Shear magnification factors for RC structural walls in Eurocode 8

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ABSTRACT:
Some shear failures of RC structural walls were observed during major earthquakes. They were due to the limited knowledge of the shear capacity as well as to the inadequate estimate of the demand. In Eurocode 8 (CEN, 2004) the actual level of the shear forces in RC structural walls during inelastic response is estimated on the basis of the shear magnification factor "ε" proposed by Kientzel (1990). It takes into account the capacity design principles and the influence of higher modes during inelastic response. While Keintzel's formula in general works fine, it has been based on rather limited parametric study. A more complete parametric study was done, major factors influencing the shear increase were identified and modified expression for "ε" was proposed.

Keywords: Shear magnification factor, structural walls, Eurocode 8, capacity design

1. INTRODUCTION

It has been long known that during the inelastic response the actual shear forces in reinforced concrete structural walls are typically much higher than the forces foreseen by the equivalent elastic procedures (Blakeley et al., 1975). This is due to the flexural overstrength as well as to the amplified effect of the higher modes in the inelastic range.

Capacity design considerations require that flexural plastic hinge develops at the base of a structural wall. Meanwhile the sufficient shear strength of the member should ensure that the inelastic deformation occurs only in a flexural mode. Therefore a robust analysis procedure which yields realistic assessments of seismic shear demand is needed.

Eurocode design provisions provide procedure to account for seismic shear amplifications in RC structural walls. However, recent research work done by Rutenberg and Nsieri (2006), Kappos and Antonidas (2007) and Priestley et al. (2007) has shown that the Eurocode procedure needs some revisions in order to estimate the shear magnification factors better. In the case of a moderate ductility design (DCM design) the design shear forces are typically to low, as they are taken simply just 1.5 times the value obtained from the equivalent elastic analysis, not taking in account the flexural overstrength of the wall. In the case of the ductility class high – DCH structures, the procedure based on the work of Keintzel (1990) is required. The theoretical background of this procedure is very robust and the results obtained by the proper use of it are mostly very satisfactory. The cause of usual conservative resulting values of shears is the lack of guidelines in Eurocode 8 (EC8) for a correct application of the Keintzel's equation.

Since the use of the RC structural walls is very common in Slovenia as well as to overcome some problems related to the application of the EC8 requirements in the everyday design, additional studies have been also done at the University of Ljubljana. A wide parametric study on multi-storey cantilever structural walls was made to determine the reliability of Eurocode procedures for the determination of seismic shear demand on cantilever walls and its results are presented in this paper. Moreover a modified procedure based on the Keintzel's formula is proposed.

2. DYNAMIC AMPLIFICATION OF SEISMIC SHEAR FORCES IN CANTILEVER WALLS

2.1. General description

Dynamic amplification of seismic shear forces occurs in multi storey structural walls which have their bending stiffness considerably larger than the horizontal elements (beams or slabs) clamped to them and are designed to exhibit flexural plasticity at the base solely. The intensity of the amplification is significantly influenced by the response spectrum shape of the applied earthquake load.

After an inelastic bending mechanism is formed at the base of a multi storey cantilever wall during a seismic action, the ratio of the contributions of individual modes of excitation to the overall seismic force considerably changes. The higher mode lateral seismic forces gain in contrast to the first mode seismic forces, lowering the position of the resultant of overall seismic force closer to the base of the wall (Figure 2.1.). Since the bending moment at the base is known (it is equal to the flexural resistance of the wall) it is obvious that the resultant seismic force (shear force) should increase.

