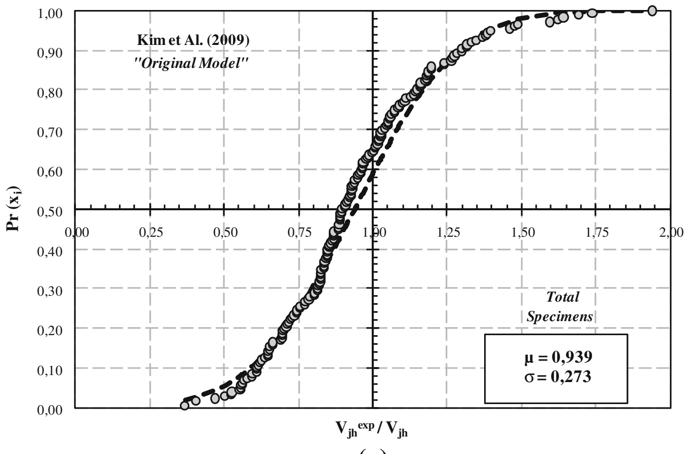


Fig. 19 Assessment of the recalibrated models: Kim et al. (2009)





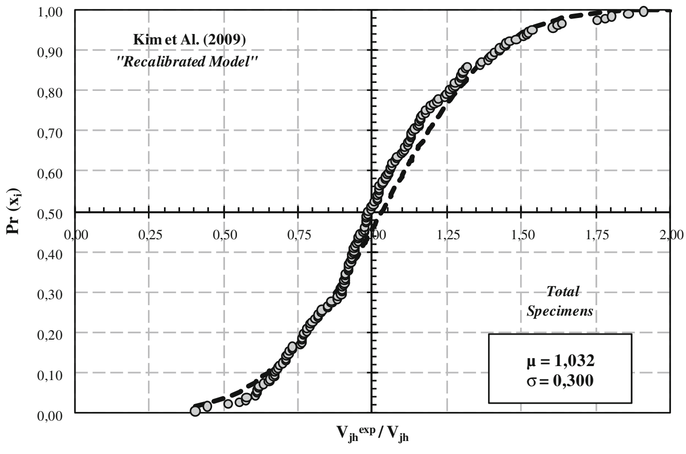


Fig. 20 Probabilistic assessment of the model by Kim et al. (2009) for total specimens. **a** Original formulation. **b** Recalibrated model

equivalence segment, and the lines corresponding to 16 and 84% percentiles evaluated by considering the reliability index β_C obtained by considering the database as a whole.

In Figs. 15 and 16 the assessment of the recalibrated models by Sarsam and Phillips (1985) and Paulay and Priestley (1992) are shown, respectively. They confirm the accuracy both models after their recalibration, as a significant number of points is close to the equivalence segment. In particular, the former is more accurate than the latter, as plenty of points are close to the equivalence in Fig. 15.

Figures 15, 16, 17, 18, 19 show the comparisons of the outperforming recalibrated models (namely, those characterised by the higher values of R^2). They confirm the good results obtained through the linear recalibration and the accuracy of the models whose predictions are as closer to the corresponding experimental results as the points are closer to the bisector segment.

