DESIGN EQUATIONS FOR ULTIMATE SHEAR CAPACITY OF REINFORCED CONCRETE WALLS

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Abstract

Reinforced concrete (RC) walls are key elements for earthquake resistant structures. Low aspect shear ratio RC walls tend to fail in shear prior to yielding of the flexural reinforcement; hence the correct estimation of their ultimate shear capacity is of major importance for both design and assessment. No general consensus on the prediction of peak shear strength of RC walls has been reached, which is demonstrated by the totally different approaches adopted by the existing relevant code provisions. Based on an assembled database of 414 RC walls with rectangular and barbell/flanged cross sections that have been reported to fail in shear, the performance of 15 existing design models (i.e. 9 code provisions, 5 models from the literature, and 1 model recently proposed by the authors), regarding their adequacy to predict the ultimate RC wall shear capacity, has been assessed. It resulted that generally better performance is achieved by empirical models which consider a broader number of variables, rather than by purely mechanical models, the applicability of which is restricted within specific range of the individual parameters. Furthermore, although the exact shape of the wall cross section, i.e. rectangular, barbell or flanged, is known to affect shear strength, only very few models consider this characteristic in their equations. Another important conclusion drawn is that the available models from codes and guidelines have been generally developed for the design of new RC walls and presuppose that the amount of reinforcement falls in the ranges established by the modern codes. Therefore, they are inappropriate for the assessment of peak shear strength of existing RC walls that have been designed according to older principles of practice which do not comply with code-prescribed reinforcement detailing for new walls. Among the design models considered the best predictive performance is obtained by the proposed model, which is applicable to all types of wall cross-section without any restrictions in the range of design parameters. It is recommended, therefore, for the assessment of the ultimate shear capacity of existing RC walls for which the existing predictive equations are in general not appropriate. Finally, among the code provisions studied, the provisions of the Architectural Institute of Japan (2016) proved to better comply with the experimental results of the RC walls in the database.

Keywords: reinforced concrete; shear walls; shear strength; assessment; rectangular and barbell walls

1. Introduction

Because of the increased stiffness of reinforced concrete (RC) walls compared to RC columns, the seismic resistance of RC walls is of utmost importance for the structural integrity of RC buildings subjected to an earthquake, especially in older structures which were not designed according to modern code principles. Therefore, reliable calculation of the ultimate shear capacity of RC walls is essential to assess the seismic resistance of existing RC buildings. Considerable relevant research has been carried out since 1960's [1, 2] and numerous design models have been proposed. However, the predictive equations for ultimate shear capacity of RC walls in current building codes, standards of practice, and guidelines vary both in functional form and in the number of parameters they consider, and often predict considerably different values of shear capacity. This indicates that no generally accepted model is yet available.

A database of 414 RC walls reported to fail in shear, consisting of 129 rectangular (R), 222 barbell (B), and 63 flanged (F) walls has been assembled. The database comprises specimens from existing databases [3, 4] to which 108 new RC walls were added, and has been used to develop an empirical model, henceforth referred as "model", that predicts the ultimate shear capacity of RC walls. 9 design code provisions, 5 models from the literature, and the proposed model have been assessed regarding their competence to predict the ultimate shear capacity of the RC walls of the database. The assembled database as well as details on the proposed model can be found in a companion paper [5].

2. Predictive equations for ultimate shear capacity of RC walls

RC walls that fail in shear prior to flexure have in general low value of aspect ratio, which is expressed either by the ratio, H_w/L_w, of the wall height, H_w, to the length, L_w, of the cross section, or by the shear span ratio M/VL_w which is equal to H_o/L_w or $H_o/2L_w$ for walls loaded as cantilevers or as double fixed, respectively (H_o is the distance between the shear force and the wall base, see Fig.1). In RC structural elements with low aspect ratio a large portion of the shear force is transferred through a diagonal concrete strut along the main diagonal (Fig.1), while in case of high aspect ratios the shear force is mainly transferred through a truss mechanism consisting of the longitudinal reinforcement, the web reinforcement parallel to the shear force and the inclined concrete struts. For elements with intermediate aspect ratios both mechanisms are supposed to contribute to shear resistance. In shear models based on a truss mechanism the ultimate shear capacity is determined by the minimum value between (a) the shear force that causes yielding of all web reinforcement parallel to the shear force and crossed by a possible inclined crack (V_s), and (b) the shear force that results in compressive failure of diagonal concrete struts included in the truss (max V_u).

