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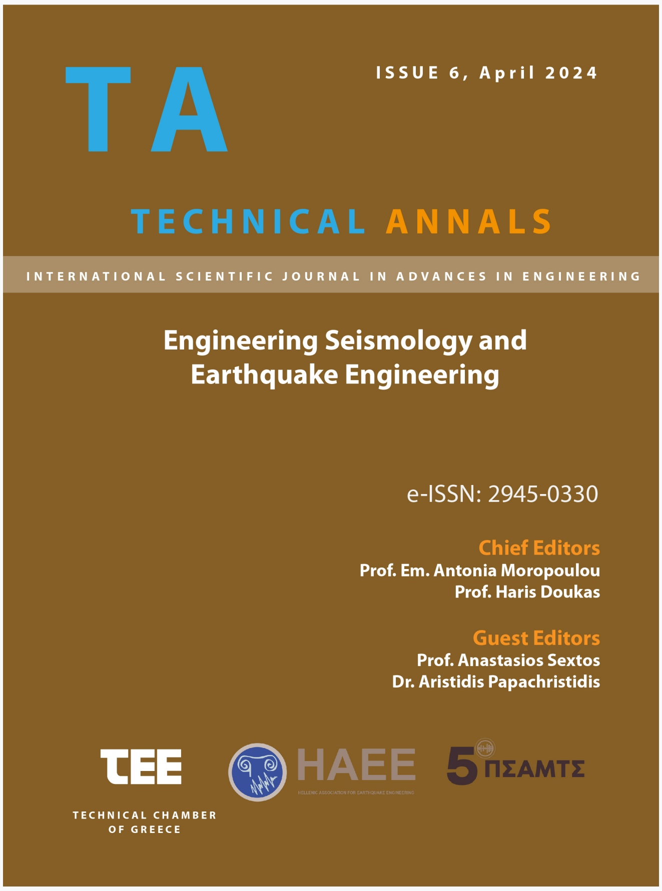

Substandard Reinforced Concrete Walls with Rectangular Cross-section: Assessment of Shear Resistance

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Substandard Reinforced Concrete Walls with Rectangular Cross-section: Assessment of Shear Resistance

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Abstract. Reinforced concrete walls in buildings constructed before 1990 possess low shear resistance and their reinforcement detailing differs considerably as compared to similar walls in modern buildings, designed according to modern code principles. Accurate estimation of shear resistance of existing RC walls is crucial for the seismic capacity assessment of older buildings. In this paper, a design model is presented for the assessment of shear resistance of RC walls with rectangular section, irrespective of reinforcement configuration. The model includes the contribution of all major mechanisms to shear resistance, namely: the longitudinal reinforcement of the confined regions at either end of the cross-section, the horizontal and vertical web reinforcement, the axial compressive force, and the concrete strut through a novel approach. The proposed equations have no restrictions in their applicability, in contrast to the majority of existing models, and proved to be the most effective in assessing the shear resistance of 129 tested RC walls, among 14 other design models considered, including existing design codes. Indicative case studies are presented to demonstrate the better predictive capacity of the proposed equations and the deficiency of four code provisions regarding the prediction of shear resistance of older RC walls with substandard reinforcement detailing.

Keywords: Shear Wall Resistance, Reinforced Concrete, Assessment, rectangular cross-section

1 Introduction

The contribution of reinforced concrete (RC) walls on the seismic behaviour of RC buildings has been investigated early on [1]. Research on the calculation of the shear resistance of reinforced concrete (RC) walls dates since the 1970's [2-4]. Different design approaches have been proposed to estimate the shear resistance of RC walls, including empirical formulas, e.g. [5], strut-and-tie models, e.g [6], truss models, e.g. [7], superposition of strut and truss mechanism, e.g. [8-9], as well as other approaches, e.g, [10]. However, it is well established that the estimation of shear resistance of RC walls is still considered an open issue [11, 12]. Further on, the predictions of available models, including the respective code provisions, differ considerably between them. The discrepancy between predicted and actual shear resistance is particularly large in case of RC walls in older buildings, which do not possess the reinforcement detailing prescribed by modern codes, given that most design models presuppose the presence of certain detailing [11].

However, the knowledge of shear resistance of RC walls is essential for the assessment of the seismic capacity of RC walls. It is noted that particularly in case of buildings constructed according to older code principles, in which the behavior of RC walls is governed by shear resistance, an accurate estimation of shear resistance of RC walls is essential in the assessment of seismic capacity. This is especially important for the existing building stock in Greece. Reinforced concrete (RC) buildings in Greece constructed prior to 1990's are, generally, frame structural systems. Occasional RC shear walls have very different reinforcement detailing compared to that prescribed by modern codes, i.e. no confined regions in their cross-section and low amount of web reinforcement. As a result, they possess low shear resistance and are liable to fail in shear in the event of a major earthquake. Seismic design according to modern codes aims at safeguarding against collapse through ductile seismic performance of the structural elements. Shear failure results in brittle failure and abrupt decrease of the element's mechanical properties. In order to reduce the possibility of shear failure, in modern codes all structural elements should be designed so as have higher shear resistance, V_R, than the shear force corresponding to the flexural resistance of the cross-section $V(M_R)$, i.e. $V_R < V(M_R)$. This prerequisite falls within the concept of "capacity design", which is a practice that did not exist in older code principles.

