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SEISMIC SHEAR FORCE MAGNIFICATION IN RC COUPLED WALL SYSTEMS, DESIGNED ACCORDING TO EUROCODE 8

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ABSTRACT

The same (Keintzel's) magnification factor is used in Eurocode 8 (EC8) to determine seismic design shear forces in cantilever walls as well as in the individual piers of the coupled walls. However, the plastic mechanism of both structural systems is basically different and Keintzel's factor, which was derived specifically for isolated multi-storey walls, is not directly applicable to the piers in coupled walls. The parametric study of the inelastic response of some representative coupled walls, which is presented in this paper, showed that the magnification of the design shear forces in coupled walls was much lower than the one predicted by the procedure in EC8. For this reason a modification of Keintzel's factor, suitable for coupled wall systems, is proposed.

INTRODUCTION

Seismic shear forces in reinforced concrete (RC) structural walls are significantly larger than the forces obtained by equivalent elastic seismic analyses. The phenomenon is recognized as shear magnification. The shear magnification in isolated (un-coupled) multi-storey cantilever walls was first documented by Blakeley et al. (1975). It is currently well understood and recently Rutenberg (2013) provided an extensive and complete overview of the past studies on shear magnification in RC wall systems. In short, the magnification occurs due to the flexural overstrength at the base of the wall and the amplified effect of the higher modes in the inelastic range. Therefore seismic shear forces in RC walls obtained by equivalent elastic analyses (e.g. modal response spectrum analyses) should be multiplied by the shear magnification factor in order to obtain the design forces.

For DCH walls Eurocode 8 (EC8; CEN, 2004) adopted the shear magnification factor proposed by Keintzel (1990). This factor was further modified by Rejec et al. (2011) and it works fine for isolated multi-storey walls in the structural systems containing walls with equal or approximately equal lengths. However, it is important to note that Keintzel's factor was derived specifically for isolated (cantilever) multi-storey walls. Therefore, it was reasonably assumed that inelastic mechanism of cantilever walls (inelastic hinge at the base) does not reduce higher mode seismic forces. This assumption is not valid for coupled walls, where yielding of coupling beams is additional source of energy dissipation. Consequently it is obvious that the same magnification factor (the one derived for cantilever walls) should not be used for the individual piers in coupled walls, as it is implemented in the present version of EC8.

The presented paper discusses the design shear forces in coupled wall systems. It is demonstrated that yielding of coupling beams allows for partial reduction of the seismic shear forces contributed by higher modes. Therefore the magnification should be lower than in the case of

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uncoupled walls. This fact also indicates that the current Eurocode procedure might be uneconomic for the design of the piers in coupled walls.

In the presented investigation the EC8 procedure was verified by means of an inelastic parametric study of some selected coupled wall models. The influence of the coupling level (or coupling ratio) on the shear magnification was investigated. A modified shear magnification factor, suitable for coupled walls designed according to EC8 was proposed. The new factor is based on the modified Keintzel's equation (Rejec et al., 2011).

KEINTZEL'S EQUATION AND EUROCODE 8 PROCEDURE

According to Eurocode 8 (CEN, 2004) the seismic shear forces in walls obtained by simplified equivalent elastic analyses (denoted V_{Ed}') should be multiplied by the shear magnification factor in order to obtain design shear forces V_{Ed}. For walls, which are designed for high ductility (DCH), the magnification factor should be evaluated with Keintzel's equation (1990):

$$\varepsilon = q \cdot \sqrt{\left(\frac{\gamma_{Rd}}{q} \cdot \frac{M_{Rd}}{M_{Ed}}\right)^2 + 0.1 \cdot \left(\frac{S_e(T_C)}{S_e(T_1)}\right)^2} \begin{cases} \leq q \\ \geq 1.5 \end{cases} \tag{1}$$

q is the behaviour (seismic force reduction) factor used in the design;
M_{Ed} is the design bending moment at the base of the wall;
M_{Rd} is the design flexural resistance at the base of the wall;
γ_{Rd} is the factor to account for overstrength due to steel strain-hardening;
T_1 is the fundamental period of vibration of the building in the direction of shear forces;
T_C is the upper limit period of the constant spectral acceleration region of the spectrum;
$S_e(T)$ is the ordinate of the elastic response spectrum.