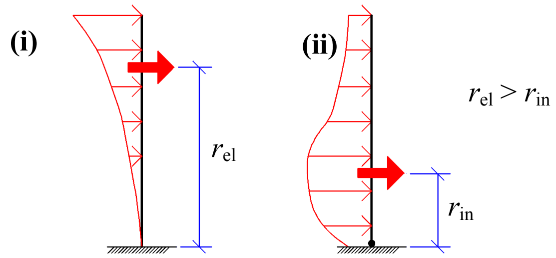

Figure 2.1. Lateral seismic forces distribution during an (i) elastic and (ii) inelastic response of a cantilever wall

2.2. Causes for the shear force amplification

2.2.1. Influence of overstrength
It is well known that flexural overstrength (the ratio between the actual flexural strength and the seismic flexural demand obtained by simplified methods) increases the design seismic shear forces. The increase is predominantly related to the first mode response although the contribution to the higher modes may be also important as it will be demonstrated in the continuation of the paper.

2.2.2. Influence of period shift
Due to the softening of the structural wall in the inelastic range the first mode spectrum value typically diminishes while the spectrum values for the higher modes remain in the spectrum plateau (the ratio of the second and first period is approximately 1:6). Therefore in the inelastic range the relative influence of the higher modes to the wall shears increases.

2.2.3. Influence of seismic force reduction
The first mode seismic forces contribute the majority of the overall seismic moment at the base of the wall, which is directly restricted by flexural resistance. On the other hand the higher mode forces have very small contribution to the overall seismic moment at the base and they are little influenced by the formation of the plastic hinge at the base of the wall. Therefore the shear forces due to the first mode should be reduced by the behaviour factor q, and the shear forces due to the higher modes should be not. This greatly increases the relative contribution of the higher modes to the shear during the inelastic response. This observation is also supported by extensive analysis done by Keintzel (1990), Rutenberg and Nsieri (2006), Kappos and Antonidas (2007) and Priestley et al. (2007) – and by investigations which are presented in the continuation of the paper. This effect not only amplifies the value of seismic shear at the base, but also in the upper half of the wall, as the second mode shears are particularly manifested there.

3. EUROCODE PROCEDURE

Eurocode procedure takes account of shear magnification in cantilever walls and requires to multiply the shear forces obtained by the equivalent elastic analysis V_{Ed}' with the shear magnification factor ε in order to obtain the design shear forces V_{Ed} (3.1).

$$V_{Ed} = \varepsilon \cdot V_{Ed}' \tag{3.1}$$

In the case of designing the wall to exhibit large plastic deformations (ductility class high – DCH structures) shear magnification factor is calculated by the expression (3.2) originally proposed by Keintzel (1990).

$$\varepsilon = q \cdot \sqrt{\left(\frac{\gamma_{Rd}}{q} \cdot \frac{M_{Rd}}{M_{Ed}}\right)^2 + 0.1 \cdot \left(\frac{S_e(T_C)}{S_e(T_1)}\right)^2} \begin{cases} \leq q \\ \geq 1.5 \end{cases} \tag{3.2}$$

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;
$S_{\mathrm{e}}(T)$ is the ordinate of the elastic response spectrum.

In the case of the moderate plastic deformations (ductility class medium – DCM design) smaller increase of the shear forces is expected and the shear magnification factor can be simply taken as ε = 1.5.

4. BACKGROUND OF THE EXPRESSION IN EC8

Keintzel (1990) made a parametric study comparing the results obtained with the lateral force method and inelastic response history analyses. Based on the results of this study he assumed that modal combination can be applied also in the inelastic range and that only the contribution of the first two modes is important (4.1).

$$V_{Ed} = \sqrt{\left(V_{Ed,1}\right)^2 + \left(V_{Ed,2}\right)^2} \tag{4.1}$$

V_{Ed} is the design seismic shear at the base of the wall;
$V_{\mathrm{Ed},1}$ is the design seismic shear at the base of the wall caused by the building oscillation in the first mode;
$V_{\mathrm{Ed},2}$ is the design seismic shear at the base of the wall caused by the building oscillation in the second mode.

