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# **FRP strengthening of RC walls with openings**

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## **ABSTRACT**

Strengthening reinforced concrete (RC) walls with openings using fibre reinforced polymers (FRP) has been experimentally proven to be a viable rehabilitation method. However, very few theoretical investigations are reported. In this paper two methods of analysis are presented. Since openings vary in size, the analysis of a strengthened wall can be divided into frame idealization method for large openings, and combined disk and frame analysis for smaller openings. The first method provides an easy to use tool in practical engineering, where the latter describes the principles of a ductile strengthening method, relying on dislocation of yield lines and creation of a new yield mechanism. The frame idealization method can be considered as a safe guideline for real strengthening projects based on commonly used principles. The principles in the latter are new and promising, but need experimental verification before use in strengthening projects.

## **INTRODUCTION**

High-rise structures are one of the most common structural systems in the world. When high-rise structures are constructed from reinforced concrete they usually include RC walls. These structural elements are designed to resist lateral loading induced by earthquakes or wind loads and gravitational loads. The walls can be loaded perpendicular to the median plane or along the median plane. These different loading systems can produce various failure modes far more complex than the ones in beams or columns. In a simplified form the main modes of failure are depicted in Figure 1.

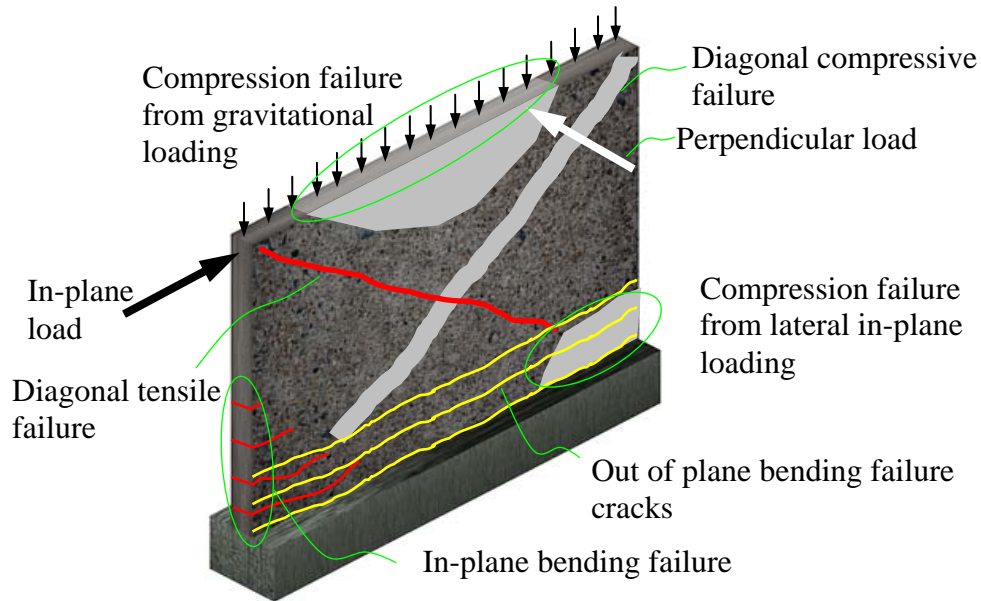


Figure 1. Failure modes in walls

An important aspect in studying the walls is the boundary conditions applied to the sides of the walls. The response of the walls under axial loading as a function of the boundary conditions has been identified by [1] as being: one-way action for walls supported at the top and bottom and two-way action for walls supported on all edges (Figure 2).