The first term of equation (1) is related to the shear forces contributed by the first mode response. It takes into account the possible amplification of seismic shear forces due to the flexural overstrength at the base of the wall, which is clear from simple equilibrium. The second term is related to the contribution of the second mode and it considers the fact that the contribution of higher modes should not be reduced, because energy dissipation is induced by inelastic flexural behaviour at the base of the cantilever wall, which is controlled by the first mode. The high bound for ε is set as the behaviour factor q used in the design. It should be also noted that ε was derived for the shear force at the base of the wall. Slightly improved version of the EC8 equation (1)

EC8 procedure is moderately conservative for walls with first vibration period between 1 sec and 2.5 sec, but generally gives reliable results (Rejec et al., 2011). The revision made by Rejec et al. (2011) showed some inconsistency in the derivation and application of Keintzel's equation. Therefore slightly modified version of Keintzel's equation was proposed (2), which yields accurate and consistent results for isolated multi storey walls.

$$\varepsilon_{mod} = q \cdot \sqrt{\left(min\left[\frac{\gamma_{Rd}}{q} \cdot \frac{M_{Rd}}{M_{Ed}}; 1\right]\right)^2 + 0.1 \cdot \left(\frac{S_e(T_C)}{S_e(T_1)}\right)^2} \geq 1.5 \tag{2}$$

Equation (2) should be applied to seismic shear forces obtained by modal response spectrum analysis considering only the first mode of vibration (shear forces denoted by $V_{Ed,1}$'):

$$V_{Ed} = \varepsilon_{mod} \cdot V_{Ed,1}' \tag{3}$$

OVERTURNING OVERSTRENGTH FACTOR AND COUPLING LEVEL OF COUPLED WALLS SYSTEMS

The term coupled walls refers to a group of two or more individual cantilever wall piers connected by relatively weak coupling beams, which may be short and deep. A proper design assures that the beams are able to dissipate energy over the height of the system. Also a ductile flexural mechanism is allowed to form at the base of the walls.

The discussion in the continuation of the paper refers to coupled walls composed by two equal wall piers (Figure 1). Before the main discussion about the shear magnification, some seismic resistance characteristics of CW systems are presented. Those are the *overturning overstrength factor* and the *coupling level*. As it is explained in the next chapters, both characteristics directly influence the shear magnification in CW systems.

The overturning moment on the CW system caused by seismic action (denoted $M_{E,sys}$) can be expressed by Eq. (4):

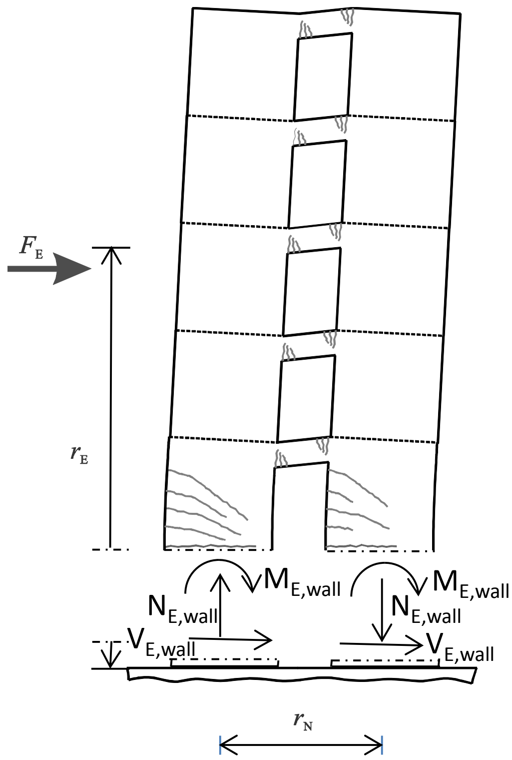

Figure 1. Plastic mechanism in a coupled wall system with two walls

$$M_{\mathrm{E,sys}} = 2 \cdot M_{\mathrm{E,wall}} + r_N \cdot N_{\mathrm{E,wall}} \tag{4}$$