This work stemmed from the practical need for a reliable design model to estimate the shear resistance of RC walls, irrespective of their reinforcement detailing. Based on the results of an extensive study, the current paper focusses on the prediction of shear resistance of RC walls with rectangular cross section, and reinforcement detailing different than that prescribed by modern code provisions.

A design model is proposed for the calculation of the shear strength of RC walls, which has no restrictions in its application regarding the values of individual characteristics of the wall, as happens with the majority of existing design models. The model proved to be the most effective among 14 other design models considered [11], based on a dataset of 129 tested RC walls. The model is compared to the performance of three other models from international codes: EN1998-1, DCM [13], EN1998-3 [14], and AIJ2016 [15], and of an empirical model include in the Greek code for RC, EKOS2000 [16]. The predictive performance of the five models is discussed based on three case-studies of tested RC walls that did not comply with modern reinforcement detailing. Shortcomings of the existing models are briefly discussed.

The better predictive performance of the proposed model, as compared to other available models, is attributed to the following:

- Inclusion of all the individual load transfer mechanisms with their contribution appropriately calibrated against a large database. The other models consider only some of the load transfer mechanisms.
- Different design equations are provided for rectangular and barbell cross-sections, while most models do not make any distinction. It is experimentally verified that

RC walls with barbell cross-section have increased shear resistance. In this paper only the equations for rectangular sections are discussed.

- A novel method is proposed to calculate the contribution of the concrete strut mechanism, which is the most significant contributor to shear resistance. The proposed equation stems from the strut contribution in infilled frames.
- No upper limit for shear resistance is included. The upper limit in shear resistance in the majority of other models is based on the upper limit in the truss analogy aimed to exclude the occurrence of concrete crushing. However, in RC walls no such type of failure is observed, so this limit is not physically justified. The models apparently require an upper limit to guarantee safe predictions.
- The model has no restrictions in its application. Other models are applicable only to RC walls with specific reinforcement detailing, the one prescribed by modern codes, as a rule, e.g. the existence of confined ends at the cross-section, minimum amount of web reinforcement, etc. Those prerequisites reduce the applicability of existing design models.

2 Modelling the shear resistance of RC walls

2.1 General aspects affecting shear resistance

It is well established that the estimation of shear resistance of RC walls is still considered as on open issue [11, 12]. In modern codes, available equations for the calculation of shear resistance, V_R, of walls are intended to be used for RC walls that comply with modern reinforcement detailing. Among the prevalent factors that are known to affect shear behavior of RC walls is the value of the shear ratio, $\alpha_s = M/V{\cdot}L_w$, where L_w is the larger dimension of the section, V is the maximum shear force that acts at the base of the wall parallel to L_w, and M is the corresponding bending moment.

(a) For walls with shear ratio $\alpha_s > 2$, the design equations for shear resistance proposed by the codes are similar to the equations for linear elements and are based on truss analogy. Shear capacity V_R is calculated, as a rule, as the sum of the contribution, V_w, of the reinforcement parallel to shear force, and the contribution, V_c, of the other load transfer mechanisms, including concrete, dowel action, etc., e.g. EN1992-1-1 [17]. For adequate ductility, failure due to concrete crushing of the inclined struts of the Moersch-type truss should be excluded. To this end, an upper limit $V_{R,max}$, which is supposed to be the shear force that results in concrete crushing is introduced. Hence, shear resistance V_R is, generally, calculated from Equation (1).

$$V_R = V_w + V_c < V_{R,max} \tag{1}$$

(b) For walls with shear ratio $\alpha_s < 2$ it is generally assumed that a large part of the shear force is carried by the mechanism of concrete strut. A similar assumption is made for other structural elements with low shear ratio, e.g. coupling beams of coupled shear walls [18] and short columns [19].

Figure 1 indicates the characteristics of a reinforced concrete (RC) wall with rectangular cross-section that contribute to shear resistance. The symbols are explained in section 2.2.

2.2 Proposed design model

Research background. The initial research on shear strength of RC walls, on which the present paper is based, had the following objectives (a) identify the major parameters that affect shear resistance, (b) assess the performance of existing design models regarding the estimation of shear capacity, and (c) proposal of an improved design model for the shear resistance of RC walls.