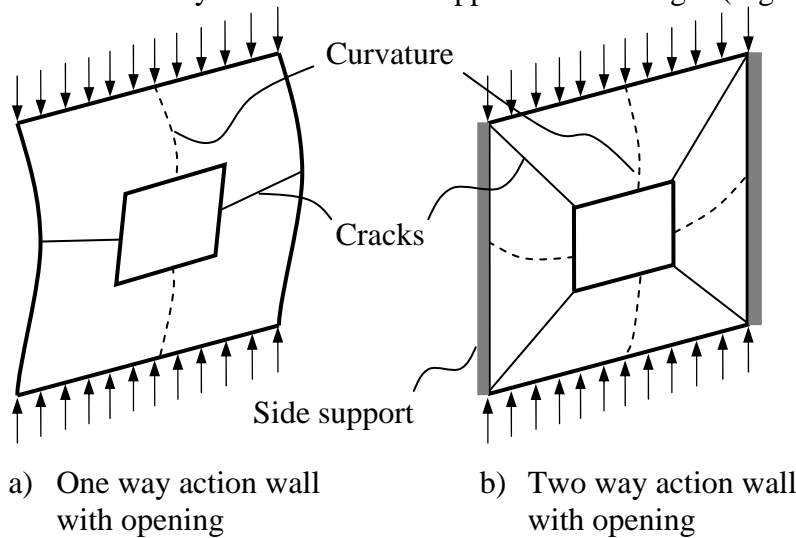


Figure 2. Response of walls in function of the boundary conditions

Nowadays, functionality modifications of the structures are often encountered. New windows, doors, paths for ventilation or heating systems demands openings in walls. Small openings does not normally create significant changes in the structural behaviour, due to the stress redistribution capability. However, in the case of larger openings, the stress distribution may change. Thus, a strengthening of the structure is imposed to recover the initial capacity. Traditional strengthening methods, such as bordering using reinforced concrete/steel frame system or increasing the cross section thickness, may not be architecturally convenient, fulfil the functionality of the opening or time consuming. An

alternative to these classical methods is fibre reinforced polymers (FRP) strengthening systems. The low weight to high strength ratio, good mechanical properties and the easy application techniques, makes the FRP materials suitable for strengthening RC walls.

## **STATE OF THE ART**

Ehsani and Saadatmanesh, [2], rehabilitated the RC walls in a high raised building following the '94 Northridge earthquake using glass fibre reinforced polymers (GFRP). Tests were conducted to establish the efficacy of this rehabilitation method. After strengthening the moment capacity of a unit width wall increased to 74%; while before retrofitting was 13.8%.

Four walls loaded in a quasi-static cyclic sequence in load control up to yielding and in displacement control from yielding to ultimate failure have been tested by [3]. Two RC walls were tested and used as reference, retrofitted with carbon fibre reinforced polymers (CFRP) and then retested. From the same group of specimens, two RC walls were strengthened using CFRP and then tested. Different configurations of the CFRP strengthened system along with mechanical anchorages at the basis of the wall have been considered. The strengthened walls developed a substantial increase of the ultimate bearing capacity compared to the retrofitted and reference specimens respectively. An empirical theoretical model was developed to predict the load-displacement envelope of reinforced concrete shear walls strengthened by CFRP based on the analogy between the cantilever beam's behaviour and the shear wall's behaviour. It was highlighted as important parameters the flexural and shear deflection at the top of the wall.

Seismic behaviour of non-structural reinforced concrete walls with openings, strengthened using FRP composite sheets, was studied by [4]. A series of tests were conducted on eight 1:3 scaled specimens with different opening configurations. Three walls with openings were tested without strengthening as reference specimens. Different strengthening arrangements using CFRP sheet systems were applied to the remaining walls. The static scheme considers the cantilever wall behaviour. The non-structural reinforced concrete walls were compared with a shear reinforced concrete wall. It was concluded that even if the bearing capacity of the non-structural walls increased, the global behaviour remained the same.

Hiotakis et al., [5], tested two series of RC walls FRP retrofitted laterally loaded. The RC walls were loaded up to failure, repaired, strengthened and then loaded up to failure again. During tests large torsion effects were observed for all elements, however the effect of the strengthening was considered successful. The ultimate load of the wall repaired with one layer of FRP sheets on each face increased by 80%. In the second series two new walls strengthened with FRP were tested. For these strengthening schemes, the increase in ultimate load was between 46% and 132% compared to the control specimen. In the second phase a reconfiguration of the stand setup was considered in order to prevent torsion and five additional tests were performed on four walls. The ultimate load for the strengthened and retrofitted elements increased with approximately 55% compared to the control element. It is important to mention that all the specimens in this set had a higher failure load compared to the first set, proving that torsion effect has a negative influence on the walls even if strengthened with FRP.