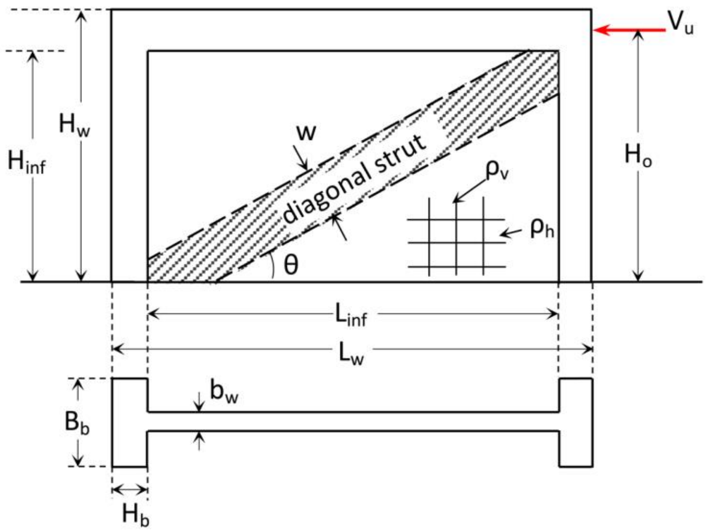

Fig. 1 – Symbols used for the characteristics of reinforced concrete walls

Table 1 – Parameters and limitations of the models

Models	**Cross section**		**Parameters considered in the model**						**Limitations of model**
	R	**B/F**	**ρ_h**	**ρ_v**	**ρ_{be}**	**N**	**B.E.**	**max V_u**	
Model [5]	√	√	√	√	√	√	√		
AIJ2016 [12]	√	√	√		√	√	√		$\rho_{be} > 0$, $\rho_h > 0$
AIJ2004 [10]	√	√	√				√		$\rho_{be} > 0$, $\rho_h > 0$
ASCE43-05 [15]		√	√	√		√		√	$H_w/L_w \leq 2$, $\rho_{be} > 0$
ACI318-14 Ch11 [6]	√	√	√			√		√	$\rho_{be} > 0$, $\rho_h > 0$
ACI318-14 Ch18 [6]	√	√	√					√	$\rho_{be} > 0$, $\rho_h > 0$
EN1998-1 DCM [7]	√	√	√					√	$\rho_{be} > 0$, $\rho_h > 0$
EN1998-1 DCH [7]	√	√	√	√	√	√		√	$\rho_{be} > 0$, $\rho_h > 0$, $\rho_v > 0$
EN 1998-3 [13]	√	√	√	√	√	√		√	
CSA A23.3.14 [8]	√	√	√					√	$\rho_{be} > 0$, $\rho_h > 0$, $\rho_v > 0$
Gulec and Whittaker [16]	√	√		√	√	√	√	√	$0.25 \leq H_w/L_w \leq 1$ $\nu \leq 0.14$ $\rho_h f_{yh} \leq 5.8$ MPa $\rho_v f_{yh} \leq 12.8$ MPa $\rho_{be,tot}\, f_{ybe} \leq 14.1$ MPa 13.7 MPa $\leq f'_c \leq$ 51 MPa cantilever test fixture
Barda (1997) [14]		√		√		√			$\rho_{be} > 0$
Wood (1990) [17]	√	√		√	√			√	ρ_{be} or $\rho_v > 0$
Krolicki et al. [11]	√	√	√			√			$\rho_{be} > 0$, $\rho_h > 0$
Kassem [9]	√	√	√	√		√		√	$\rho_{be} > 0$, $\rho_h > 0$, $\rho_v > 0$

R model applicable to Rectangular cross-section
B/F model applicable to Barbell/Flanged cross-section
ρ_h, ρ_v, ρ_{be} contribution of horizontal web-, vertical web-, longitudinal boundary element-reinforcement
N contribution of axial force
B.E. geometry of Boundary Elements considered by the model
max V_u upper limit for ultimate shear capacity

Although ultimate shear capacity of low aspect ratio RC walls is not likely to be determined by a truss mechanism, it is interesting to observe that many design models propose a truss based model to calculated the peak shear strength of RC walls, and also include an upper limit of shear capacity, max V_u, to safeguard against crushing of the concrete strut. The models studied in this paper that fall in this category are: ACI318-14 Chapter 11 [6], ACI318-14 Chapter 18 [6] for earthquake resistant structures, EN1998-1 DCM (Medium Ductility level) [7], EN1998-1 DCH (High Ductility level) [7], CSA A23.3.14 [8], and the model of Kassem

[9] which includes two strut-and-tie models consisting of the vertical and of the horizontal web reinforcement. It is noted that EN1998-1 [7] calculates the shear capacity using a truss mechanism formed for inclined cracks at an angle, θ, determined in such a way that the shear force carried by web reinforcement parallel to the shear force is equal to the resistance in compression of the concrete struts, assuming $0.4 \leq \tan\theta \leq 1$ for medium level of ductility (DCM), and $\tan\theta=1$ for high level of ductility (DCH).