$M_{E,wall}$ is the seismic moment demand at the base of the walls (Note: Because $M_{E,wall}$ is obtained with simplified elastic analysis, it is equal for both walls);
$N_{E,wall}$ is the seismic axial force demand at the base of the walls;
r_N is the horizontal distance between the section centroids of the walls (Figure 1).

By analogy, overturning moment is resisted by two mechanisms: (i) Flexural resistance at the base of the walls; (ii) The couple of axial forces, which form in the walls due to the coupling effect. The coupled wall system reaches its maximum overturning resistance when the full plastic mechanism is developed (Figure 1). The change of the axial forces at the base of the walls $\Delta N_{R,wall}$ is equal to the sum of the transverse resistances of all coupling beams:

$$\Delta N_{\mathrm{R,wall}} = \sum_{i=0}^{n} V_{\mathrm{R,beam,i}} \tag{5}$$

n is the number of storeys, which is equal to the number of beams;
$V_{R,beam,i}$ is the transverse resistance of coupling beam i, located in i-th storey.

The axial force at the base of the walls due to non-seismic loads is denoted with $N_{G,wall}$ (both walls are geometrically equal). At maximum overturning resistance the axial force in tension and compressive wall equals $N_{G,wall}$ - $\Delta N_{R,wall}$ and $N_{G,wall}$ + $\Delta N_{R,wall}$ respectively. Thus, the overturning resistance of the system $M_{R,sys}$ is expressed by:

$$M_{\mathrm{R,sys}} = M_{\mathrm{R,wall}}\left(N_{\mathrm{G,wall}} + \Delta N_{\mathrm{R,wall}}\right) + M_{\mathrm{R,wall}}\left(N_{\mathrm{G,wall}} - \Delta N_{\mathrm{R,wall}}\right) + r_N \cdot \Delta N_{\mathrm{R,wall}} \quad (6)$$

In (6) $M_{R,wall}(N)$ is the flexural resistance at the base of one wall at axial force N. The overturning overstrength of the system $\omega_{R,sys}$ is defined by the ratio:

$$\omega_{\mathrm{R,sys}} = {M_{\mathrm{R,sys}}}\big/{M_{\mathrm{E,sys}}} \quad (7)$$

The coupling level (or coupling ratio) can be defined in different ways. In this paper it is defined as the ratio between the overturning resistance provided by the couple of axial forces and the total overturning resistance $M_{R,sys}$:

$$\eta_{\mathrm{c}} = {r_N \cdot \Delta N_{\mathrm{R,wall}}}\big/{M_{\mathrm{R,sys}}} \quad (8)$$

CHARACTERISTICS OF COUPLED WALL MODELS USED IN THE STUDY

The verification of Eurocode 8 procedure was done by comparing the shear forces obtained by the equivalent elastic code procedure with the results obtained by the inelastic response history analyses. Two 12-storey and two 20-storey representative CW systems were analysed. The systems were designed for high ductility using modal response spectrum analysis and considering a behaviour factor of $q=q_0\cdot\alpha_u/\alpha_1=4.0\cdot1.3=5.4$. Eurocode design response spectra for PGA=0.25·g and soil type C were used. Redistribution of forces between walls (EC8 allows up to 30%) and between coupling beams (up to 20%) was considered. All examined systems had wall-to-floor ratio equal to 2.0% and floor vertical load due to non-seismic actions 10 kN/m^2. The requirements in the Slovenian national Annex to Eurocode 2 (CEN, 2005) were also considered: (i) the minimum amount of total vertical reinforcement in the walls was $A_{s,vmin}$ = 0.003·A_c and (ii) the minimum size of the vertical reinforcing bars in the boundary elements was 12 mm. Standard C30/37 concrete and S500 steel were used in the design.