In two series of tests [6] analyzed the results of seismic loading on low-medium slenderness cantilever reinforced concrete walls strengthened with FRP. The walls, designed according to modern code provisions, were subjected to cyclic loading up to failure. After a conventional repair, the walls were retrofitted with FRP to increase both flexural and shear capacity. Special attention was given to the FRP anchorage system: GFRP tows, U-shaped strips, C-shaped strips and metal plates, steel angles fixed with resin and metal bolts. A new series of tests was performed on the strengthened specimens. A comparison between initial specimens and retrofitted ones was used to show the effect of FRP strengthening. The dominant failure mode in all cases was flexural with local anchorage failure. Appropriate confinement of the compressed concrete could not be reached even if visible damage such as concrete crushing or reinforcement buckling was not observed. The strengthened walls showed an increase of capacity between 2-48% with respect to unstrengthened repaired walls and a loss of 6% compared to initial undamaged walls.

Khalil and Ghobarah, [7], conducted an experimental investigation on the behaviour of RC structural walls strengthened with FRP. The potential of the plastic hinges retrofitted with composite materials under earthquake loading was studied on 1:3 scaled models. Three specimens reproducing the plastic hinge of a ten storeys structure, 33 m high and 3 m long wall were tested. According to the design methods when the building was constructed, the plastic hinge region was considered at 3 m from the bottom of the real structural wall. The first specimen has been tested as a reference specimen without any strengthening. Two different mechanical devices have been used for anchoring the applied FRP strengthening. The control specimen failed in shear at a load level of 363KN. Diagonal debonding of the FRP followed by crushing of concrete at the bottom has been reported for the second element at a 515KN load level. The third element had a more complex failure mechanism as a result of the conjugated tensile failure of the steel bolts and debonding of the FRP with crushing of the concrete for 571 KN load. It is important to notice the large displacement of this specimen. It was reported that the wall was shortened by 100mm as a result of the crushing.

Following a pattern of a real four-levels building arrangement (i.e. different positions of doors and windows), five 1:4 scale reinforced concrete walls specimens, strengthened with FRP were tested by [8]. Initially all the walls were seismically tested up to failure in cyclic loading. The FRP strengthening system was applied on one face of the walls after a standard repair of the damaged specimens. The FRP was anchored at the toe of the walls using bonded steel angle profiles fixed with bolts. Different configurations of strengthening were used in function of the openings positions in the walls. The effect of the strengthening was evaluated by average values (relative to baseline records). The elastic limit increased by 47%, average failure load increased by 45%, average stiffness decreased by 53% and average ductility decreased by 60%.

## **STRENGTHENING RC WALLS WITH OPENINGS USING FRP MATERIALS**

Using FRP materials on RC walls is proved to be a viable solution for strengthening or retrofitting [3-8], mostly on the premises of experimental investigation. However theoretical models and design recommendations have not been reported at the same extent as the experimental work. Here two theoretical approaches are presented for investigating the effect of the FRP strengthening on walls with openings.

## Frame idealization

In this paragraph several aspects considering a safe calculation procedure for axially loaded FRP strengthened walls with openings are outlined. This simple model is under development and here general aspects are presented only, due to space limitations. A more analytical approach can be followed in [9]. According to [10] the efforts surrounding the opening can be determined using a frame idealization of the wall with openings. Based on these efforts the necessary steel reinforcement surrounding the opening can be determined. In a similarly manner the FRP necessary strengthening can be determined as it will be presented below. It must be noted, in this case only an axial load is used, but other types of loading can be used too.

Consider a solid one-way action wall loaded with an initial axial load  $q$  acting on the top, as in figure 3. Now assume a door opening is created in the wall. The objective is to determine the necessary FRP strengthening system to rehabilitate the wall considering the new created opening. The area surrounding the opening, figure 3, is considered to be acting as a frame and is idealized as in figure 4a.