He further assumed that the level of the reduction of seismic forces belonging to each mode was proportional to the level of the seismic moment at the base of the wall contributed by the excitation of that mode. In the case of the seismic forces related to the first mode of excitation, the reduction is high, equalling seismic reduction factor q, as the first mode related moment contributes the majority of the overall seismic moment (as well as related energy dissipation) at the base. On the other hand, seismic forces due to the higher mode act on the structure with the unreduced elastic value ($q \cdot V_{\mathrm{Ed},2}$)

$$V_{Ed} = \sqrt{\left(V_{Ed,1}\right)^2 + \left(q \cdot V_{Ed,2}\right)^2} \tag{4.2}$$

Considering that the flexural overstrength affects only the first mode shears and that in the response spectrum analysis the contribution of the second mode is about $\sqrt{0.1} \cdot S_{Ed}(T_2)/ S_{Ed}(T_1)$ of the contribution of the first mode, expression (4.3) can be derived.

$$V_{Ed} = \sqrt{\left(\frac{M_{Rd}}{M_{Ed}} \cdot \gamma_{Rd} \cdot V_{Ed,1}\right)^2 + \left(q \cdot V_{Ed,1} \cdot \sqrt{0.1} \cdot \frac{S_{Ed}(T_C)}{S_{Ed}(T_1)}\right)^2} \tag{4.3}$$

By subtracting $V_{Ed,1}$ in (4.3), the final form of expression (3.2) is obtained, meaning that Keintzel's magnification factor should be applied on seismic shear forces obtained by simplified analysis considering only the first mode of excitation.

Keintzel also determined that ε is limited by the upper value of q. The same assumption was adopted in EC8. While it is true that the upper bound for V_{Ed} is its elastic value V_E, the assumption that V_E equals $V_{Ed,1} \cdot q$, neglecting the contribution of higher modes, is not valid. This will be further discussed in the continuation of the paper.

5. VERIFICATION OF THE SHEAR MAGNIFICATION FACTOR IN THE EUROCODE

5.1. Parametric study outline

While Keintzel's research was certainly up-to-date in its time, the parametric study was rather limited in the view of the modern earthquake engineering. Keintzel's expression was originally tested with a limited number of wall parameters (just 2 and 3 storey walls were analyzed) and a very simple analytical model for RC elements was used from the today's point of view. The limitation $\varepsilon \leq q$ is not adequate. Although Keintzel's equation was developed to be applied on the seismic shear forces obtained by considering just the first mode of excitation, this is not specified in Eurocode. In the design practice multi-modal analysis is typically performed and this can lead to quite conservative results. Consequently there has been a need for additional research on shear magnification factors for structural walls.

In addition to research done by Rutenberg and Nsieri (2006), Kappos and Antonidas (2007) and Priestley et al. (2007) an extensive parametric study was performed at the University of Ljubljana. 74 different cantilever walls were analyzed and designed for the EC8 DCH requirements. Number of stories (n) varied from 4 to 20. Within each group of walls having the same number of stories the following parameters were varied depending on the design requirements and the feasibility of the construction: (i) the length of the wall l_w (between 2 and 8 m); (ii) the longitudinal reinforcement resulting in different overstrength ratios ($\omega_{Rd}=M_{Rd}/M_{Ed}$ between 1.1 to 5.5) and (iii) the wall-to-floor area ratio A_w/A (1.5%, 2.0% and 2.5%). Seismic shears obtained by modal response spectrum analyses and multiplied by Eurocode prescribed shear magnification factor were compared with the results obtained by the inelastic response history analyses.

Modal response spectrum analyses were carried with ETABS (CSI, 2009) using standard analysis parameters. The elastic flexural and shear stiffness properties equalled one-half of corresponding stiffness of uncracked elements. Eurocode response spectrums for PGA=$0.25 \cdot g$ and soil type C were used. Behaviour factor q=4.4 was assumed in the analyses as it corresponds to the DCH design of uncoupled wall systems.