The superposition of an arch mechanism (diagonal strut) and a truss mechanism is adopted by AIJ2004 [10] and by Krolicki et al. [11]. AIJ2004 model, based on the AIJ1999 Guidelines, requires enough longitudinal reinforcement in the boundary elements so that the arch mechanism may be fully activated.

Empirically derived models based on experimental data presented in this paper are AIJ2016 [12], EN1998-3 [13], Barda et al. [14], ASCE43-05 [15] (derived from [14]), Gulec and Whittaker [4, 16], and the model proposed by the authors [5]. The model of Wood [17] is based on shear friction resistance along the base of the RC wall (hence considers only the contribution of the total RC wall vertical reinforcement) and introduces a lower and an upper limit for shear resistance.

Table 1 displays the wall characteristics each model considers and the limitations of the models' applicability. It may be observed that the models that endorse the truss load bearing mechanism include the contribution of the horizontal wall web reinforcement only, and not that of the vertical web reinforcement. An upper limit, max V_u, for peak shear strength is included in all truss-based models and also in several other models with the intention to ensure safe predictions for the RC walls of the database from which they were derived (ASCE43-05 [15], Gulec and Whittaker [16], Kassem [9], Wood [17]).

Most existing design models are equally applicable to all types of cross section, although it has been experimentally verified that barbell and flanged RC walls have increased peak shear strength compared to otherwise similar walls with rectangular cross section. The effect of the shape of the cross section is indirectly considered in AIJ2004 [10] and AIJ2016 [12] which calculate an equivalent cross section for barbell/flanged cross sections. Kassem [9] proposes different sets of equations for rectangular and barbell/flanged cross sections, while Gulec and Whittaker [16] apply different equations for barbell/flanged walls only if $A_t/A_w \geq 1.25$, where A_t is the total area of the wall cross section, and $A_w=L_w b_w$ (Fig.1), and also introduce un upper limit for the width of flanges, B_b, equal to $H_w/2$. The proposed model is the only one that reckons the exact shape of the wall cross section at calculating the strut width, w, using an equation for infilled frames first proposed by Mainstone [18] and adopted by FEMA 306 [19] and ASCE41-06 [20], which considers the relative stiffness of infill and the frame columns. The good performance of the proposed model is partly attributed to linking the strut width w to the shape of the RC wall boundary elements, which results in increased w for larger boundary elements, as it has been experimentally observed. The issue is of importance because the strut contributes significantly in shear capacity of RC walls with low aspect ratio.

3. Ultimate shear capacity of RC walls

3.1 Performance evaluation of the models

The reliability of the models is assessed by three statistical indices that demonstrate the scatter between predicted (V_{mod}) and experimental (V_{exp}) ultimate shear capacity: (a) coefficient of variation (COV) of the ratio V_{mod}/V_{exp}, equal to the ratio of standard deviation to the mean value of the ratios (STDEV/MEAN), (b) the average absolute error (AAE) calculated by Eq. (1) [21], and (c) the average overestimation of predicted versus measured ultimate shear capacity, i.e. $\overline{\Delta}=\left(\sum_{i=1}^{N}\Delta_i\right)/N\times 100$, where $\Delta_i=[(V_{exp,i}-V_{mod,i})/V_{exp,i}] < 0$.

$$AAE=\frac{\sum_{i=1}^{N}\frac{\left|V_{mod,i}-V_{exp,i}\right|}{V_{exp,i}}}{N}\times 100 \tag{1}$$

Table 2 summarizes the performance of the models for the ratios of predicted-to-experimental ultimate shear capacity, V_{mod}/V_{exp}, separately for each type of wall cross section. The number of specimens on which each model is applied taking into account the respective limitations is designated by "test data". The results for the models ASCE43-05 [15] and Barda et al. [14] on rectangular walls (for which the models are not applicable) are shown in italics. Evaluation of the predictive performance of the models is attempted in the following section.

Table 2 – Statistics for the ratios V_{mod}/V_{exp}, for the RC walls of the database