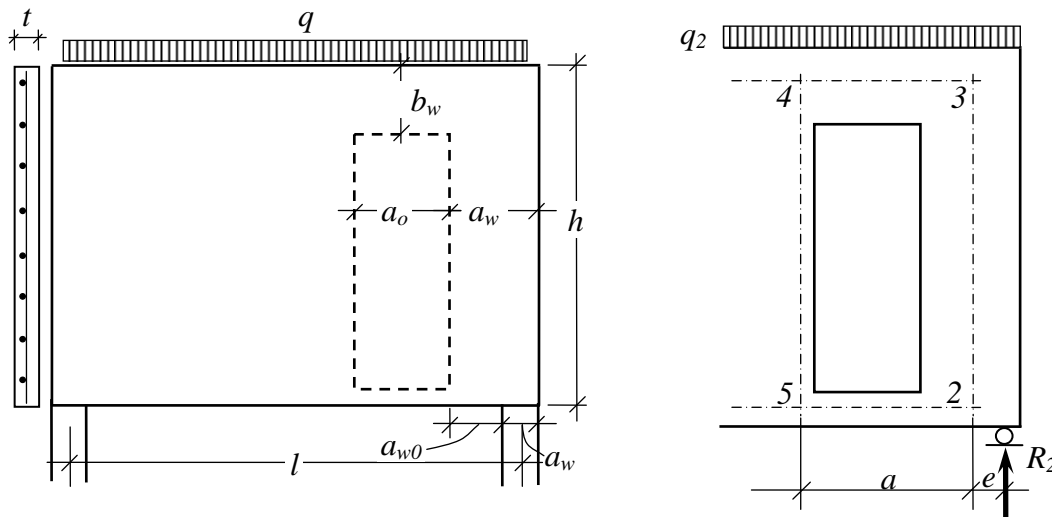


Figure 3. Wall with opening (left), centre lines of the frame (right)

The diagrams of the efforts are presented in figures 4c, 4d ad 4e and are according to the loading scheme and supports depicted in the figure 4b. Obviously changing the loading scheme and the support system will modify the distribution of the efforts. The influence of these parameters should be investigated and always the less favourable case should be chosen for design.

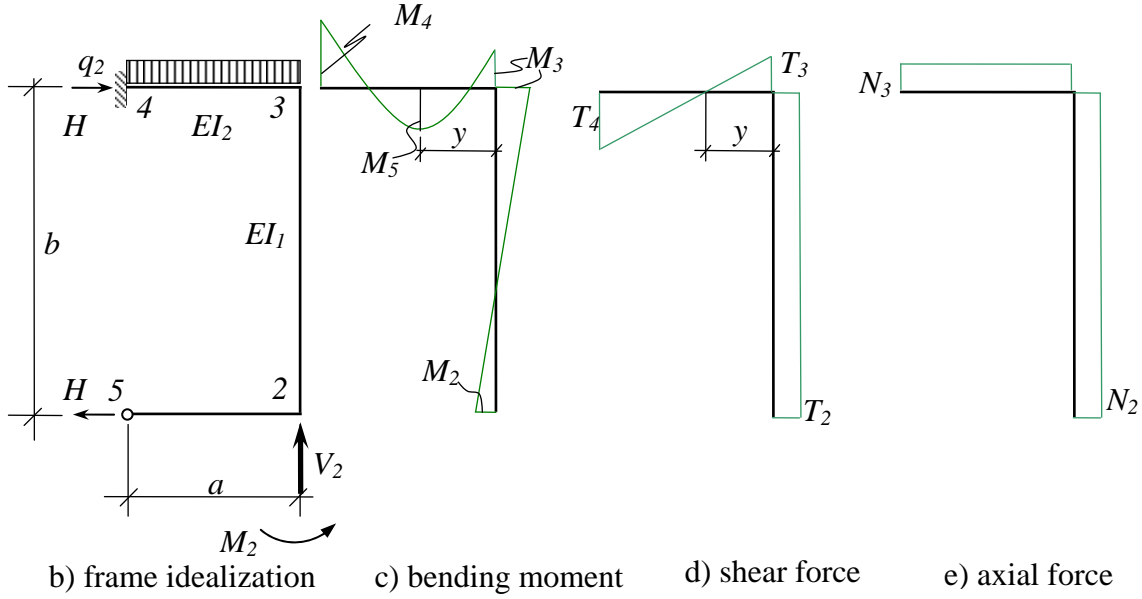


Figure 4. Frame idealization and efforts on the frame

To simplify the design procedure the following assumptions are made:

