been also elaborated for two-way bending assessment (Vaculik 2012). It provides a method mainly depending on the kinematic mechanism of cracked URM walls, which is based on the rigid block motions. Furthermore, AS3700 (2018) and NPR 9998 (2020) propose an elastic force-based check approach, which is based on the Virtual Work Method (VWM). In this way, the masonry strength is considered to calculate an initial cracking resistance. In this section, the important details of each method are presented and discussed.

2.1 Eurocode 6 method

As a part of Eurocode 6 (NEN 2013), *Design of masonry structures*, describes the general principles and requirements for safety, serviceability and durability of masonry structures. It is based on the limit state concept used in conjunction with a partial factor method. For the lateral loading, *e.g.* seismic action, document defined the general rule of evaluation at the ultimate limit state: the design value of applied moment of masonry wall, M_{ED}, shall less or equal to the design value of moment resistance of the wall, M_{RD} (see Eq. (1)).

$$M_{ED} \leq M_{RD} \tag{1}$$

The design value of the lateral moment resistance of wall can be calculated by Eq. (2) per unit height or length.

$$M_{RD} = f_{xd} Z \tag{2}$$

In which, f_{xd} is the design flexural strength appropriate to the plane of bending. Z is the elastic section modulus of unit height or length of the wall.
The characteristic bending value is supposedly to be used in the Eq. (2). Therefore, the design flexural strength f_{xd} can be estimated based on the two failure mechanisms: parallel to the bed joint (f_{xk1}) and perpendicular to the bed joint (f_{xk2}). The values can be referred to the tested results, or to national code or to the tables listed in Eurocode 6 (NEN, 2013). Meanwhile, partial factor, the bending strength coefficient and the favorable effect of vertical compressive stress should be considered (NEN, 2013).
The applied moment (M_{ED}) can be calculated based on the different failure plane using Eq. (3) for failure parallel and perpendicular to the bed joints, respectively.

$$M_{EDi} = \alpha_i W_{ED} l^2 \tag{3}$$

In which, α_i (i = 1, 2) is the bending moment coefficients taking account of the degree of fixity at edges of the walls and the height to length ratio of the walls (Lw/Ht), shown in Fig.2. The values of α_1 and α_2 can be referred to Annex E of Eurocode 6 (NEN, 2013): $\alpha_1 = \mu\alpha_2$, μ is the orthogonal ratio of the design flexural strengths of masonry, f_{xd1}/f_{xd2} or $f_{xd1,app}/f_{xd2}$. W_{ED} is design lateral load per unit area. Therefore, the critical acceleration a_c (relative to gravity acceleration g) both in two directions can be rewritten as Eq. (4).

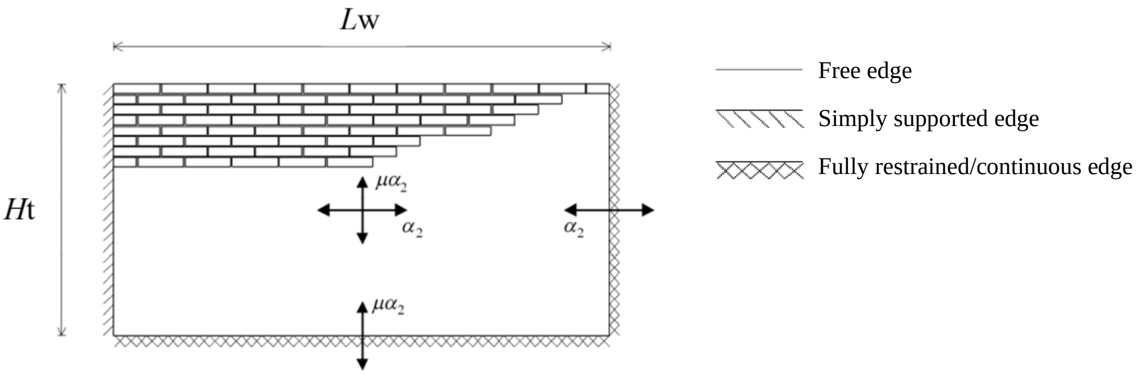


Fig. 2 Bending moment coefficients, α_1 and α_2, after Eurocode 6 (NEN, 2013)

$$a_c = \frac{f_{xd2}t}{6\alpha_2 \rho {L_w}^2 g} \tag{4}$$

In which, ρ is the density of masonry, and *t* is the wall thickness.