Equations for peak shear strength	**Rectangular cross section**				**Barbell / Flanged cross section**			
	Test data	**COV**	**AAE (%)**	**$\bar{\Delta}$<0 (%)**	**Test data**	**COV**	**AAE (%)**	**$\bar{\Delta}$<0 (%)**
Proposed model [5]	129	0.164	15.7	7.2	285	0.218	19.6	12.3
AIJ2016 [12]	97	0.250	19.8	21.5	274	0.223	18.4	15.7
AIJ2004 (AIJ1999 Guidelines) [10]	97	0.383	67.1	69.7	274	0.301	29.9	36.9
ASCE43-05 [15]	*107*	*0.353*	*26.5*	*29.5*	285	0.270	30.0	13.7
ACI318-14 Chapter 11 [6]	97	0.385	28.8	40.4	274	0.302	41.2	13.5
ACI318-14 Chapter 18 [6]	97	0.404	29.7	37.9	274	0.326	33.8	4.1
EN1998-1 DCM [7]	97	0.491	43.1	59.4	274	0.374	28.5	22.8
EN1998-1 DCH [7]	92	0.468	42.9	22.6	273	0.389	62.6	0
EN1998-3 [13]	129	0.419	56.7	0	285	0.407	64.8	0
CSA A23.3.14 [8]	92	0.598	47.6	41.8	273	0.514	55.8	28.1
Gulec and Whittaker [16]	69	0.228	28.0	12.0	214	0.271	23.0	16.4
Barda et al. [14]	*107*	*0.356*	*34.3*	*41.1*	285	0.275	21.7	19.8
Wood [17]	129	0.288	22.6	24.7	285	0.306	42.4	5.8
Krolicki et al. [11]	97	0.353	49.7	54.8	274	0.391	36.2	42.6
Kassem [9]	92	0.289	31.1	24.6	273	0.389	78.5	80.8

3.2 Discussion on the predictive performance of the models

The results displayed in Table 2 indicate that the proposed model leads to better overall predictions of ultimate shear capacity for both types of wall cross section. Among the codes that have been studied, better predictions are obtained from AIJ2016 [12]. It is noted that all predictions of EN1998-1 DCH [7] and EN1998-3 [13] are on the safe side ($V_{mod} < V_{exp}$) because they calculate the residual shear capacity for ductile behavior which is lower than the actual maximum shear strength observed; however, the predictions of both codes result in very large scatter and, therefore, are not reliable.

In order to demonstrate some issues pertaining to the associated performance of the models, eight specimens of relatively larger scale have been selected from the database and are depicted in Figs.2 to 9. On each figure the measured ultimate shear capacity, V_{exp}, is shown with dashed line, while the predictions of the models are presented in bar charts, with the contribution of each load bearing mechanism shown separately. In AIJ2016 [12] the strut includes the contribution of the longitudinal reinforcement in the boundary elements. When a model's prediction of shear capacity is determined by an upper (or lower) limit, usually related to the compressive strength of concrete, it is indicated by max V_u (or min V_c) under the name of the model. On each figure are indicated the most significant wall characteristics, i.e. the geometrical properties of the walls (height, H_w, total length of cross section, L_w, web width, b_w, boundary element width, B_b), the shear arm ratio M/VL_w, the compressive strength of concrete, fc', the axial load ratio $\nu=N/A_{cw}f'_c$ and the geometrical percentage of horizontal web-, vertical web- and boundary element- reinforcement, ρ_h, ρ_v and ρ_{be}, respectively (A_{cw}=total area of wall cross section).

It is interesting to notice that different models may result in comparable predictions of the ultimate shear capacity, V_u. For example, for specimen S3 [22] with rectangular cross section shown in Fig. 2, AIJ2016 [12], EN1998-1 DCM (EC8-DCM) [7], Wood [17], and the proposed model [5] predict similar values of V_u. However, the models differ considerably both in the concept on which they are based and in respect to the RC wall characteristics they consider. Similarity in models' predictions should be rather attributed to coincidence.