As a first step of the research, a broad database of 414 reinforced concrete (RC) wall specimens reported to have failed in shear has been assembled from the literature. Reinforcement and geometrical characteristics of the walls of the database are available in Moretti et al. 2019 [11]. Moreover, 14 different design models aiming at the estimation of shear strength of RC walls were collected and assessed in relation to their capacity to accurately predict the shear resistance of the wall of the database. Major differences were observed between the models, which led to discrepancies in the predictions of shear resistance for the same wall specimens. Increased differences in models' predictions were observed for walls with reinforcement characteristics not in accordance to modern code provisions. To address this issue, new empirical equations were proposed which consider all the wall characteristics that affect shear resistance of walls, namely: geometry, materials, axial force, horizontal and vertical web reinforcement, longitudinal reinforcement of the end parts of the cross-section, without any restrictions of applicability. Different sets of equations were proposed for rectangular section and for section H, i.e. barbell/flanged section with reduced web width, compared to the end parts where larger boundary elements are present. It was already established that shear resistance of walls is considerably influenced by the shape of the cross-section [6,12,20-21]. It is important to note that in the design equations proposed by the majority of codes and researchers, including the Eurocodes and the Greek codes, no distinction is made between different shapes of section.

In this paper design equations for shear resistance of rectangular wall section are presented, which is the section generally used in buildings in Greece. More detailed presentation and comments on the proposed design equations for both types of cross-sections, and comments on the performance of other design models may be found in [11,22-23].

In this paper the set of design equations proposed for walls with rectangular section are provided in equations 2 to 4.

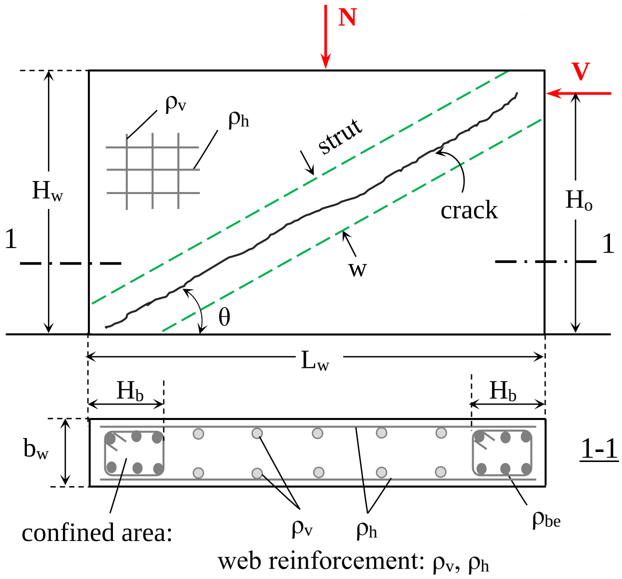

Fig. 1. Geometric and reinforcement characteristics that affect shear resistance of a reinforced concrete wall (RC) with rectangular section. Symbols are explained in section 2.2.

Design equations. Discussion on the contribution of the individual mechanisms. In the proposed model, shear resistance, V_u, of a reinforced concrete wall with rectangular cross-section is calculated through equation (2) by summing up the contribution of five (5) individual constituents, calculated through equations (3a) to (4d). The effect of each component to the wall shear resistance is briefly discussed in the following.

Concrete contribution to shear resistance consists in the shear force carried by the diagonal strut mechanism, V_{strut}, and is calculated by equation (3a). Strut mechanism in more activated in structural elements with low shear ratio, e.g. [24]. Strut width, w, depends on the wall dimensions and the amount of longitudinal reinforcement at the end sections of the wall, and is calculated through equations (3a-1), (3a-2) and (4). It has been verified [11] that the contribution of strut mechanism is enhanced in walls (a) with larger cross-section width and (b) in the presence of higher amount of longitudinal reinforcement at the confined regions. The width of the diagonal strut, *w*, is calculated from equation (4) [25]. It is pointed out that the provisions of FEMA 306 [25], originally intended for the case of infilled frames, are applied for the first time for the calculation of shear resistance of RC walls. Appropriate modifications are proposed to better describe the strut contribution to shear in RC walls, namely the equations (3a-1), (3a-2) and (4d).

$$V_u = V_{strut} + V_h + V_v + V_{be} + V_N \quad (2)$$

$$V_{strut} = w \cdot b_w \cdot f_c^{'} \cdot (0.78 - \frac{f_c^{'}}{200}) \frac{1}{\sqrt{M / VL_w} + 0.18} \cos\theta \quad (3a)$$

$$w = \max(b_w; w_{FEMA}) \text{ for } b_w \geq 120 \text{ mm or } \rho_{be} \geq 0.018 \quad (3a\text{-}1)$$

$$w = \min(b_w; w_{FEMA}) \text{ for } b_w < 120 \text{ mm and } \rho_{be} < 0.018 \quad (3a\text{-}2)$$