2.2 NLKA method

As introduced above, NLKA method has been adopted for the evaluation of one-way OOP bending capacity in NPR 9998 (2018). However, it should be extended to two-way OOP bending for a more accurate assessment. Vaculik (2012) elaborated the NLKA method for this purpose. It simulates the failure of rocking mechanism. The wall is assumed to be a cracked one and it is divided into several rigid blocks (see Fig. 3). The stability of mechanism is analyzed considering the non-linear load-displacement characteristics. The most of strength of the masonry is not taken into account by this method (Vaculik 2012).

The wall is firstly divided into an infinite number of vertical strips and evaluated the stability of strips. The ultimate overturning load δ_{ro} (critical acceleration) and instability displacement δ_{ru} can be calculated based on the equations in Table 1. The meanings of the main parameters are listed in Table 1 (refer to (Vaculik 2012) for all the other details).

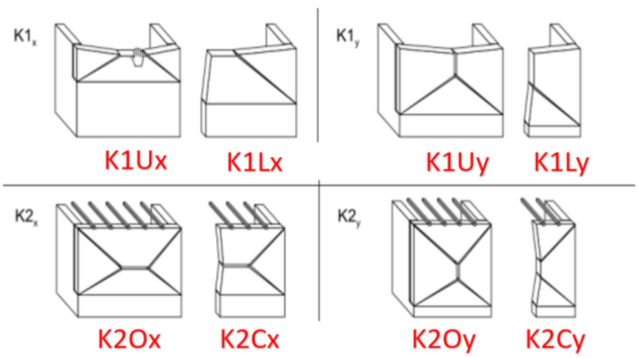


Fig. 3 Failure modes of masonry wall due to the two-way OOP bending, after (Vaculik 2012)

Table 1 Ultimate overturning load λ_{ro} and instability displacement δ_{ru}, after (Vaculik 2012)

Mechanism	Formula	Notations
$K1_x$	$\lambda_{ro}=\frac{t}{H_t}\frac{\left[\frac{3}{2}-\frac{a}{2}+2\psi(1-a\varepsilon)\right]-\frac{\Delta_T}{t}\left[\frac{2}{3}+\frac{a}{3}+\psi(1+a)\right]}{\frac{2}{3}+\frac{a}{3}}$	H_t: wall height;
	$\delta_{ru}=\frac{\frac{3}{2}-\frac{a}{2}+2\psi(1-a\varepsilon)}{\frac{2}{3}+\frac{a}{3}+\psi(1+a)}-\frac{\Delta_T}{t}$	$\Psi= W_{vo}/W_{tot}$: Overburden ratio (overburden load / weight of wall)
$K1_y$	$\lambda_{ro}=\frac{t}{H_t}\frac{\left[\frac{3}{2}+\frac{r}{2}+2\psi)\right]-\frac{\alpha\Delta_T}{t}\left[\frac{2}{3}+\frac{r}{3}+\psi\right]}{\alpha\left(\frac{2}{3}+\frac{r}{3}\right)}$	$\alpha=\beta*G_n= L_e/H_e*[2*(h_u+t_j)/(l_u+t_j)]$: Normalised effective aspect ratio mechanism, refer to (Vaculik 2012)
	$\delta_{ru}=\frac{\frac{3}{2}+\frac{r}{2}+2\psi}{\frac{2}{3}+\frac{r}{3}+\psi}-\frac{\alpha\Delta t}{t}$	Δ_T: Displacement top of wall (fixed value)
$K2_x$	$\lambda_{ro}=\frac{t}{H_t}\frac{4[1+\psi(2-\varepsilon)]}{\frac{2}{3}+\frac{a}{3}}-\frac{\Delta_T}{H_t}$	ε: Eccentricity overburden load (0, 0.5, 1 represent at the upward, middle and downward deflection point, respectively
	$\delta_{ru}=\frac{2[1+\psi(2-\varepsilon)]-\left(\frac{1}{3}+\frac{a}{6}\right)\frac{\Delta_T}{t}}{(1+a)(1+2\psi)}$	a=1-1/α: Shape parameter K2x and K1x mechanism ($\alpha\geq1$)
$K2_y$	$\lambda_{ro}=\frac{t}{H_t}\frac{4[1+\psi(2-\varepsilon)]}{\alpha\left(\frac{2}{3}+\frac{r}{3}\right)}-\frac{\Delta_T}{H_t}$	r=1-α: Shape parameter K2y and K1y mechanism ($\alpha\leq1$)
	$\delta_{ru}=\frac{2[1+\psi(2-\varepsilon)]-\frac{\alpha\Delta_T}{t}(\frac{1}{3}+\frac{r}{6})}{1+2\psi}$	t: wall thickness