Table 1. Characteristics of the analysed coupled walls

Tag	No of stories	Wall pier: Section	Beam: Length	Beam: Section	System: Stiffness	Coupling level
CW_12s_05EI	12	30 x 300 cm	200 cm	30 x 70 cm	50% of gross sections	0.58
CW_12s_Iy	12	30 x 300 cm	200 cm	30 x 70 cm	Secant at yield	0.54
CW_20s_05EI	20	30 x 600 cm	300 cm	30 x 50 cm	50% of gross sections	0.33
CW_20s_Iy	20	30 x 600 cm	300 cm	30 x 30 cm	Secant at yield	0.36

Note that according to EC8 one can design RC structures either by considering secant stiffness of the elements at first yield or by simply assuming 50% of the gross sections stiffness. Adopting the second assumption structures are typically much stiffer than in the case of the actual inelastic response. Therefore this factor should be considered in the comparisons.

The walls in the inelastic models were modelled by inelastic beam elements with distributed plasticity and fiber sections. Therefore the axial-flexural interaction was covered. The beams were modelled by elastic line elements with inelastic rotational springs at both ends. The initial stiffness of coupling beams was determined according to equation (5.8a) in Paulay and Priestley (1992). Design values for the material strengths were used. Five percent mass and current stiffness proportional Rayleigh damping was considered in the first and second modes. The response history analyses were performed using OpenSees (2013). A set of 14 artificial accelerograms with spectra matching the EC8 elastic spectrum for soil type C and a_g=0.25g were used in the response history analyses (for details, see Rejec et al., 2011). The shear forces V_{IA} were determined as the mean values of the results, obtained by using the 14 selected accelerograms.

VERIFICATION OF THE EC8 PROCEDURE

Keintzel's factors were evaluated for each wall separately, as it is implied in the EC8 provisions. Because the maximum shear demand is likely to occur approximately simultaneously as the maximum overturning demand, the overstrength factors were evaluated considering the maximum compressive force at the base of the walls ($N_{G,wall} + \Delta N_{R,wall}$). The input parameters for Keintzel's factors and results of the verification of EC8 procedure for coupled wall systems are presented in Table 2.

The overstrenght of walls at the base ω_{Rd} is quite large, which is due to: (i) Requirements for minimum amount of total vertical reinforcement; (ii) Evaluation of overstrength factor at maximum compressive axial force. Large overstrength factors and rather large spectral acceleration ratios $S_e(T_C)/S_e(T_1)$ result in the highest possible magnification factors provided by EC8 ($\varepsilon = q$). In all the cases the Eurocode procedure overestimated the shear forces obtained by the inelastic analyses V_{IA}. For the 12-storey systems the ratio V_{Ed}/V_{IA} was approximately 2; for 20-storey systems it was around 1.4. It can be also observed that for the analysed systems magnifications V_{IA}/V_{Ed}' (Table 2) are lower than the flexural overstrengths of the walls ω_{Rd}.