$$V_h = 0.2 \cdot \rho_h \cdot b_w \cdot (0.8L_w - H_b) \tan\theta \cdot f_{yh} \quad (3b)$$

$$V_v = 0.3 \cdot \rho_v \cdot b_w \cdot (0.8L_w - H_b) \cdot f_{yv} / \sqrt{H_w / L_w} \quad (3c)$$

$$V_{be} = 0.25 \cdot \rho_{be} \cdot H_b \cdot b_w \cdot \min(f_{ybe}; 700MPa) / \sqrt{H_w / L_w} \quad (3d)$$

$$V_N = 0.15 \cdot N / \sqrt{M / V \cdot L_w} \quad (3e)$$

$$w_{FEMA} = 0.175(\lambda \cdot H_o)^{-0.4} \cdot r_{\inf} \quad (4)$$

$$\lambda = \left(\frac{b_w \cdot \sin 2\theta}{4 \cdot I_{bc} \cdot H_w} \right)^{0.25} \quad (4a)$$

$$r_{\inf} = \sqrt{L_w^2 + H_w^2} \quad (4b)$$

$$\theta = \arctan(H_w / L_w) \quad (4c)$$

$$\mathrm{I}_{bc} = b_w \cdot H_b^3 / 12 \quad (4d)$$

where:

V_{strut} = shear force carried through the mechanism of diagonal strut

V_h = contribution of horizontal web reinforcement to shear resistance

V_v = contribution of vertical web reinforcement to shear resistance

V_{be} = contribution of longitudinal reinforcement in the confined boundary elements

V_N = contribution of compressive axial force, N, of the wall to shear resistance

M, V = bending moment and respective shear force at the wall base

b_w = width of wall cross-section

L_w = length of wall cross-section

H_w = height of wall

$r_{\inf}$ = length of diagonal strut

$w =$ width of diagonal strut
$\rho_{be} =$ geometric ratio of longitudinal reinforcement of confined end wall regions
$\rho_h =$ geometric ratio of horizontal web reinforcement
$\rho_v =$ geometric ratio of vertical web reinforcement
$H_o =$ distance between base of wall and horizontal force (see Fig. 1)
$H_b =$ length of confined regions.
$\mathrm{I}_{bc} =$ moment of inertia of confined regions at the cross-section ends

For the calculation of strut width from equation (4), for I_{be} in (4d):
$\mathrm{H}_b = b_w / 2$ for $\rho_{be} > 0$ or
$\mathrm{H}_b = b_w / 4$ for $\rho_{be} = 0$

The reinforcement in the wall is supposed to contribute to shear resistance in relation to the amount of reinforcement bars activated by the potential diagonal crack at an angle θ, shown in Figure 1. The contribution to shear resistance of the web reinforcement is calculated from equations (3b) for the horizontal bars, and (3c) for the vertical bars. It is noted that the majority of existing design models consider only one of the two types of web reinforcement, as described in [11].

The contribution to shear resistance of the longitudinal bars in the confined regions is calculated from equation (3d). The presence of high percentage of longitudinal reinforcement, although neglected in many design models, proved to result in increased shear resistance [11]. For that reason, in the proposed design model the effect of the longitudinal reinforcement is considered both directly through equation (3d) and also indirectly by increasing the strut width, as described in the respective equations (3a-1), (3a-2) and (4).

The presence of higher compressive axial force in a wall results in increased shear resistance. The contribution of axial force in calculated by equation (3e) and is inversely proportionate to the magnitude of the wall shear ratio.

2.3 Code design provisions discussed

In this paper, besides the proposed equations presented in section 2.2, four design models from codes are applied, and their assumptions are briefly outlined, namely: (a) the equation of Eurocode 8 part 1 [13] intended for new structures, (b) the equation of Eurocode 8 part 3 [14] for the assessment of existing structures, (c) a Japanese model included in AIJ2016 [15], which resulted in the second best predictions among the 14 models considered, and (d) the equation for squat walls in EKOS2000 [16], the Greek code for the design of new RC structures. The criterion for selecting the two Eurocode models is their use in Greece rather than their predictive performance, which is deficient.

(a) EN1998-1 [13], for medium ductility level (DCM). The code provisions address new structures. Shear resistance is calculated from a truss model formed by the potential inclined cracks at an angle θ as per the direction of the longitudinal axis of the wall. Angle θ is determined in such a way that the shear resistance of the concrete struts equals the shear resistance of the reinforcement parallel to the shear force, within the limits $0.4 \leq \tan\theta \leq 1$ (EN1992-1-1 [17]). For the application of the model the wall should include reinforcement detailing that enables the formation of a truss at ultimate state, i.e. adequate horizontal web reinforcement and reinforcement at both ends of the section, i.e. in the upper and lower chord of the truss. It is noted that the above restrictions are not stated in the code, because they are guaranteed in new structures.