2.3 VWM method

Virtual Work Method (VWM) has been adopted by several codes, *e.g.* AS3700 (2018), NPR 9998 (2020), *etc*. for two-way OOP bending assessment. An important parameter, called initial cracking resistance (ICR), is calculated to represent the bending capacity (Sharma *et al.* 2018). The ICR is then compared to the seismic demand based to check the wall safety. The ICR considers the horizontal and diagonal bending moment capacities and can be calculated by Eq. (5) (Sharma *et al.* 2018).

$$ICR=\frac{2a_f}{g\times L_d^2}(k_1M_h+k_2kM_d)\times Lw\times Ht \tag{5}$$

Where, g is the gravity acceleration; a_f is the aspect factor (refer to NPR 9998 (2020)); Lw and Ht are the length and height of the masonry wall; L_d is the design length (values based different conditions); M_h is the horizontal bending moment capacity per unit crack length based on Eq.(6). M_d is the diagonal bending moment capacity per unit crack length calculated based on Eq. (7) (Sharma *et al.* 2018).

$$M_h = less\ of\begin{cases}\frac{1}{2(h_u+t_j)}\left[(f_{bt}-v\sigma)h_u\frac{t_u^2}{6}\right] & (line\ failure)\\ \frac{1}{h_u+t_j}\left[0.5\tau_u k_b(l_u+t_j)t_u^2\right] & (stepped\ failure)\end{cases} \tag{6}$$

$$M_d = \frac{sin\varphi}{h_u+t_j}[0.5(sin\varphi)^3 t_u k_b (l_u+t_j) t_u^2 + (cos\varphi)^3 (f_m+\sigma)\frac{0.5(l_u+t_j)t_u^2}{6}] \quad (7)$$

In which, l_u, h_u and t_u are the length, height and thickness of a brick unit; t_j is the thickness of the mortar joint; f_{bt} is the flexural tensile strength of a brick; σ is the vertical pre-compression at mid height of wall; ν is the poison's ratio of masonry; τ_u is the ultimate torsional shear stress in bed joint $\tau_u = 0.9\sigma + 1.6f_{mt}$; k_b is a constant as 0.213; φ ($G_n = tan\varphi$) is the natural slope of masonry cracks, $\varphi = \text{atan}\,(\frac{2(h_u+t_j)}{l_u+t_j})$ for half-overlaps masonry; R_{f1} and R_{f2} are the restrain factor for the first and second supported edges, 0 if without rotational constrain, 1 if with full constrain, 0.5 based on some experiments (Sharma *et al.* 2018).

3. CASE COMPARISON STUDY

Based on introduction of three potential methods for the evaluation of two-way OOP bending capacity, some typical cases can be selected for the comparison of these methods. Besides some general information like wall dimensions: height (*h*), length (l), thickness (*t*), overburden stress (*σ*), some other parameters are required by different methods, which are summarized in Table 2. It shows Eurocode 6 method requires quite few geometry and material properties. NLKA method has almost no requirement for the material properties. VWM method has the greatest number of required material inputs.

Table 2 Summary of required inputs for the different methods

Methods	Eurocode 6	NLKA	VWM
Material inputs	Flexural strength f_{1x}	Compressive strength f_c	Masonry type
	Flexural strength f_{1y}	Density ρ	Density *ρ*
	Density *ρ*		Poisson's ratio *v*
			Flexural tensile strength of masonry f_{mt}
			Flexural tensile strength of unit f_{bt}
			Compressive strength of masonry f_b (f_m)
Other model inputs	Constrain type (simple support, fully constrained or free)	Natural diagonal crack slope G_n	Natural diagonal crack slope G_n
		Constraint type (support or free)	Constrain type (constrain level)
		Overburden eccentricity ε	Opening
		Top displacement Δ_T	Brick unit dimensions and joint thickness
		Cavity wall or single leaf	

Therefore, some two-way OOP bending capacities of typical masonry walls are evaluated with these three methods. Three cases are proposed for the comparison:

- Case 1: Four sides simply supported wall;
- Case 2; Three sides simply supported (top edge is free) wall;
- Case 3: Three sides simply supported (right edge is free) wall.