- The moment resistance for bars 2-5 is set to be equal to zero, since in reality for making the opening the bar is sectioned.
- The resultant of the axial load acting on the assumed frame is equal to the reaction force in the support  $V_2=R_2$  and is determined as in equation (1).
- The bending produced by the eccentricity  $e$ , is determined as in equation (2)

$$V_2 = \frac{ql}{2} \quad (1)$$

$$M_2 = eR_2 \quad (2)$$

- The horizontal reaction force  $H$  is determined from equation (3).

$$H = \frac{M_2 - M_3}{b} \quad (3)$$

### ***Design efforts***

The unknown design efforts are derived considering the static analysis of the frame. The bar 3-4 is considered fixed in node 4 and hinged in node 3, while the bar 2-3 is simply supported. According to these assumptions the rotation condition of node 3 ( $\theta_{23}=\theta_{34}$ ) is used to determine the design moment  $M_3$ . The derivations and the resulting design efforts are not presented here due to space limitation but full derivations can be found in [9].

### ***Design of the FRP strengthening***

At this stage no contribution from the concrete is considered in this analysis for the elements subjected to bending or shear, and all forces are transmitted to the composite

material. The FRP strengthening has to be designed for each element considering all the efforts in the section of interest, i.e. bending moment, shear force and axial force, see figure 5.

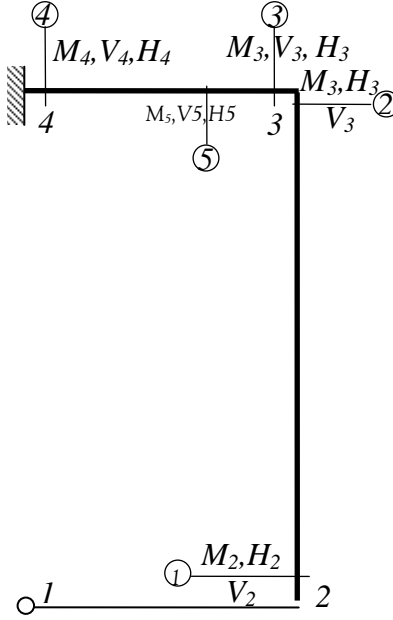


Figure 5. Considered section for the strengthening and the specific efforts

#### Design for bending moment

The design for bending is similar for all elements of the frame and is performed considering the approach found in [11].

$$A_{frp,b} = \frac{\frac{M_d}{0.9d} - A_{st}f_y}{\varepsilon_{frp}E_{frp}} \quad (4)$$

Where  $A_{frp,b}$  is the needed FRP area for bending strengthening,  $d$  is the internal lever arm,  $\varepsilon_{frp}$  is the design strain in the FRP,  $E_{frp}$  is the Young modulus of the FRP. The steel area  $A_{st}$  and the yield strength of the steel,  $f_{st}$ , should not be accounted if no steel is present in the section.  $M_d$  is the design bending moment for each element calculated.

#### Design for shear force

The shear contribution attributed to the strengthening material is determined as in [11]:

$$A_{frp,s} = \frac{V_d}{0.6\varepsilon_{frp}E_{frp}} \quad (5)$$

Where  $A_{frp,s}$  is the needed FRP area for shear strengthening and  $V_d$  is the design shear force for each element calculated. The partial safety factor 0.6 presented in equation (5) is based on experimental investigations.

#### Design for axial load

A simple check adopted from [11] is considered for the axial load design. Equation (6) defines the necessary FRP material thickness.



$$t_{frp} = \frac{\sigma_l \sqrt{a_w^2 + t^2}}{2k_g \varepsilon_{frp} E_{frp}} \quad (6)$$

Where  $k_g$  is the gap factor,  $\sigma_l$  is the confinement pressure provided by the FRP material. Detailed derivations of the formulas used for the design of the FRP strengthening for bending, shear and axial load are presented in [11].

### Disk theory

Inspired by tests carried out in [8], a model for calculating the failure mechanism of a rectangular disk with opening FRP strengthened, and loaded in pure shear is suggested (Figure 6a). This setup has been used in a successful test series on fibre reinforced concrete panels presented in [13] and all details have been reported in [14]. The analytical derivations have the origin in the fictitious crack model and limit analysis. By using principles of equality between inner and outer work, a good agreement between the upper bound analytical results and test results was reported. The investigation presented here is based on the observations reported in [14] and adopts some simple principles for strengthening using FRP materials.