(b) EN1998-3 [14]. The provisions are intended for the assessment of shear resistance of existing buildings. Empirical equations for the calculation of shear resistance of walls as well as for the maximum shear force, $V_{R,max}$, that results in crushing of the concrete struts are provided. The contribution of horizontal web reinforcement, the total vertical web reinforcement, the axial force and the shear ratio are considered. The equations include the ductility factor $\mu_{\Delta}^{pl}(=\theta_{pl}/\theta_{y})$ which expresses the ratio of the plastic part of the chord rotation, θ_{pl}, to the chord rotation at yielding, θ_y, the estimation of which presents uncertainties, which increase for walls constructed according to older code principles. At application of the equations it was assumed that $\mu_{\Delta}^{pl}=0$. No restrictions for the values of the wall characteristics are included for the application of the design equations.

(c) AIJ2016 [15]. It is an empirical model from the Japanese provisions, easy to apply, which may be used for all types of cross section (i.e. rectangular and barbell). The model expresses the contribution to shear resistance of horizontal web reinforcement, longitudinal reinforcement at the end confined regions, shear ratio and axial force. Prerequisite for the application is the existence of reinforcement at both ends of the cross-section and of horizontal web reinforcement. This design model is presented in detail in [11], and results in the second best predictions of shear resistance for the specimens of the database, among the 14 models originally applied from the literature.

(d) EKOS2000 [16]. The Greek code for the design of reinforced concrete structures includes an empirical design equation for the shear resistance of RC walls with shear ratio $\alpha_s \leq 1.30$, which considers the contribution of both horizontal and web reinforcement of the wall. The code is intended for the design of new structures, and therefore presupposes modern reinforcement detailing and minimum requirements for the amount of reinforcement. The model has been applied only on the three test specimens presented in Figures 2 to 4, and was not included in the original comparative research based on the whole database, the results of which are shown in Table 1.

3 Results

3.1 Comparative evaluation of predictive capacity of the design equations

The accuracy of the design models was assessed by their capacity to predict the experimental ultimate shear force of 129 walls with rectangular cross-section, from an assembled experimental database. The database is available in Moretti et al. (2019) [11]. In the evaluation process, nine code models and five other design models from the literature were compared. It is interesting to note that apart from the proposed model and the model of EN1988-3 [14], all the other design models have restrictions in their applicability, related to the individual wall characteristics. Details on the predictive performance of all 14 models considered are available in [11] and [22].

The performance of the proposed model and the three international code equations herein discussed was assessed by their capacity to predict the experimental ultimate shear resistance of tested shear walls. For assessing the accuracy of the shear predictions, three statistic indices for the ratios V_{mod} / V_{exp}, where V_{mod} is the predicted shear resistance by each model and V_{exp} is the experimental peak shear strength for the same wall, were calculated: (a) the Covariance, COV(= STDEV/MEAN), (b) the average value $\overline{\Delta} = \left(\Sigma_{i=1}^{N} \Delta_i\right) / N \times 100(\ )$, where Δ_i =[($V_{exp,i}$-$V_{mod,i}$)/$V_{exp,i}$]<0 of the model's overestimation of peak shear strength of –i specimen, and (c) the average absolute error of the model's prediction $AAE = \Sigma_{i=1}^{N}\left(\left|V_{\mathrm{mod},i} - V_{\mathrm{exp},i}\right| / V_{\mathrm{exp},i}\right) / N \times 100$ for each –i wall specimen, where N is the total number of specimens considered in each case.

Table 1 displays the statistical indices for the ratios V_{mod} / V_{exp} for the four models. The number, N, of specimens on which each model was applied is also displayed on the Table. Only the proposed model and EN1998-3 could be applied to all 129 specimens of the database, as the specific models do not include any restrictions regarding the wall parameters.

According to Table 1, among the four models discussed, the worst predictions are those of EN1998-1, based on truss analogy, a load carrying shear mechanism not expected to be predominant for RC walls that fail in shear.

The performance of EN1998-3, which is supposed to be used for the assessment of existing structural elements, is not good either. Although the model has no restrictions in its application and could be applied on all 129 specimens of the database, a considerable scatter between calculated and estimated shear strength values is observed. Also, this model results in considerable amount of unsafe predictions, indicated by $\overline{\Delta}$ despite the fact that it was generally taken: $\mu_{\Delta}^{pl} = 0$.

AIJ model results in the second best predictions. More details on the model are available in [11].

The proposed design model results in the best predictions. It is noted that the undisputable better performance of the proposed model was also verified against 14 design models in a broader database of 414 RC walls, which included also barbell walls.