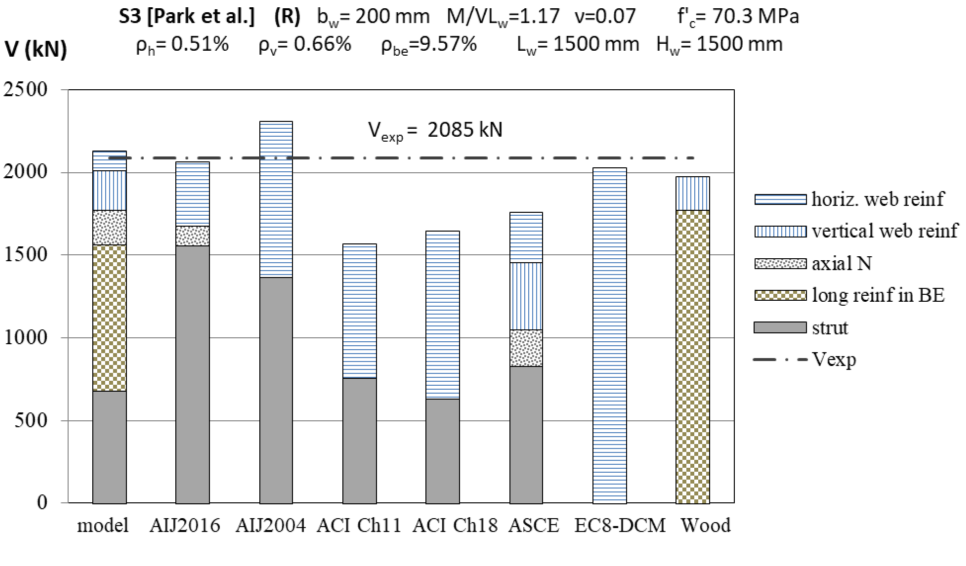

Fig. 2 – Rectangular RC wall

AIJ2004 [10] model, which is based on the AIJ1999 Guidelines, despite its comparatively bad overall predictive capacity in terms of statistical indicators, being a purely mechanical model which takes into account both the arch and the truss mechanism, proves to predict well the ultimate shear capacity, V_u, of certain specimens when the wall characteristics result in significant activation of the strut (arch) mechanism, e.g. walls tested under doubled fixed condition with sufficient reinforcement, in which the contribution of the diagonal strut mechanism is expected to be more enhanced compared to similar walls loaded as cantilevers. In case of the double fixed flanged wall shown in Fig.3 (b_w=200 mm, obtained from [4]), all models appear to considerably underestimate V_u with the exception of AIJ2004. In case of the double fixed barbell wall depicted in Fig.4 (b_w=120 mm, obtained from [23]), V_u is well estimated by AIJ2004, and also by the proposed model because of the comparatively increased contribution of the axial load and of the vertical web reinforcement as shown from the respective components of the bar chart.