Table 2. Input parameters and results of the verification of EC8 procedure for coupled wall systems

System tag	*CW_12s_05EI*		*CW_12s_1y*		*CW_20s_05EI*		*CW_20s_1y*	
T_1, T_2	1.04 s, 0.28 s		1.35 s, 0.41 s		2.13 s, 0.53 s		2.28 s, 0.65 s	
	Wall 1	Wall 2	Wall 1	Wall 2	Wall 1	Wall 2	Wall 1	Wall 2
ω_{Rd}	4.07	4.07	5.89	5.89	3.50	3.50	5.53	5.53
ε	5.40	5.40	5.40	5.40	5.40	5.40	5.40	5.40
V_{IA}/V_{Ed}'	2.47	2.61	3.10	3.07	3.78	3.53	4.22	4.06
V_{Ed}/V_{IA}	2.19	2.07	1.74	1.76	1.43	1.53	1.28	1.33

DERIVATION OF A NEW MAGNIFICATION FACTOR FOR COUPLED WALL SYSTEMS

The modified Keintzel's equation (equation 2) was selected as the initial form for the new magnification factor. The reasons for such choice were: (i) consistency with the current Eurocode procedure; and (ii) good performance for isolated wall systems. In the introduced procedure, the coupled wall is considered as an integrated system. Therefore the wall piers are not addressed separately, as it is suggested in the current EC8 procedure. Therefore the first modification has been the substitution of the flexural overstrength factor ω_{Rd} with the overturning overstrength factor $\omega_{R,sys}$ (equation 7).

Keintzel's equation assumes that the higher modes contribution to shear forces is not reduced by the inelastic mechanism. As discussed before coupled walls are characterised by additional plastification/energy dissipation in the coupling beams along the height of the wall. Therefore an additional factor R_2 that considers the reduction of the second mode shear forces was introduced in the second term of the modified Keintzel's equation. A simple and representative measure for the level of distribution of dissipative zones along the height is the coupling level η_c. Therefore R_2 is a function of η_c. At η_c = 0 (uncoupled system) the reduction second/higher modes contribution is negligible. Therefore $R_2(\eta_c = 0) = 1$. At $\eta_c = 1$ it was assumed that all the modes are equally reduced, thus $R_2(\eta_c = 1) = q$. Although the realistic systems with very strong coupling have coupling levels below 1.0

(around 0.75), the upper value $R_2(\eta_c = 1) = q$ was introduced only for the mathematical formulation of $R_2(\eta_c)$. The shape of the function at the interval $0<\eta_c<1$ was calibrated with the results of the parametric study.

Energy dissipation in cantilever walls is restricted to the contribution of the first mode. Therefore Keintzel's equation is considering flexural overstrength only in the first term. However, in the case of coupled walls flexural overstrength should be considered also in the second term. The larger the coupling is, the larger this factor should be. The boundary values are: $\omega_{R,2}(\eta_c=0) = 1$ (uncoupled system) and $\omega_{R,2}(\eta_c=1) = \omega_{R,sys}$.

Based on the above considerations, a new magnification factor ε_{cw} for coupled walls is proposed:

$$\varepsilon_{cw} = \sqrt{\left(min\left[\omega_{R,sys}; q\right]\right)^2 + 0.1 \cdot \left(\omega_{R,2} \cdot \frac{q}{R_2} \cdot \frac{S_e(T_2)}{S_e(T_1)}\right)^2} \geq 1.5 \quad (9)$$

Note that in the expression for ε_{cw} the spectral acceleration $S_e(T_C)$ was substituted by $S_e(T_2)$.

To obtain the design shear forces (denoted $V_{Ed,cw}$) the shear magnification factor ε_{cw} should be used in combination with the shear forces contributed by the first mode at the base of the coupled walls:

$$V_{Ed,cw} = \varepsilon_{cw} \cdot V_{Ed,1}{'} \quad (10)$$

The distribution of the shear forces along the height of the coupled wall is not discussed in this paper.

The set of CW systems, which was used for the verification of the EC8 procedure, was extended in order to obtain systems with a wider range of coupling levels and overturning overstrength factors. The additional systems were obtained by increasing/lowering the capacity of the coupling beams or walls and therefore they were not strictly designed according to Eurocode. Nevertheless all systems met the overturning moment demand in EC8. This means that larger force redistributions were allowed and the requirements for minimal amount of reinforcement were neglected in some cases. The data for 12 storey systems are presented in Table 3. The data for *CW_20s_05EI* and its variants are presented in Table 4 and for *CW_20s_1y* in Table 5.