As the axial force in cantilever walls remains constant during earthquakes and the walls were designed to exhibit inelastic flexural deformation only at their bases, the nonlinear model was obtained by adding a nonlinear hinge with Takeda hysteresis at the base of the elastic model. Moment-curvature section analyses were carried in Opensees (McKenna et al., 2008) in order to obtain the characteristic moments and curvatures for the wall cross section at the base. Values for characteristic rotations of plastic hinges were calculated by multiplying the curvatures with equivalent plastic hinge length L_P over which the plastic curvature is considered constant. The equation for plastic hinge length was taken according to Priestley et al. (2007). 14 artificial accelerograms with spectra matching the EC8 elastic spectrum (for PGA=0.25·g and soil type C) were used in the response history analyses, which were carried with Opensees (McKenna et al., 2008).

5.2. Analyses results and verification of Eurocode procedure

The values of the EC8 seismic design shear forces at the base of the walls (denoted as V_{Ed}) were compared with the ones obtained by the inelastic response history analysis (denoted as V_{IA}). V_{Ed}' in equation (3.1) was determined by the modal response spectrum analysis considering all important modes. Results are presented in Figures 5.1. and 5.2., in which each integer on the horizontal axes denotes an analysed wall configuration. The variation of the basic input parameters l_w , $\omega_{Rd}=M_{Rd}/M_{Ed}$, and A_w/A is illustrated on the Figures 5.1. (d) to 5.1. (f).