Some parameters are pre-defined for all the cases to have a fair comparison: A clay masonry (before 1945) is assumed for the material; its design flexural strengths (f_{xd1} and f_{xd2}) are assumed to be 0.15 MPa and 0.4 MPa for two directions; all the walls have 3 m height and 0.1 m thickness; brick dimension: 0.208 m (l_u) X 0.05 m (h_u) X 0.10 m (t_u); mortar joint is assumed to be a thin one with 2.67 mm thickness; Compressive strength of masonry (f_c) is 8.5 MPa; no overburden load is applied for all the cases. Furthermore, linear extrapolation and interpolation is used for the coefficients in the tables of Annex E of Eurocode 6 (NEN, 2013). Meanwhile, the partial factor (γ_m =1.5) and a bending strength coefficient (1.3) are used in the Eurocode 6 method.
The final results of critical accelerations with different lengths of wall are plotted in Fig.4 to Fig. 6 for Case 1 to Case 3, respectively. It shows that the Eurocode 6 method reveals the relatively lower bending capacity and the NLKA method has a higher capacity for all the three cases with a larger wall length. In most cases, two-way bending capacity is higher than the corresponding one-way OOP bending one with the same wall properties. The difference between these two bending situations is increased with decrease of wall length. In other words, the two-way bending capacity is close to the corresponding one-way bending capacity with a large length, except in Case 3. NLKA seems to have a slightly higher capacity for a wall with larger width (>6 m for Case 1, >2 m for Case 2 and >3 m for Case 3). In general, the capacities evaluated by the Eurocode 6 and VWM methods are similar, especially for a wall with a large width. Meanwhile, the capacities of wall assessed by these two methods are unrealistically low for Case 3 (>3 m), which should be carefully noticed in the real applications.
Case study shows the different results by various methods. The Eurocode 6 or VWM methods lead to higher capacity compared to the NLKA method for almost all the cases with aspect ratio Lw/Ht<1. This may be partly due to the idealization of the Eurocode 6 or VWM methods, which consider strength effects of masonry material. Furthermore, the wall is assumed to be cracked one in the NLKA method. Therefore, no tensile bond strength is considered by this method. The presence of tensile strength can lead the peak capacity be higher than the NLKA results.

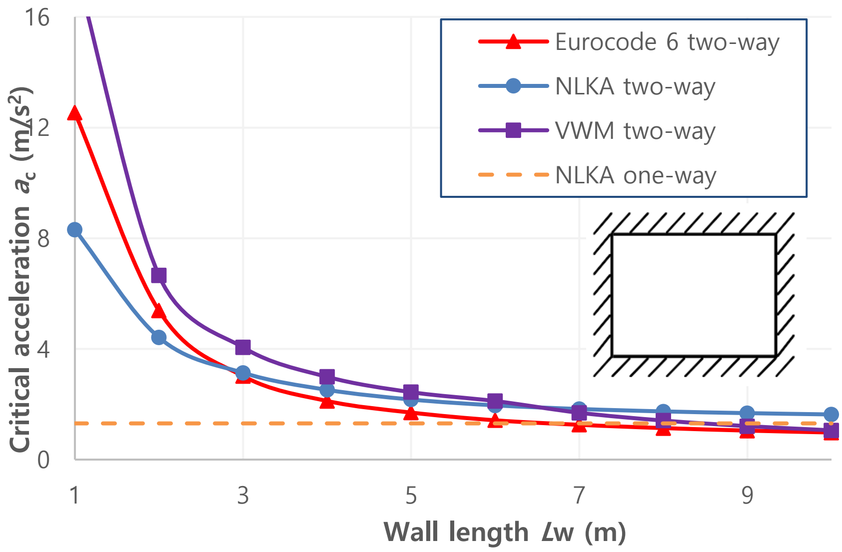


Fig. 4 The critical accelerations with different length by various methods (Case 1)