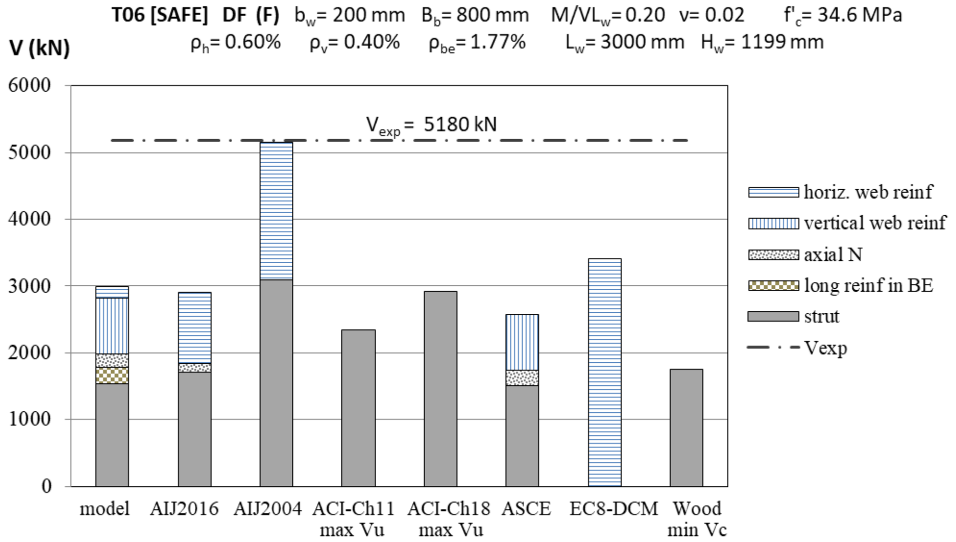

Fig. 3 – RC wall with flanged cross section and double fixed loading conditions

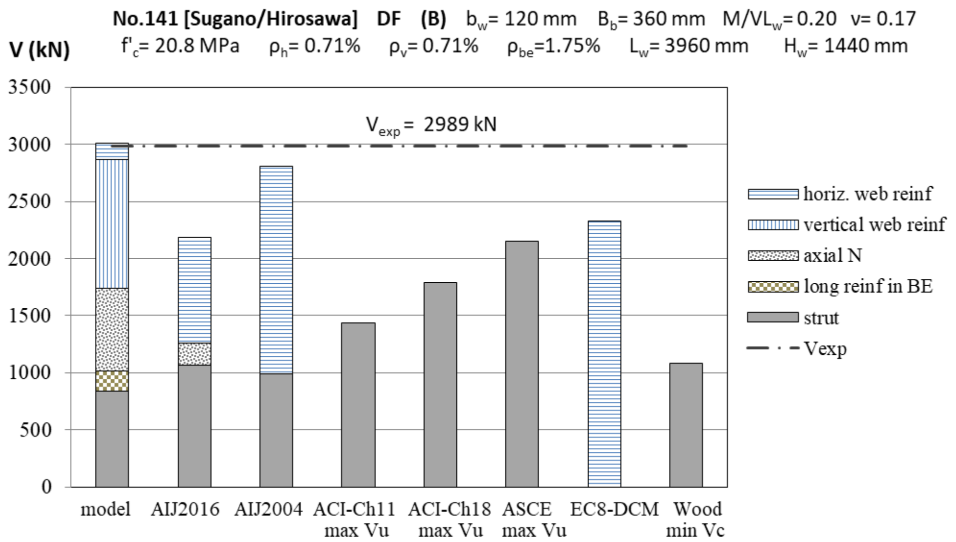

Fig. 4 – RC wall with barbell cross section and double fixed loading conditions

Furthermore, AIJ2004 [10] captures satisfactorily the observed experimental increase in V_u between specimens No.5 (M/VL_w=1.76, $\rho_h = \rho_v$ =0.53%, ν=0.14) [24] and No.7 (M/VL_w=1.18, $\rho_h = \rho_v$ = 1.0%, ν=0.14) [24] and otherwise similar characteristics, displayed in Figs. 5 and 6, respectively. It is noted that the proposed model tends to overestimate V_u for high axial load ratios and higher aspect ratios M/VL_w (specimen No.5, Fig.5).

Limits in shear capacity included in the models, which are not related to the actual mechanical behavior of the specimen but are rather imposed to guarantee safe predictions, generally lead to predictions that diverge from the experimental ones, as may be observed for the upper limit max V_u, e.g. in ACI-Ch11, ACI-Ch18, ASCE43-05, Wood, and the lower limit min V_c in Wood.