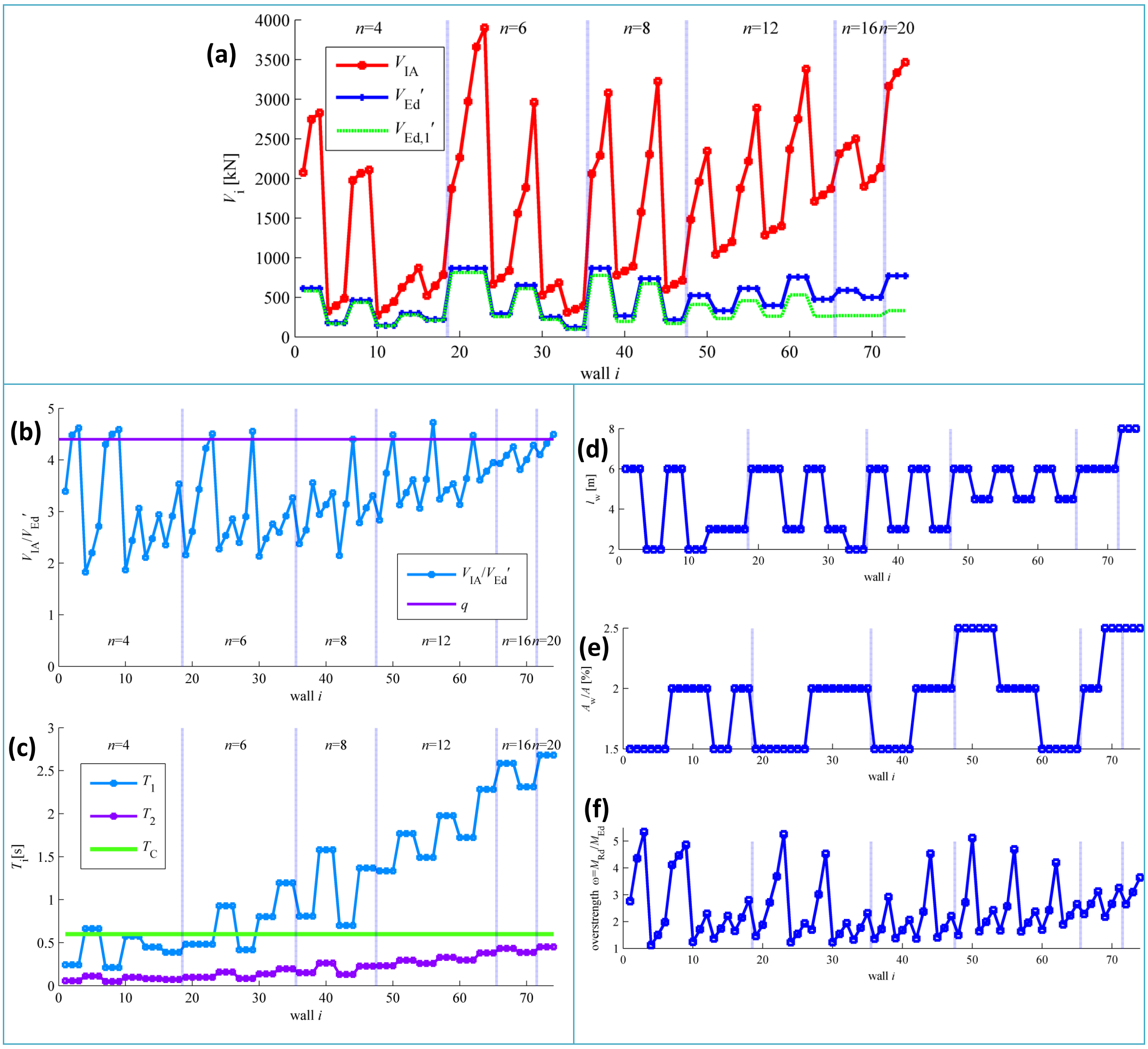

Figure 5.1. **(a)** Base shear for the analyzed walls obtained by different methods; **(b)** Shear magnification ratios V_{IA}/V_{Ed}'; **(c)** First and second periods of analysed walls. The variation of the basic input parameters is shown in Figures: **(d)** – length of the wall, **(e)** – wall-to-floor ratio and **(f)** – overstrength factor.
(Each integer on the horizontal axes denotes a particular combination of these parameters)

Figure 5.1. (a) illustrates large differences between V_{IA} and V_{Ed}', in particular for the structures with longer fundamental periods (Figure 5.1. - c) and large flexural overstrength (Figure 5.1. - f) resulting into the V_{IA} / V_{Ed}' ratios up to 4.5 (Figure 5.1. - b). It is also important to notice substantial difference between the base shear $V_{Ed,1}$' obtained by considering the fundamental mode only and the base shear considering all important higher modes V_{Ed}' for more flexible walls.

The EC8 values (denoted V_{Ed} and illustrated with a green line) are compared with the mean results of the inelastic response history analysis V_{IA} (red thick line) in Figure 5.2. Although the formula in EC8 has been based on the limited parametric study and several simplifications (see discussion in the previous sections) it yielded very good results in the case of the analyzed walls. Nevertheless some modifications have been proposed by the authors to further improve the results.

Similar study, not discussed in this paper showed that using constant value of ε = 1.5 for the ductility class medium walls is typically too small (similar conclusions were made by Rutenberg and Nsieri, 2006). The authors suggest that the procedure required for DCH walls is also used for DCM walls.