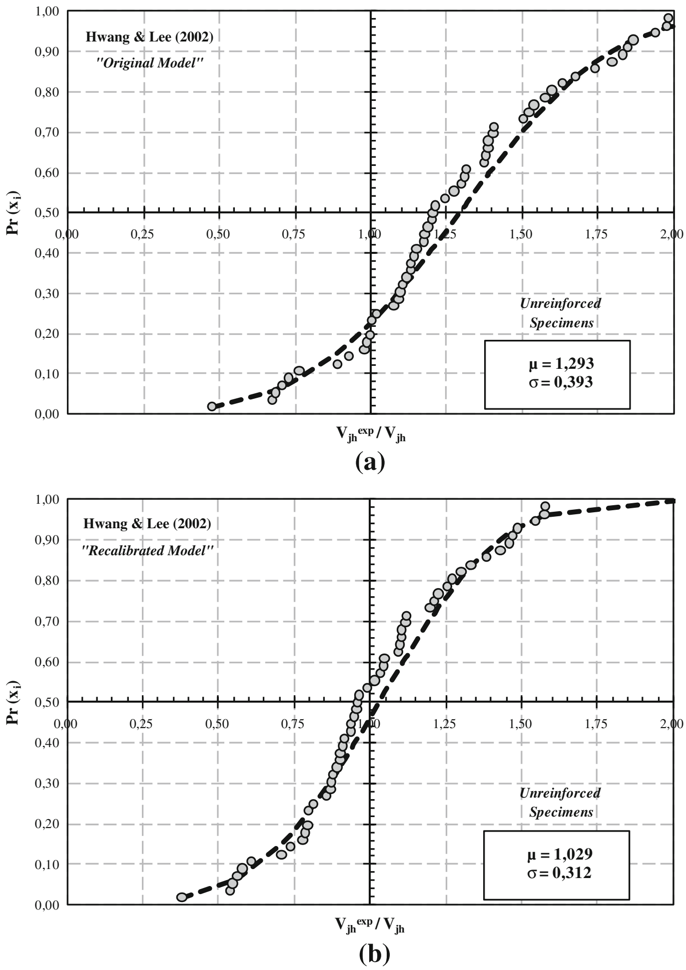


Fig. 21 Probabilistic assessment of the model by Hwang and Lee (2002) for unreinforced joints. **a** Original formulation. **b** Recalibrated model

Further representations about the probabilistic description of the model accuracy can be made. A simple one is the cumulative distribution of the experimental-to-theoretical ratios V_{jh}^{exp}/V_{jh}. Figure 20 shows the distribution obtained by applying the model by Kim et al. (2009) to all the experimental results collected within the database. In particular, Fig. 20a reports the distribution for the original model, while Fig. 20b refers to the recalibrated one. The original model tends to overestimate the experimental results, as the mean value μ is equal to 0.936 (on the x-axis). However, the average value of the distribution of V_{jh}^{exp}/V_{jh} is much closer to the unit (namely, it is 1.032) for the recalibrated model.

In Fig. 21 the same probabilistic assessment is proposed the model by Hwang and Lee (2002) for unreinforced joints only. Recalibration results in a similar effect by moving the average value of V_{jh}^{exp}/V_{jh} rather closer to the unit.

Thus, the two above mentioned models can be utilised for calibrating consistent formulae for either designing joints in new structures or assessing their vulnerability in existing buildings (EN 1990 2002).

Finally, the same probabilistic assessment has been carried out for the other models (both before and after recalibration), but their graphical representations are omitted herein for sake of brevity.

5 Conclusions

This paper reports a detailed research about the assessment of existing models for evaluating shear strength of RC joints. The examination of various theoretical models currently available in the scientific literature (and outlined in Lima et al. 2012) pointed out that they generally lead to even significantly different predictions, as they have been originally calibrated on a rather limited number of experimental results.

Therefore, a large collection of experimental data has been assembled for assessing those models. Various relevant parameters have been determined for checking the predictive capacity of those models by considering both experimental database as a whole and three relevant subclasses of joints ideally concerned with different design criteria and realised with different amount of reinforcement.

The results of this study lead to a possible ranking of the mentioned capacity models, even depending on the particular class of RC joints under consideration. Moreover, as far as vulnerability assessment is of concern, the values of a well-known reliability index have been determined for each one of the capacity models covered by the present study. They are now available to structural engineers interested in carrying out simplified analyses for quantifying seismic reliability of existing concrete structures.

Finally, the capacity models have been also recalibrated for enhancing their predictive capacity. A simple linear scaling has been adopted for reducing the bias of their predictions, though generally characterised by rather high correlation with respect to the corresponding experimental results.

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