Table 3. Characteristics and analyses results for the 12 storey coupled wall systems

System tag	*CW_12s_05EI* **-1-**	*CW_12s_05EI* **-2-**	*CW_12s_05EI* **-3-**	*CW_12s_05EI* **-4-**	*CW_12s_1y* **-1-**	*CW_12s_1y* **-2-**
Description	Basic variant (EC8)	Reduced reinforcement in walls	Increased reinforcement in walls	Reduced reinforcement in beams	Basic variant (EC8)	Reduced reinforcement in walls
η_c	0.58	0.62	0.53	0.39	0.54	0.58
$\omega_{R,sys}$	1.40	1.31	1.53	1.04	1.67	1.56
V_{IA}/V_{Ed}'	2.54	2.67	2.47	2.29	3.09	3.10
$V_{Ed,EC8}/V_{IA}$	2.13	2.02	2.19	2.36	1.75	1.75
$V_{Ed,cw}/V_{IA}$	0.94	0.85	1.02	1.11	1.02	0.95

NOTE: V_{IA}/V_{Ed}', $V_{Ed,EC8}/V_{IA}$ and $V_{Ed,cw}/V_{IA}$ are average values for both walls. For all analysed walls the difference between the maximum and average values were less than 5%

Table 4. Characteristics and analyses results for CW_20s_05EI system and its variants

System tag	*CW_20s_05EI* **-1-**	*CW_20s_05EI* **-2-**	*CW_20s_05EI* **-3-**	*CW_20s_05EI* **-4-**	*CW_20s_05EI* **-5-**	*CW_20s_05EI* **-6-**
Description	Basic variant (EC8)	Reduced reinforcement in walls	Increased reinforcement in walls	Increased reinforcement in beams	Reduced reinforcement in beams	Highly increased reinforcement in beams and reduced in walls
η_c	0.33	0.35	0.29	0.42	0.19	0.67
$\omega_{R,sys}$	1.96	1.81	2.16	2.25	1.66	2.84
V_{IA}/V_{Ed}’	3.65	3.42	3.60	3.65	3.44	4.70
$V_{Ed,EC8}/V_{IA}$	1.48	1.58	1.50	1.48	1.57	1.15
$V_{Ed,cw}/V_{IA}$	1.04	1.07	1.10	0.98	1.21	1.01

NOTE: V_{IA}/V_{Ed}’, $V_{Ed,EC8}/V_{IA}$ and $V_{Ed,cw}/V_{IA}$ are average values for both walls. For all analysed walls the difference between the maximum and average values were less than 5%

Table 5. Characteristics and analyses results for CW_20s_05EI system and its variants

System tag	*CW_20s_1y* **-1-**	*CW_20s_1y* **-2-**
Description	Basic variant (EC8)	Highly increased reinforcement in beams and reduced in walls
η_c	0.36	0.70
$\omega_{R,sys}$	2.30	2.44
V_{IA}/V_{Ed}’	4.19	4.06
$V_{Ed,EC8}/V_{IA}$	1.29	1.33
$V_{Ed,cw}/V_{IA}$	0.99	1.03

NOTE: V_{IA}/V_{Ed}’, $V_{Ed,EC8}/V_{IA}$ and $V_{Ed,cw}/V_{IA}$ are average values for both walls.