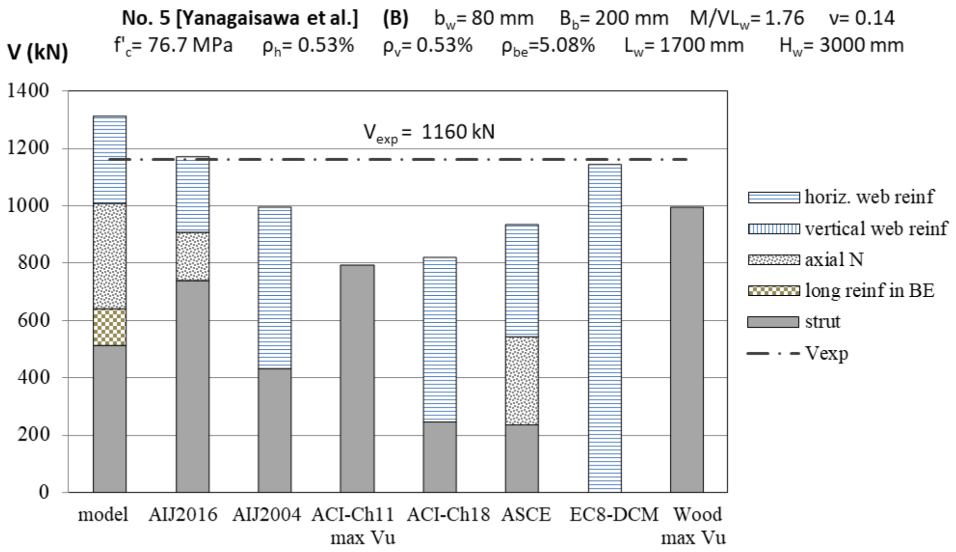

Fig. 5 –RC wall with barbell cross section

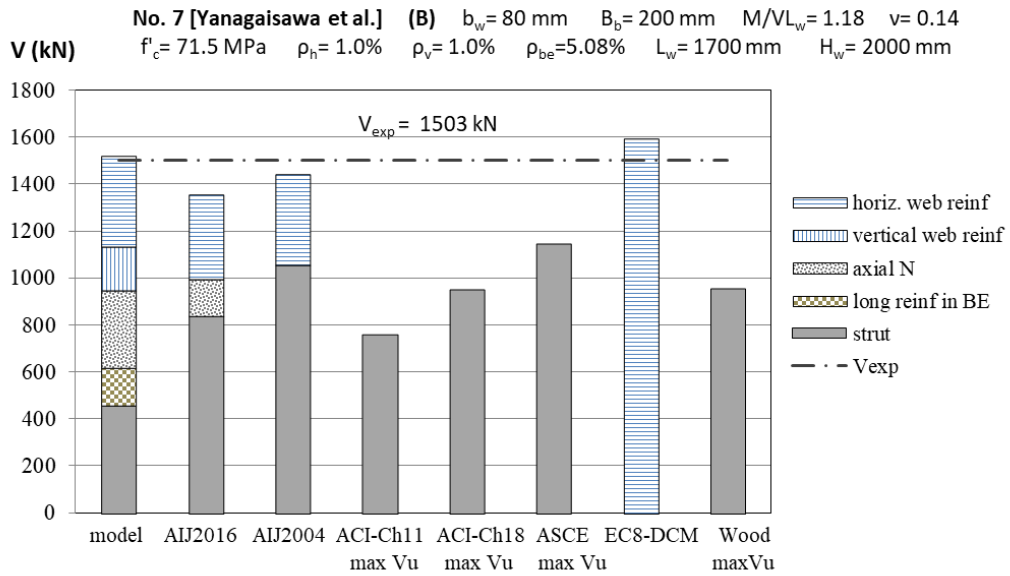

Fig. 6 – RC wall with barbell cross section

For the large-scale flanged specimen S-2 [25], displayed in Fig.7, better predictions are obtained by the proposed model [5] and AIJ2016 [12]. Underestimation of the prediction by the Gulec and Whittaker model (G.&Wh.) [16] may be partly attributed (a) to the fact that the model does not consider the contribution of the horizontal web reinforcement, (b) to the limitation of the flange width to $H_w/2$=1410 mm.

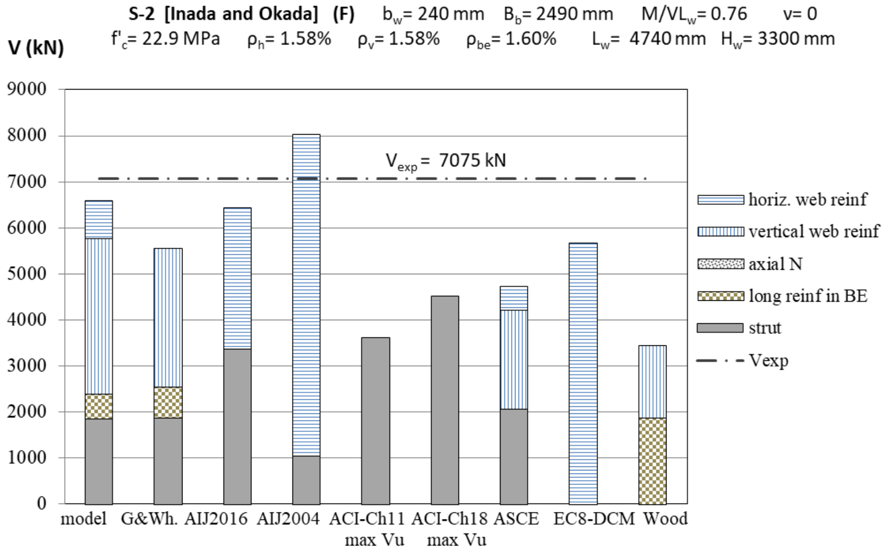

Fig. 7 – RC wall with flanged cross section

The proposed model predicts well the peak shear strength of RC walls inadequately reinforced according to modern code provisions. Fig.8 displays a wall with rectangular cross section and no longitudinal reinforcement in the boundary elements: SW7 (M/VL_w=0.33, ρ_h=ρ_v=0.33%, ρ_{be}=0) [26, 27]. Fig.9 displays a rectangular wall with no web reinforcement: SW-10 (M/VL_w=1.08, ρ_h=ρ_v=0, ρ_{be}=8.31%) [28]. In the case of walls SW7 and SW-10 all truss- and strut-and-tie-based models, as well as the AIJ2004 and AIJ2016 models are not applicable because the presence of both the longitudinal reinforcement in the boundary elements and horizontal wall web reinforcement is fundamental for the models to function. Nevertheless the predictions of those models are shown on Figs.8 and 9, with the indication N.A. (not applicable) under their name.

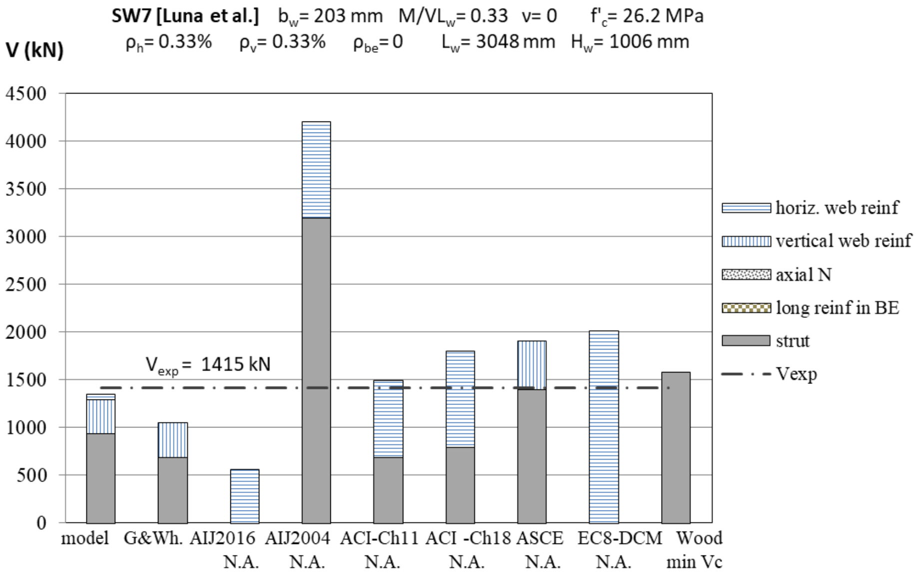

Fig. 8 – Rectangular RC wall with no longitudinal reinforcement (ρ_{be}=0) in the boundary elements

As expected, the predictions of the models which presuppose the presence of boundary element longitudinal reinforcement and horizontal web reinforcement are not satisfactory. Most adversely is affected the purely mechanical model of AIJ2004.