Table 1. Statistical indices for the ratio V_{mod}/V_{exp} for walls with rectangular section

Design equations	Number of specimens, N	COV	AAE (%)	$\overline{\Delta} < 0$ (%)
Proposed model	129	0.164	15.7	7.2
EN1998-1, DCM [13]	97	0.491	43.1	59.4
EN1998-3 [14]	129	0.423	32.1	26.5
AIJ 2016 [11], [15]	97	0.250	19.8	21.5

3.2 Case studies on the estimation of shear resistance of RC walls that do not comply to modern design provisions

In the following, some shortcomings typically encountered at the application of existing design equations for the assessment of shear resistance of RC walls with different reinforcement characteristics as compared to those prescribed by modern codes for new structures are discussed. Specific pertinent examples from tested shear walls are provided for RC walls with rectangular section, through comparison of their experimental peak shear strength to the predicted one.

In Figures 2 to 4 the performance of the design models shown in Table 1 is compared for wall specimens from the literature. Moreover, the respective predictions of the Greek code EKOS2000 [16] are also shown. The predictions of EN1998-3 are indicated as EC8-3, while the predictions of EN1998-1 are indicated as EC8-1.

On the Figures the value of the experimental peak shear strength, V_{exp}, is indicated with dashed line. When feasible, different symbols are used to mark the contribution of each shear transfer mechanism, i.e. types of reinforcement, concrete strut, axial force. In the EN1998-3 model the contributions of the individual carrying mechanisms cannot be unlinked, and therefore are not indicated separately. Similarly, in AIJ2016 the contribution of the longitudinal reinforcement of the confined regions is included within the concrete strut, therefore both are depicted as concrete strut (in Figure 4). On each figure the following characteristics of the wall specimens are indicated, as defined in Figure 1: the wall geometric characteristics, b_w, L_w, H_w, the shear ratio α_s, the axial load ratio, ν (=$N/(L_w b_w f_c)$), the compressive strength of concrete, f_c, and the geometric reinforcement ratios of the longitudinal reinforcement of the confined regions, ρ_{be}, as well as the ratios of horizontal web reinforcement, ρ_h, and of vertical web reinforcement, ρ_v.

Absence of longitudinal reinforcement in the end sections ρ_{be}=0. Figure 2 shows the predictions of the five models for a large- scale wall with low shear ratio, $\alpha_s = 0.33$ and no axial force ($\nu = 0$). The wall has normal concrete strength, $f'_c = 26.2$ MPa. The web reinforcement ratio $\rho_h = \rho_v = 0.0033$ is larger than the minimum amount of web reinforcement required in the Greek code [16], which is: min(ρ_h, ρ_v) = 0.0025. The specimen does not include reinforced confined areas at the ends of the section ($\rho_{be} = 0$). Hence truss-based models AIJ2016 and EN1998-1 cannot be applied for the estimation of shear strength, as the upper and lower chord of the truss cannot develop. This is indicated by symbol N.A. (=Not Applicable) on the X axis under the models' names. For comparison purposes, the predictions of the two models are also shown on Fig. 2. Models EN1998-3 and EKOS2000 underestimate peak shear strength. The proposed model estimates very well the peak shear strength of this specimen: V_{mod} =1346 kN. According to the proposed model the major part of shear resistance is attributed to the concrete strut, i.e. V_{strut} = 941 kN, followed by the contribution of the vertical web reinforcement, V_v = 352 kN, and only minor contribution of the horizontal web reinforcement, V_h = 53 kN. This behavior stems from the particularly small value of the shear ratio.

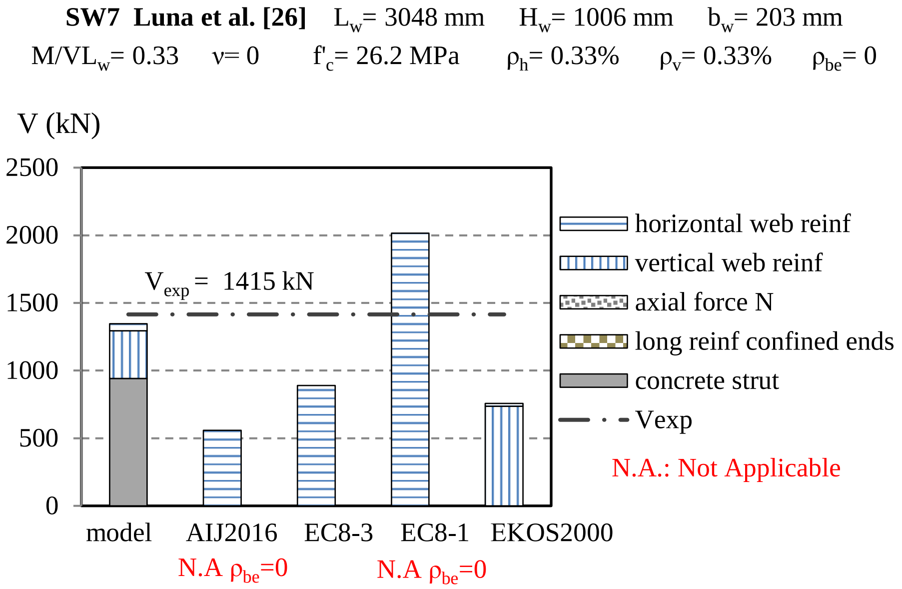

Fig. 2. Prediction of shear resistance, V_R, allocated to the shear resisting mechanisms considered by each model for a wall without without longitudinal reinforcement at the cross-section ends (ρ_{be}= 0).