Factors R_2 and $\omega_{R,2}$ were calibrated on the basis of the extended set of CW systems (Tables 2 to 4). The aim was to find mathematical relations, which are as simple as possible. It was found out that, the relation $R_2(\eta_c)$ can be represented by a linear function (Figure 2a, equation 11) and relation $\omega_{R,2}(\eta_c)$ by a piecewise linear function (Figure 2b, equation 12).

$$R_2 = 1 + \eta_c \cdot (q - 1) \tag{11}$$

$$\omega_{R,2} = \begin{cases} 2 \cdot (\omega_{R,sys} - 1) \cdot \eta_c - \omega_{R,sys} + 2, & \eta_c \geq 0.5 \\ 1, & \eta_c < 0.5 \end{cases} \tag{12}$$

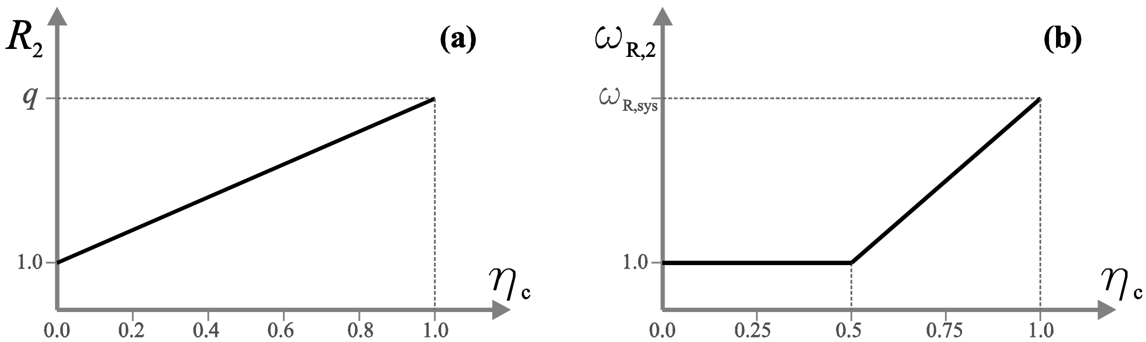

Figure 2. Relations (a) $R_2(\eta_c)$ and (b) $\omega_{R,2}(\eta_c)$

The use of more refined mathematical functions was not warranted, because the set of analysed CW wall is relatively limited. Moreover the magnification factors should be as simple as possible for an efficient use in the design practice.

Figure 3 and Table 3 show $V_{Ed,cw}$ and $V_{Ed,EC8}$ (current EC8 procedure) values compared to V_{IA} for the analysed 12-storey CW systems. $V_{Ed,EC8}$ overestimates the inelastic analyses shears by approximately factor 2.0. $V_{Ed,cw}$ gives very good results with an average $V_{Ed,cw}/V_{IA}$ equalling 0.98 and maximum deviation of 15% (for *CW_12s_05EI-2*).

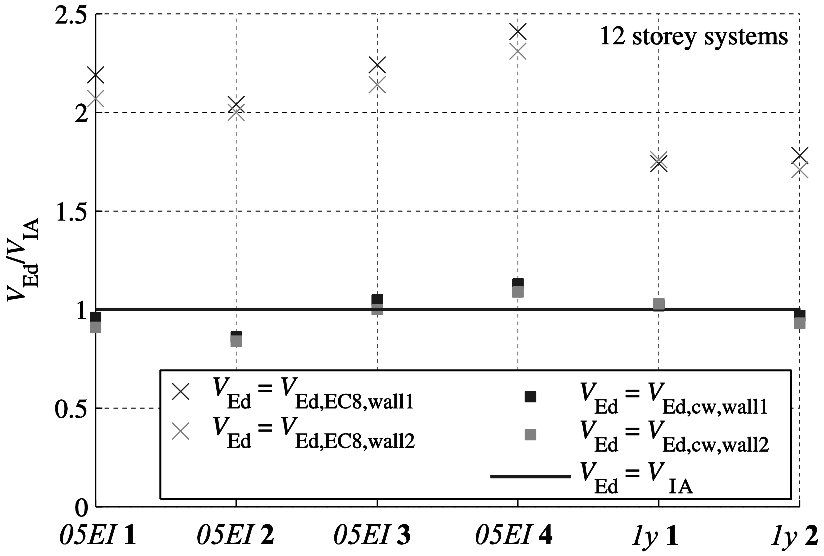

Figure 3. Values $V_{Ed,EC8}/V_{IA}$ and $V_{Ed,cw}/V_{IA}$ for 12-storey coupled wall systems