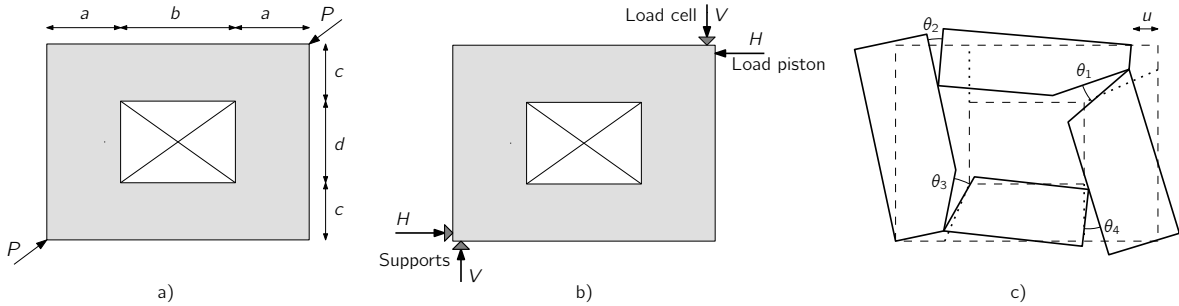


Figure 6. a) Principle sketch of test, b) Test setup c) Kinematic yield mechanism from previous tests of un-strengthened and conventionally fibre reinforced specimens.  
 $a=225\text{mm}$ ,  $b=350\text{mm}$ ,  $c=225\text{mm}$ ,  $d=240$ .

The development of yield mechanisms for disks has been refined during the last decades with the aid of computer based programs. Generation of stress fields and prediction of load capacities for conventionally reinforced concrete panels has been undertaken in [15]. However this method relies on ductility of the RC wall. It is known that most FRP materials are linear elastic until fracture, since they contain no ductility as a single material. To avoid strengthened disks from failing in brittle manner, the following method named the yield line dislocation method is used.

### Yield line dislocation method

The proposed method assumes ductility in the original RC disk which is available when it contains minimum reinforcement prescribed by a design code. The areas reinforced with FRP are assumed to strengthen the structure to a level where no yield lines or mechanisms can appear. With this method and these simple assumptions, it is now possible to strengthen the yield lines in the mechanism and change the yield lines to another place in the disk. The specimen presented in Figure 6a-c is strengthened with FRP material in the corners as in

Figure 7a. Assuming the natural optimum placement of the yield lines is as in Figure 6c, any dislocation of the yield lines will provide a larger capacity. The structure to model is shown as principle sketch in Figure 7b-c.

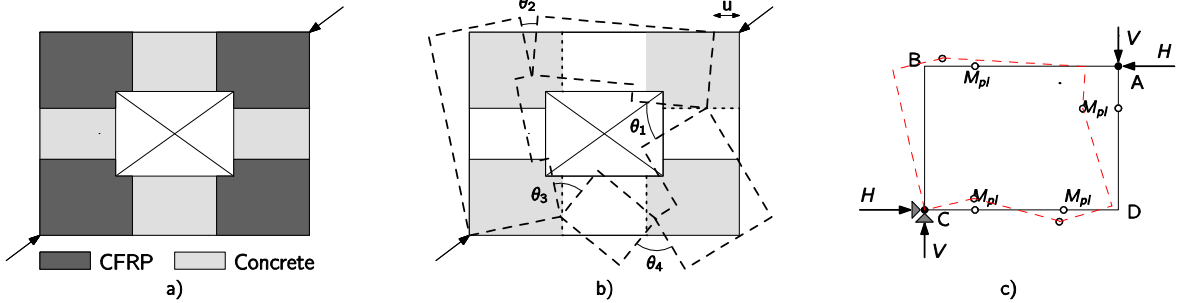


Figure 7. a) Strengthening in shaded areas, b) Possible yield mechanism, c) Yield mechanism as a frame structure.