No web reinforcement ρ_v=ρ_h=0 - High longitudinal reinforcement at ends of cross-section. Figure 3 displays the predictions for a wall with shear ratio α_s = 1.08 and no axial force (ν = 0). The wall has moderate to high concrete strength, f'_c = 40.3 MPa and has no web reinforcement (ρ_v = ρ_h =0). High longitudinal reinforcement ratio at both ends of the cross-section is present, ρ_{be} = 8.31%. It is noted that the longitudinal reinforcement ratio at either end of the section is higher than the maximum allowable reinforcement ratio, max ρ_{be} = 4%, prescribed by EKOS2000 and EN1998-1. The models of EN1998-1 and EKOS2000 cannot be applied (N.A) because of the absence of the web reinforcement. AIJ2016 is also not applicable because the presence of horizontal web reinforcement is a prerequisite for the model, however the peak shear force calculated from the equation of AIJ from the mechanism of concrete strut and the longitudinal reinforcement at the end confined regions is indicated on Figure 3 for comparison purpose. Overestimation of AIJ2016 is simply attributed to the fact that it is not correct to apply the model when ρ_h = 0. It is observed that EN1998-3 underestimates considerably the peak shear strength of the wall. The proposed model predicts exactly the peak shear strength of the specimen, V_{mod} =307 kN, by considering the contribution of the concrete strut, V_{strut} =172 kN, and the contribution of the longitudinal reinforcement at the confined regions V_{be} =135 kN.

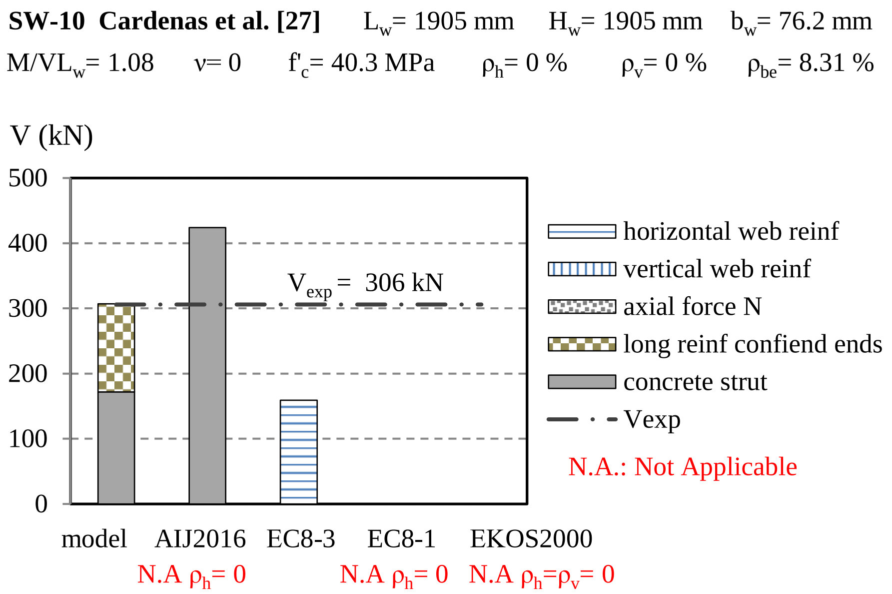

Fig. 3. Prediction of shear resistance, V_R, allocated to the shear resisting mechanisms considered by each model for a wall without web reinforcement ($\rho_h = \rho_v = 0$).

High concrete strength-High longitudinal reinforcement at end section regions. Figure 4 presents a wall with shear ratio $\alpha_s = 1.17$, axial load ratio $\nu = 0.07$, high concrete strength (f_c = 70.3 MPa) and particularly high percentage of longitudinal reinforcement at the end regions ρ_{be} = 9.57%, which is higher than the maximum allowable reinforcement ratio max ρ_{be} = 4%, prescribed by EKOS2000 and EN1998-1. The web reinforcement ratio is more than twice the minimum amount prescribed by EN1998-1 and EKOS2000 (min (ρ_v, ρ_h) = 0.0025). The values of the reinforcement characteristics render all the models applicable. With the exception of EKOS2000 which underestimates the peak shear strength, the other four models result in good predictions of peak shear strength. AIJ2016 yields the best prediction, i.e. V_{mod} = 2063 kN. The proposed model slightly overestimates shear strength, i.e. V_{mod} = 2129 kN, with V_{mod} / V_{exp} = 1.02. EN1998-1 results in a slight underestimation, V_{mod} / V_{exp} = 0.97, while EKOS2000 in significant underestimation, V_{mod} / V_{exp} = 0.41. It is worth noting that EN1998-3 overestimates by 7% peak shear strength, i.e. V_{mod} = 2229 kN, while the code equation serving as an upper limit (to safeguard against concrete crushing) results in even higher shear resistance, $V_{R,max}$ = 2676 kN.