To the best knowledge of the authors the issue of non-applicability of certain models, e.g. truss models, to assess the ultimate shear capacity of RC walls in which reinforcement essential for the models to function is missing, has not been raised when the models' predictive performance was assessed relatively to a given database in previous studies.

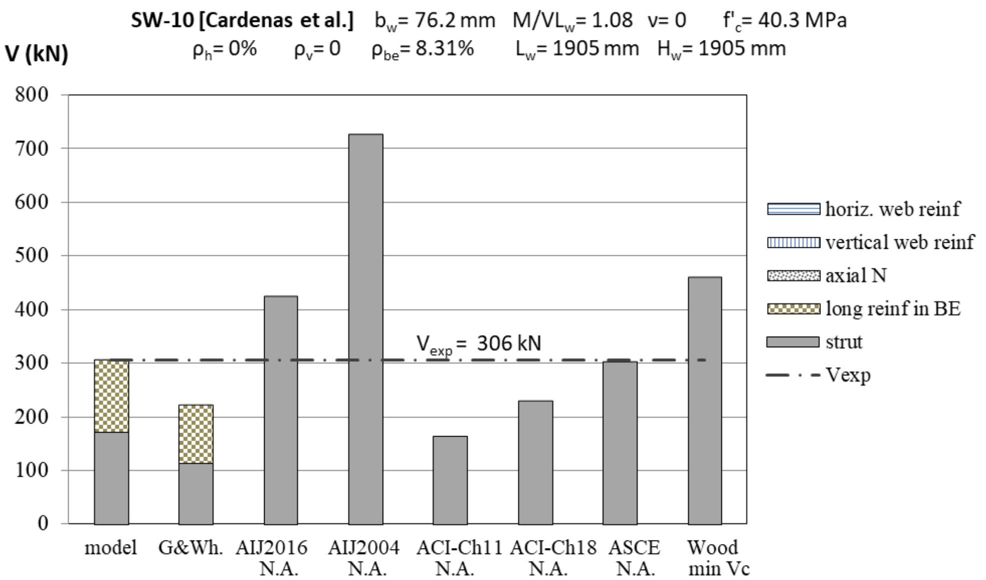

Fig. 9 – Rectangular RC wall with no vertical (ρ_v =0) and no horizontal (ρ_h =0) web reinforcement

It is specified that the equation proposed by Wood [17] has been included in Figs.2 to 9 with the intention to demonstrate that the comparatively good statistical indices of this model, more particularly for the rectangular wall cross section, are rather attributed to limits imposed on shear predictions and do not reflect reliable predictions. Among the wall specimens shown in Figs.2 to 9, only in the case of wall S3 (Fig.2) the model proposed by Wood predicts well the peak shear strength, and this is attributed mainly to the high percentage of longitudinal reinforcement, as shown in the associated mechanisms that contribute to shear capacity in the bar chart.

3. Conclusions

The performance of existing code provisions and design models regarding their ability to predict the ultimate shear capacity of reinforced concrete walls is assessed on a database of 414 RC walls reported to have failed in shear. Best performance is shown by a new empirical model proposed by the authors which has no limitations of applicability and therefore is also appropriate for assessing the shear capacity of existing substandard RC walls. Among the code provisions studied, the model in AIJ2016 Guidelines exhibits the best performance. The basic conclusions drawn regarding the models considered are summarized in the following.

Best predictive capacity is demonstrated by models that are developed especially for RC walls, take into account more wall parameters, and consider the effect of the shape of the cross section.

Truss- and strut-and-tie- based models do not seem appropriate for low aspect ratio RC walls that fail in shear. For RC walls with low aspect ratio it is essential to consider appropriately the contribution of the shear transferred through the mechanism of the diagonal concrete strut (arch), and how this is affected by other parameters such as the axial force and the longitudinal reinforcement in the boundary elements.

Limits imposed in shear capacity, when they do not arise from a physical basis that determines the element's behavior, entail reduced accuracy of predictions.

Design code provisions for RC walls are intended for the dimensioning of walls that comply with detailing provisions included in modern codes. Therefore they are not adequate for the assessment of existing RC walls the detailing of which does not in general conform to new codes.

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