The results of un-strengthened and strengthened frame is shown in Figure 8. In Figure 8a, the original disk from Figure 6 is idealized as a frame structure, where the cracks are interpreted as plastic hinges with a given yield moment  $M_{pl}=1\text{kNm}$ . In Figure 8b, the strengthened specimen is shown with the dislocated plastic hinges. The hinges are moved corresponding to a new yield mechanism as seen in Figure 7b and c.

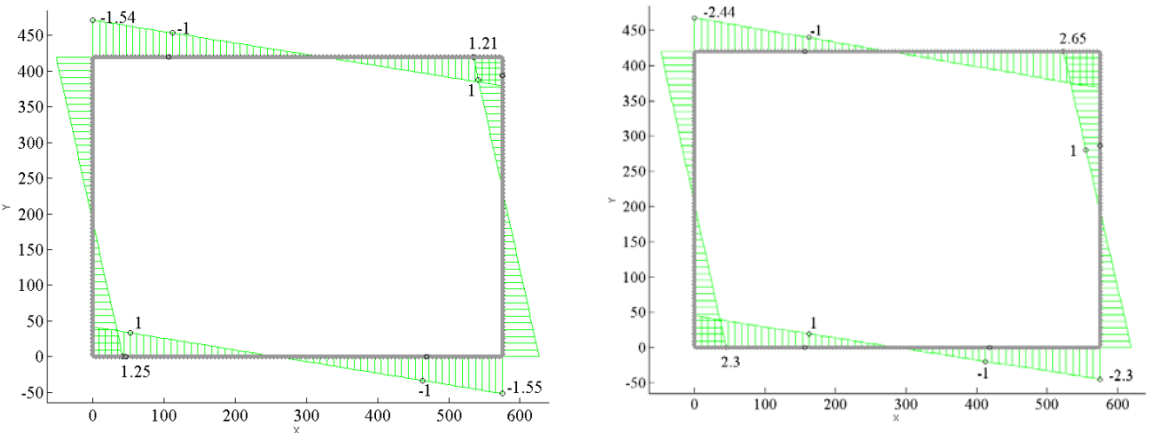


Figure 8. a – left) Statically admissible moment distribution for un-strengthened case. b – right) strengthened case. Max moments are annotated on both figures. Axis are in mm.

The results show us that the maximum tensile moment in the un-strengthened disk is 1.55kNm, which is larger than the yield moment. This is allowed because the corner of the disk has a stronger cross-section. The maximum moment in the strengthened disk was found to be 2.65kNm in one corner. The moment capacity of the strengthened RC concrete corner should be able to withstand this moment to dislocate the yield lines. If the strengthened corners resist moment, shear and axial force, the disk will have a ductile failure following the new yield lines, with an increase in capacity corresponding approximately to the lowest ratio between corner moments. Thus, in this case an estimated increase of carrying capacity is  $\min(M_{ini}/M_{str})=1.4$ , where is the original un-strengthened corner moment, and  $M_{str}$  is the strengthened moment. At this time the program calculating the yield mechanism is not able to calculate the critical load; therefore the comparison is done on moments.

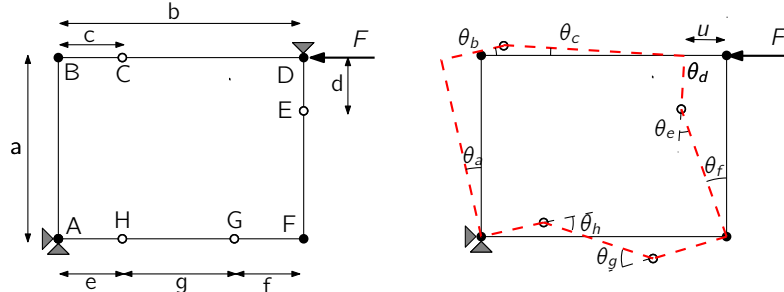


Figure 9. Definitions for calculation of upper bound load.

### Calculation of upper bound load

Analytical expressions can be written to estimate the upper bound load of the disk. The geometry in the un-strengthened and strengthened case is as before. New definitions have been introduced in Figure 9.