Attention should be drawn on the importance of the contribution of each individual shear transfer mechanism included in the design equations. In case of wall specimen S3 depicted in Figure 4, in the four models that reach similar peak shear strength estimates, the equations are completely different. For example, comparing between AIJ2016 and the proposed model, it is interesting to note both models calculated similar total shear contribution of strut and longitudinal reinforcement, while the remaining part of shear transfer is attributed in AIJ2016 model to the horizontal web reinforcement and axial load, while in the proposed model mainly to the axial force and vertical web reinforcement, and less to the horizontal web reinforcement.

Therefore, the appropriateness of a model should be judged by its capacity to predict well the shear resistance of a large number of specimens with different characteristics, as is the case of the models applied in the whole database shown in Table1.

Further on, it is worth mentioning that the introduction of an upper limit in shear resistance of RC walls is not apposite as it has been demonstrated [11,22-23]. This upper limit, although claimed to prevent from concrete crushing, similar to Moersch truss theory, in the case of RC walls it seems to serve exclusively towards safe predictions –which, in fact, did not happen for specimen S3 (Fig. 4).

S3 Park et al. [28] L_w= 1500 mm H_w= 1500 mm b_w= 200 mm
M/VL_w= 1.17 ν= 0.07 f'_c= 70.3 MPa ρ_h= 0.51 % ρ_v= 0.66 % ρ_{be}= 9.57 %

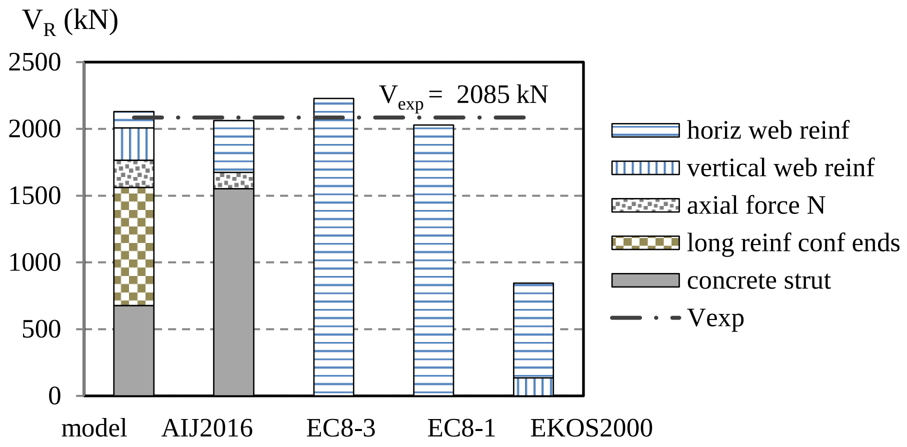

Fig. 4. Prediction of shear resistance, V_R, allocated to the shear resisting mechanisms considered by each model for a wall with high reinforcement ratios and high concrete strength.

The good predictions of the proposed model, for the three walls discussed, are achieved through the correct estimation of the contribution of the individual mechanisms of load transfer to shear resistance, which have been determined over a broad range of values for the wall characteristics.

4 Conclusions

This paper addresses the prediction of peak shear strength of RC walls with rectangular cross-section, which is known to be still an open issue. The lack of a generally accepted design model for shear resistance of RC walls has a more pronounced impact in the assessment of shear strength of older RC walls, which do not comply with the minimum required reinforcement detailing prescribed by modern codes.

A set of design equations is proposed and presented in detail. The model has no restrictions in its application and is capable of reliably estimating the shear strength of RC walls, irrespective of the wall reinforcement characteristics. Besides the proposed model, the performance of four other design code-based models is discussed in relation to their ability to predict the experimental peak shear strength of tested RC walls. It is shown that in case of RC walls with reinforcement characteristics that do not comply with modern codes, existing models fail to accurately predict shear capacity.

The main problem of the existing design models is that they do not include all the individual characteristics of the RC walls which contribute to shear resistance. This shortcoming results in reduced predictive capacity, restrictions in applicability related to minimum reinforcement requirements, and also the need of introducing an upper limit in shear resistance, with no physical justification.

The design equations presented in this paper model all the RC wall parameters that contribute to shear resistance. They are easy to apply and have no restrictions of applicability in terms of reinforcement detailing and geometry. Given the model's superior performance, as compared to available design models, it is pertained that the proposed model could be used for the assessment of shear resistance of existing substandard RC walls in older structures.

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