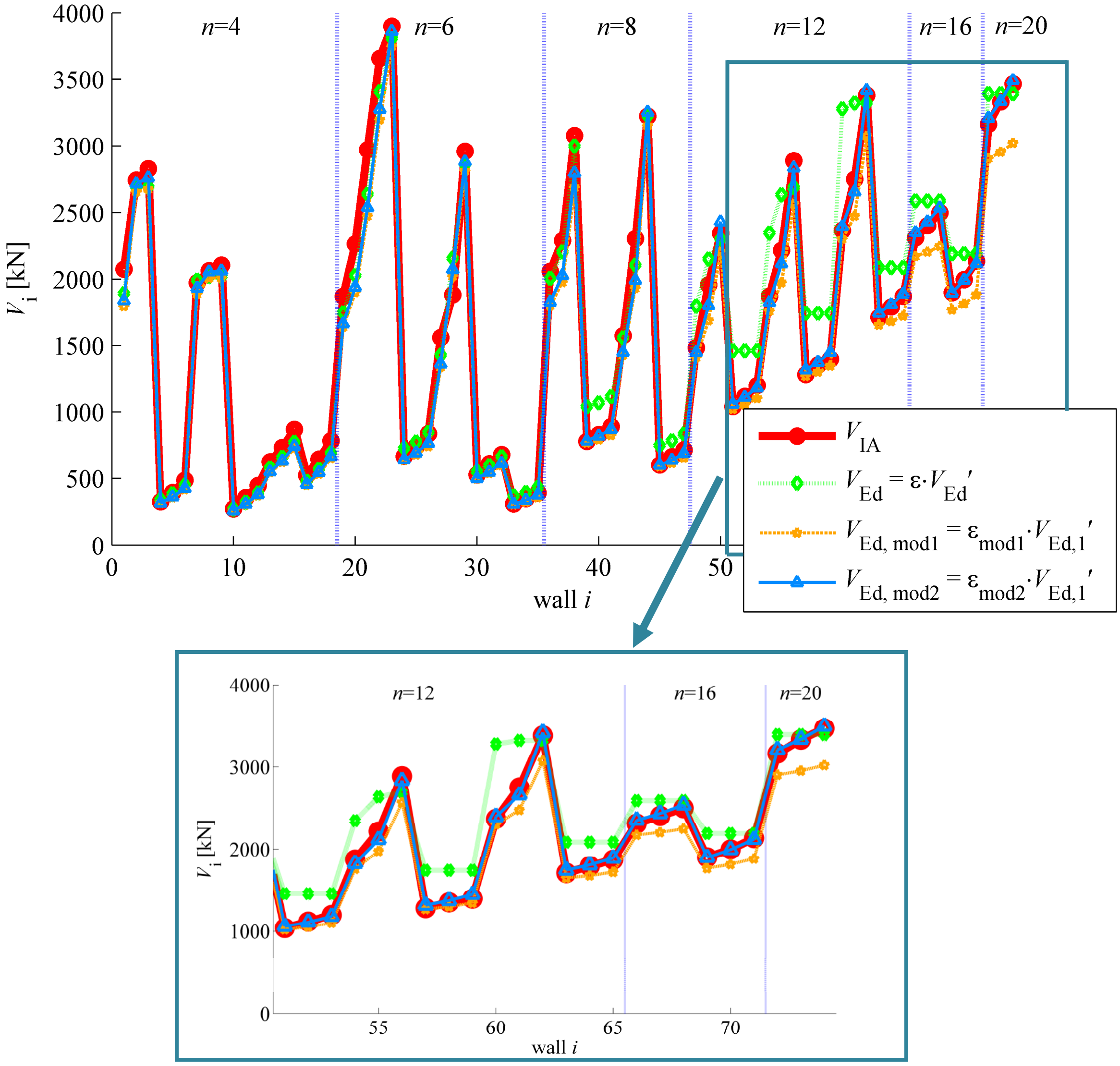

Figure 5.2. Comparison between the base shears obtained by the EC procedure, modified EC procedure and inelastic response history analysis. The results for wall configurations in which the modified procedure improvement is more pronounced are additionally zoomed.
(Each integer on the horizontal axes denotes an analysed wall configuration)

5.3. Possible improvements in the formulation of the shear magnification factor ε in EC8

The proposed improvement is presented in two steps.

First it has been considered that only the increase of the shear force contributed by the first mode is limited by q. However, Keinzel imposed this limitation on the combined contribution of both modes. While it is true that the upper bound for V_{Ed} is its elastic value of V_{E}, the assumption that V_{E} equals $V_{\mathrm{Ed,1}} \cdot q$, neglecting the contribution of higher modes, is not valid.