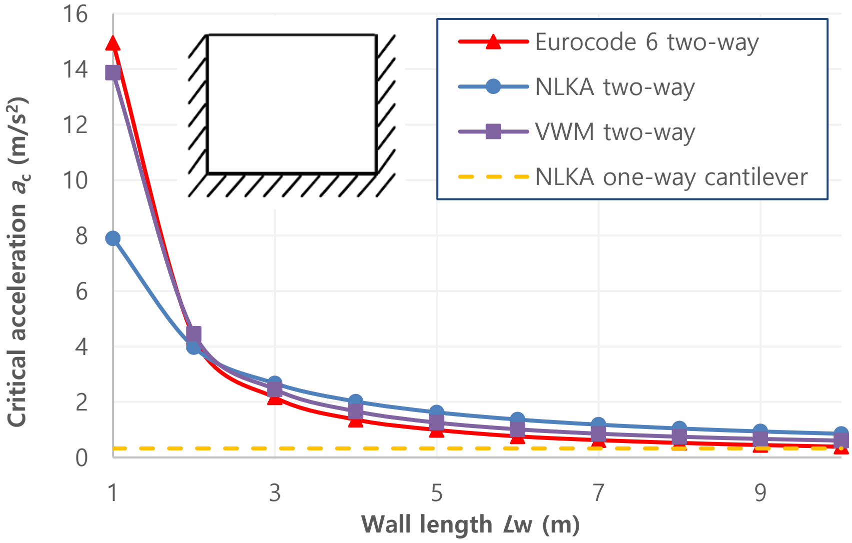


Fig. 5 The critical accelerations with different length by various methods (Case 2)

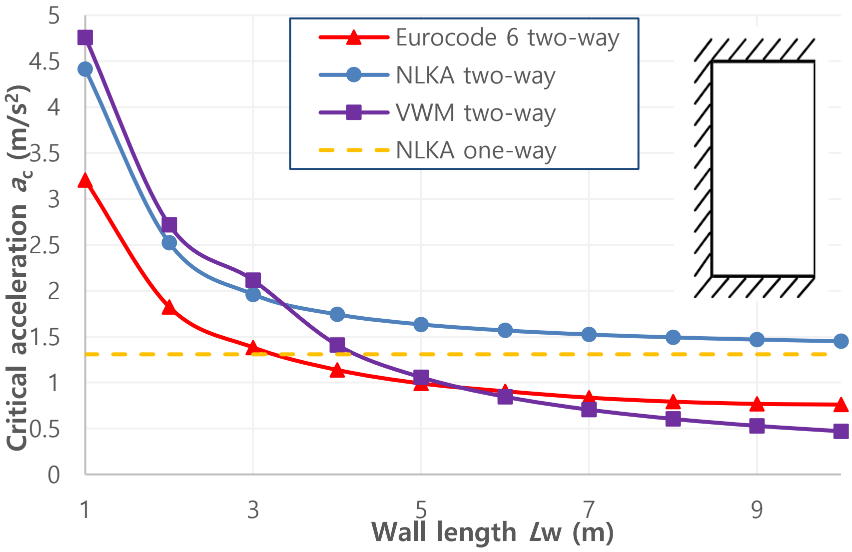


Fig. 6 The critical accelerations with different length by various methods (Case 3)

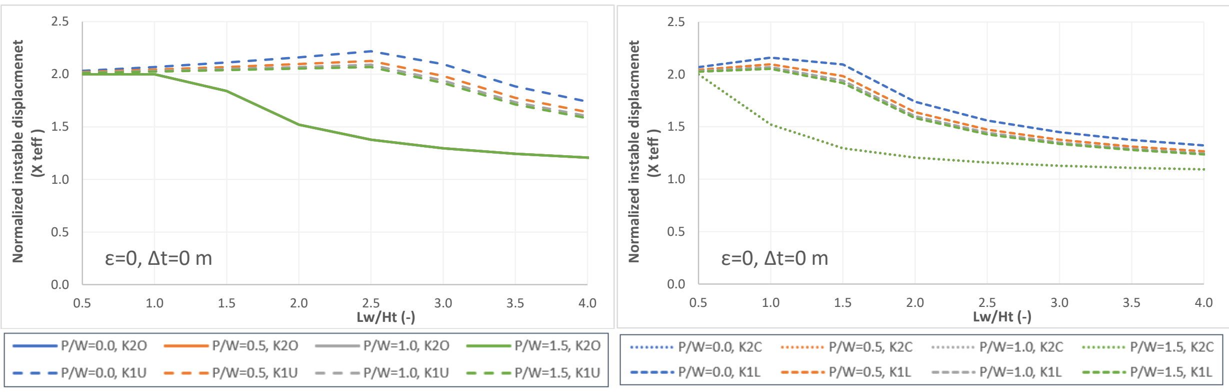
For Case 3 (see Fig. 6), the VWM method may underestimate the capacity when the length is larger than 3 m. This is mainly due to the assumption of simple support, which leads to the restraint factors to be 0. It may hardly happen based on some experiments (Sharma *et al.* 2018). A value of 0.5 would be more rational for this factor (Sharma *et al.* 2018).