The accuracy of $V_{Ed,cw}$ when comparing to V_{IA} is also very good in the case of the addressed 20-story CW systems (Figure 4, Table 4 and 5). The average of $V_{Ed,cw}/V_{IA}$ is 1.05. The maximum deviation is 21% and belongs to system *CW_20s_05EI-5*, which has the smallest η_c in the analysed set ($\eta_c = 0.19$ and did not fulfil the EC8 criteria for coupled walls). In other cases the difference between $V_{Ed,cw}$ and V_{IA} was less than 10%. In average $V_{Ed,EC8}$ overestimated the inelastic analyses shears by approximately 40%.

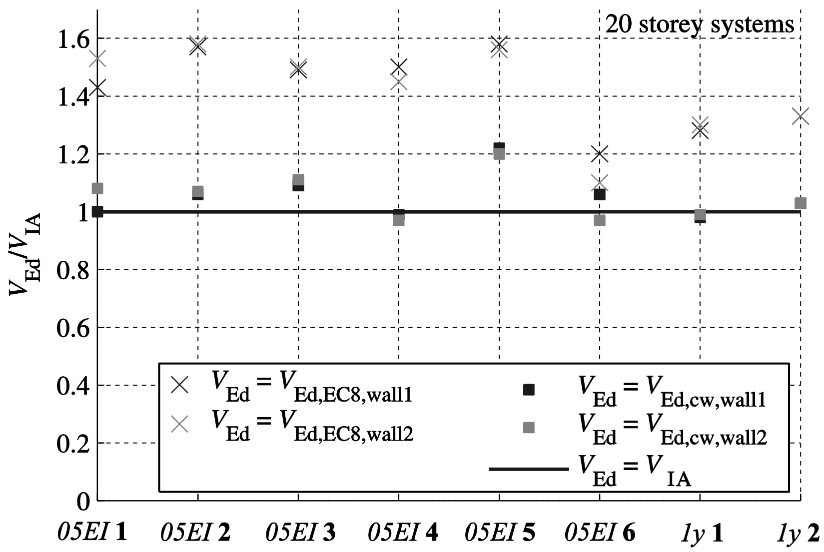

Figure 4. Values $V_{Ed,EC8}/V_{IA}$ and $V_{Ed,cw}/V_{IA}$ for 20-storey coupled wall systems

CONCLUSIONS

The paper addresses the seismic shear force magnification in coupled wall systems. The current Eurocode 8 (CEN, 2004) procedure was tested on a limited set of representative structural systems. On the basis of the obtained results, modifications of the current EC8 magnification factors (strictly valid for cantilever walls only) were proposed. The study yielded the following conclusions:

1) The shear magnification should be in general lower for the coupled walls than for the uncoupled walls. This is due to the completely different plastic mechanism, which allows for energy dissipation in the coupling beams along the height of the coupled wall. This reduces the shear forces contributed by the higher modes as opposed to the case of cantilever walls, where only the reduction of the contribution of the fundamental mode is warranted.
2) Design seismic shear forces obtained by the current EC8 procedure significantly overestimate the seismic demand, impeding an optimal design, and in some cases even the feasibility of the design.
3) The new magnification factor ε_{cw} has been introduced. In ε_{cw} the level of the reduction of seismic shear forces contributed by the second mode is considered as a function of the coupling strength ratio η_c. The influence of the overturning overstrength on the contribution of the higher modes is also taken into account.
4) The proposed magnification factor ε_{cw} yielded very good and consistent results for the set of the coupled wall models analysed in the presented study. It is fully realised that only a very limited sample of coupled walls was analysed. While it is therefore obvious that the proposed shear force magnification factor needs further calibration, it is nevertheless believed that the general idea of its formulation is valid and interesting.

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