This first modification yields the following formula (5.1), which should be used in combination with $V_{\mathrm{Ed,1}}$.

$$\varepsilon_{\mathrm{mod1}} = q \cdot \sqrt{\left(\min\left[\frac{\gamma_{Rd}}{q} \cdot \frac{M_{Rd}}{M_{Ed}};\ \ 1 \right] \right)^2 + 0.1 \cdot \left(\frac{S_e(T_C)}{S_e(T_1)} \right)^2} \geq 1.5 \tag{5.1}$$

The seismic shear at the base of the analysed walls obtained by the first modification of the procedure (denoted as $V_{\mathrm{Ed,mod1}}$) are shown in Figure 5.2. with an orange dotted line. Except for 16 and 20 storey walls, the modified procedure yielded similar or better estimations of shears than the original EC8 procedure.

The major differences between V_{IA} and $V_{\mathrm{Ed,mod1}}$ occurred in walls with high flexural overstrength and significant contribution of second mode shears $V_{\mathrm{Ed,2}}$, suggesting that a portion of flexural overstrength should be also considered in the second term of (5.1), which represents the contribution of the second mode of excitation.

Therefore, a coefficient considering the influence of flexural overstrength on the second mode shears $\omega_{\mathrm{Rd,2}}$ (5.2) was added to the second term of (5.1).

$$\omega_{Rd,2} = 1 + A \cdot \left(\frac{\gamma_{Rd} \cdot M_{Rd}}{M_{Ed}} - 1 \right) \tag{5.2}$$

The value of A was determined by the condition of achieving the best fitting with inelastic response history analyses results. By inserting (5.2) with the constant A equalling 0.07 in the second term of (5.1), the second modification of Keintzel's expression is obtained (5.3).

$$\varepsilon_{\mathrm{mod2}} = q \cdot \sqrt{\left(\min\left[\frac{\gamma_{Rd}}{q} \cdot \frac{M_{Rd}}{M_{Ed}};\ \ 1 \right] \right)^2 + 0.1 \cdot \left(\left(1 + 0.07 \cdot \left(\frac{\gamma_{Rd} \cdot M_{Rd}}{M_{Ed}} - 1 \right) \right) \cdot \frac{S_e(T_C)}{S_e(T_1)} \right)^2} \geq 1.5 \tag{5.3}$$

The results obtained by multiplying $V_{\mathrm{Ed,1}}$ with $\varepsilon_{\mathrm{mod2}}$ are presented in figure 5.2 with a full blue line. The comparison with inelastic response history analyses results is very good. The flaws observed in the case of Eurocode results were eliminated. Additional analyses (using also different assumptions for initial stiffness and different amounts of non-seismic vertical load) were done on other configurations of walls (which were not utilized for the fitting of constant A), for a supplementary confirmation of the new procedure performance and proved its adequacy as well.

It should be emphasized that just simple cantilever walls were considered in the study. Further studies are required to determine the suitability of the EC8 procedure for more general systems containing structural walls. Preliminary studies on walls with openings have demonstrated even greater efficiency of the proposed modifications.

6. CONCLUSIONS

The issue of dynamic amplification of seismic shear forces in cantilever walls of has been discussed in the paper.

Large shear magnification factors ε (up to 4.5) have been re-confirmed by extensive parametric study, although questioned by many design practitioners. The expression for the shear magnification factor given in Eurocode (originally proposed by Keintzel) worked fine for the Ductility Class High structural walls, although it had been based on very limited parametric study and some crude assumptions. Nevertheless the EC8 formula typically yields slightly conservative results, if it is applied to the shear forces obtained from the multimodal equivalent elastic analysis.

Therefore some modifications were proposed by the authors to further improve the results. It was considered that only the increase of the shear force contributed by the first mode is limited by seismic force reduction factor q. Coefficient considering the influence of flexural overstrength on the second mode was added.

Similar study (not shown in this paper) re-confirms that that the constant value $\varepsilon = 1.5$ allowed by Eurocode for Ductility Class Medium walls is too low.

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