Opening is an important part of masonry buildings. It could be directly considered by VWM, which is difficult for other two methods. Spitting wall into separate solid parts by the openings would be a feasible way to overcome the problem. However, the influences should be separately discussed in the future.

4. NC OOP DISPLACEMENT

For the assessment of the near collapse (NC) limit state of unreinforced masonry walls under seismic loading, guidance on the out-of-plane displacement limit of such walls is needed if the assessment is performed by a NLTHA, particularly when using implicit time marching schemes. Since implicit NLTHA does not explicitly show the collapse of parts or the whole structure, the near collapse limit state can only be inferred from divergence of the numerical process or evaluation of strains and displacements.

Some comparisons between NLTHA and experimental or analytical results are therefore helpful for the assessment of OOP NC displacement of URM walls in NLTHA. Compared to the one-way OOP bending, two-way OOP bending is more popular for the majority of walls. The two-way NLKA method elaborated by Vaculik (2012) seems the only feasible way for this assessment purpose. Fig. 7 shows the instability displacement with different geometries and boundary conditions of walls by the two-way NLKA method as a ratio of the effective thickness (around 0.9 time of wall thickness). Overburden ratio (*P*/*W*) has almost no influences on the OOP NC displacement when the top edge is constrained (K2O and K2C). Meanwhile, wall with a higher overburden ratio has also lower OOP NC displacement when the top edge is free (K1U and K1L). This phenomenon is similar as one-way NLKA OOP bending results. Generally, wall with a wider length has a lower OOP NC displacement. Considering the normal conditions of walls in Groningen buildings (aspect ratio *L*w/*H*t < 3 and overburden ratio *P*/*W* < 1.5), most of the lowest instable displacement is larger than the effective thickness, which is also higher than the one-way NLKA criterion.



(a) (b)

Fig. 7 Minimum normalized instability displacement according to the two-way NLKA method for the mechanisms (a) K1U and K2O; (b)K2C and K1L in Fig.3 : overburden ratio is *P*/*W*, *L*w is the length of the wall, *H*t is the height of the wall, *ε* is the eccentricity of top overburden load at the upward deflection point, *Δ*t is the displacement of wall top.

5. CONCLUSIONS

Two-way OOP bending performances are important for the URM buildings under the seismic risk. Three feasible analytical methods are discussed in this paper. Case studies show the different results by these methods. The pros and cons of each method can be listed in Table 3. Some other conclusions can also be drawn here.

1. It seems that two-way bending can largely improve the seismic OOP capacity, especially with a low l/h-ratio, compared to original one-way bending capacity.
2. Partial factor and the bending strength coefficient for the Eurocode 6 method and more realistic constraint factors for the VWM method should be considerred for a rational assessment.
3. The two-way NLKA method elaborated by Vaculik (2012) is a feasible way for the assessment of the near collapse (NC) OOP displacement. The results show the lowest instable two-way bending displacement is at least 100% of wall thickness, which is larger than the one-way NLKA criterion, considering the normal conditions of walls in Groningen buildings ($Lw/Ht < 3$ and $P/W < 1.5$).
4. This study is only on the analytical methods. Alternative numerical and experimental studies would be helpful for extended verification. Furthermore, some other parameters like masonry types, constraint conditions, overburden stress, openings, *etc.*, can be considered for a complete comparison.

Table 3 Summary of pros and cons of different methods

Methods	Eurocode 6	NLKA	VWM
Pros	Well-known reference	Less material properties inputs	Considering opening
		Consider the loading details	Constraint types
		Geometry details	Cavity wall considered
		Cavity wall considered	
Cons	Limited boundary conditions	Limited constraint types	A number of material parameters required
	Without opening	Without opening	
	Not for a cavity wall		
Results	Seems conservative (especially with a high *Lw*/*H*t-ratio)	Seems less conservative with a high *Lw*/*H*t-ratio	Seems closer to the Eurocode 6 method and less conservative for some cases with high *Lw*/*H*t-ratio

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