Equilibrium between internal and external work is written as:

$$W_i = W_e \quad \text{where} \quad W_i = \sum_{i=1}^n m_{y,n} \theta_n \quad (7)$$

$n$  is index for the yield joint,  $m_y$  the yield moment and  $\theta$  the angular change. The external work is written as the force  $F$  times the movement  $u$  and load factor  $\lambda^+$  as

$$W_e = \lambda^+ Fu \quad \text{and} \quad u = a\theta \quad (8)$$

The following rotations are used to calculate the load factor:

$$\theta_C = \theta \left( 1 + \frac{c}{b-c} \right), \quad \theta_E = \theta \left( \frac{c}{b-c} + \frac{a + \frac{cd}{b-c}}{a-d} \right), \quad \theta_F = \theta \frac{a + \frac{cd}{b-c}}{a-d} \quad (9)$$

$$\theta_G = \frac{e\theta + f\theta_F}{g} + \theta_F, \quad \theta_H = \frac{e\theta + f\theta_F}{g} + \theta$$

The load factor is then given as

$$\lambda^+ = \frac{m_y (\theta_C + \theta_E + \theta_G + \theta_H)}{F\theta a} \quad (10)$$

For un-strengthened case and  $a=420\text{mm}$ ,  $b=575\text{mm}$ ,  $c=112.5\text{mm}$ ,  $d=32.5\text{mm}$ ,  $e=52.2\text{mm}$ ,  $f=c$ ,  $\lambda^+ = 13.2$ . In the strengthened case  $c=162.5\text{mm}$ ,  $d=140\text{mm}$ ,  $e=162.5\text{mm}$ ,  $\lambda^+ = 23.1$ . The ratio and increase in capacity is then  $23.1/13.2=1.75$ , hence the strengthening should increase capacity significantly. This method does also provide a larger increase than the approximated method presented previously.

### CONCLUSIONS AND FUTURE RESEARCH

RC walls have not been studied at the same extend as other structural elements even though they are common structural elements in RC constructions. The reasons may be found in the complex nature of failure of these elements and in the difficulty of performing full scale

size experiments and the large costs associated to these investigations. The literature survey carried out for this research confirmed the lack of analytical theoretical investigations for strengthening RC walls with FRP materials. Moreover, to the best knowledge of the authors, very few attempts on investigating theoretically the behaviour of the RC wall with openings have been made. In addition these derivations are based on regression analysis from experimental results, and not on an intrinsic mechanism approach, results making their use limited in design applications.

At this stage the frame idealization procedure can be regarded as a guideline on how to strengthen RC walls with openings. Simplifications adopted and the omission of the contribution from the steel reinforcement provided in the middle plane of the wall, are factors decisively influencing the behaviour of the elements. If walls with existing openings are the subject of an investigation, the presence of structural steel reinforcement cannot be disregarded. In what manner existing reinforcement in the wall is influencing the strengthening effect is a subject of a future research.

The real behaviour of a structural wall with openings is not always covered by the simplification assumed in this design procedure, because large variation of the efforts can occur if different frame models are selected. To avoid these situations critical aspects such as support systems and boundary conditions of the wall should not be disregarded in the analysis. Until further investigations of the behaviour of FRP strengthened walls with opening are performed mechanical anchorages are suggested to be used to ensure full utilization of the strengthening and avoiding the loss of bond. However, the strain in the FRP can be calculated considering different theoretical approaches available in the literature.

The design efforts determined analytically in this model can be viewed as a specific case but the principle is similar for other configurations too. The interaction between the efforts (bending moment-axial force and bending moment-shear force) in a section of an element is another subject to be followed. Furthermore, for different types of openings the configuration of the efforts can also change. It is of high interest to determine in what manner the size of the opening is influencing the structural behaviour of the walls. In other words when will the wall stop acting like a single element and start to behave partially or fully as a frame? A fast solution for determining the efforts acting on the wall can be provided by simple finite element analysis. Normally this should be carried out considering different support systems and an envelope of the maximum efforts can be used for design considerations.

For walls with smaller openings, the creation of a new yield mechanism outside the strengthened areas is a natural and rational approach, and the benefit of a ductile failure of the structure is worth considering. The ductility is an important aspect, since the wall must possess sufficient ductility to allow the use of the yield mechanism approach.

Until validated against experimental results the two methods should be regarded as the basis for a future theoretical model.

## **ACKNOWLEDGMENTS**

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