Reinforced concrete shear walls damage characterisation for seismic loads: crack width evaluation and alternative methods

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ABSTRACT

Damage evaluation of reinforced concrete shear wall cracks openings submitted to seismic loads is an issue which mobilises nuclear engineering actors because the safety requirements for this type of buildings are based on permanent cracks openings limitation for containment and on cyclic openings limitation for anchorage resistance.

Actually, today practice consists in limiting resistance criteria of both concrete and steel, but remaining blind on expected damage. Accurate engineering methods to evaluate directly crack opening for shear wall are not available: codified formulas giving crack width are based on beams or ties experiments and not on shear effects. There is no universal method: this topic remains a difficult one and the numerical model are not self sufficient to solve the problem. Actually the brittle characteristic of the concrete prevents the engineers to access to the very local information which is the crack width. However the numerical model can give precious information about a more global behaviour such as the mean strain value. Our research will give some data which will allow making global information profitable to the access to the local information which is our key point of interest.

Our work is based on a detailed analysis of the SAFE experimental campaign which took place in ISPRA in Italy. Based on the experimental obtained results, we were able to compare the measured values with different calculation methods (from basic ones to more sophisticated numerical methods). The main contribution of our research is the proposition of a bond stress value for the specific case of shear wall (as a function of concrete confinement) which can give analytically the distance between cracks. Based on these findings, we could then validate a "numerical-analytical" approach and also propose a more simple one based on the drift limitation concept with practical tools to evaluate a realistic drift.
1. INTRODUCTION

A lot of reinforced concrete structures have functional requirements after or even during an earthquake. These requirements are absolutely more strict than the stability which is the target of most of earthquake design codes. They may concern containment issues or seismic required equipments anchorages. For both cases, crack width limitation is the most relevant and the most objective criteria. The main difference between these two fundamental criteria is the type of cracks: for containment issues we deal with permanent cracks but for anchorage problems, we have to take into account active cracks. Therefore, we have to consider the variation of the cracks width. Actually, the anchors bolts which are numerous in Nuclear Power Plant facilities may be affected by a crack through the anchorage cavity because even if the instantaneous maximum load on it does not coincide with the instantaneous maximum load on the wall itself, a large part of these two loads may coincide.

Structural codes, even those specific to nuclear structures do not deal explicitly with this question, but nuclear codes and practice carefully use to limit the stress level on both materials: concrete and reinforcement steel. Even if this attitude seems to be a wise one, the engineers remain quite blind in what concerns the expected damage during earthquakes, because this justification is formal and scientifically very limited.

This practice is based on the well known elastic method. By limiting the steel stress and by ignoring the concrete capacity, this method assumes no damage for the structure: this point of view may be convenient for axial (or flexural) type of load. However, for shear walls the main resistance capacity is given by the concrete and not the steel bars. This may lead to the paradoxic situation, when a very thin highly reinforced concrete wall is justified by the traditional elastic method, but not safe enough because of the large cracks width.

A lot of formulas are available to evaluate the crack widths (ACI, EC2, CEB and other experimental ones) but they are not applicable to shear walls and in particular to seismic loading conditions: the reason why they are not applicable is the fact the steel stress is not an accessible value.

So this research consists in giving a state of the art of the engineering methods and to test the ones which seem to be the more relevant: so we will have analytic, numerical (FEM), experimental and what we call alternative methods which are based on an appropriate damage index.

2 Why focus on crack width and for which requirement?

Containment function:
We focus a lot on crack width for containment problems because the leakage rate throw the concrete cracks depends on the cube of its opening, as we can see in the classical formula:

\[ Q = \xi LM(P_1^2 - P_2^2) W^3/(24 RT\mu e) \]

With \( \xi \) tortuousness coefficient, \( L \) crack length, \( M \) molar mass, \( P_1 \) and \( P_2 \) fluid pressure, \( W \) crack width, \( R \) perfect gas coefficient, \( \mu \) dynamic viscosity and \( e \) wall thickness.

Anchorage function:
During the earthquake, the equipment is acting as a dynamic load, generally with shear and axial components and the hypothetic crack through the concrete surrounding the anchor bolt may dramatically weaken the capacity of the device. In this case we could consider a “cliff” effect. The engineering practice is to consider a loss of the anchorage capacity beyond a half millimetre crack with for a 10 mm anchor bolt (the critical crack width increasing with the bolt diameter).

So the cracks width is a critical issue which has to be seriously analysed with the up to date methods. It is to be noted that there is no universal method to deal with this aspect. The topic remains a difficult one and the numerical models are not self sufficient to solve the problem. In fact the brittle character of the concrete prevents the engineers to access to the very local information. However the numerical model can give precious information about the mean strain value. Our research will give some data which will allow to make this more global information useful to the access to the local information which is our key point.
3 General methodology

The general methodology consists in first giving a state of the art of the shear wall seismic design practice, taking into account the following methods:
  o The stress limitation methods which is a very poor method from a concrete damage evaluation point of view, but which remains the reference method
  o The analytical methods which give the cracks width as a function of steel stress at the crack (or as a function of the mean steel strain): the expression depending on the steel stress on the crack has been largely codified in each country and recently in Europe in the EC2.
  o The non linear finite element method, which greatly interests a large number of researchers. This method needs however a post-treatment to deliver the crack width values.
  o The engineering methods which do not give the cracks width but are based on a drift approach: these methods may constitute an alternative solution for the engineers but a lot of care has to be taken when evaluating the stiffness of the structure.

One or several methods of each family has been tested and compared to the experimental results: so we have been able to give the advantages and the limitations of each one of these methods. To do that and also in order to explain in detail the experimental results, we have focused on the steel concrete bond stress, because it is a major issue concerning cracking effects.

4 The SAFE experimental program

Under the SAFE research project between Electricite de France (EDF-SEPTEN), COGEMA and the Joint Research Centre of Ispra (JRC) a series of pseudodynamic tests on 13 reinforced concrete shear wall specimens were conducted at the ELSA reaction wall of JRC. The differences between each series of tests are related to the steel ratio of reinforcement, the natural frequency of the wall and the vertical loading.

The specimen geometry is described in the figure n°1: the large and highly reinforced beams at the bottom and on the top are designed to stiffen the wall in the out of plain direction and to transmit the load along the wall. A rib on each side of the wall has also been conceived in order to simulate the perpendicular walls which are present in an actual building and play a key role in the shear load transmission as ribs and struts.

![Figure n° 1: specimen geometry of the 2nd family](image)

The loading device has been designed to prevent any rotation of the upper longitudinal girder and to apply a pure shear force without any flexure.

The reinforcement ratio were 0.8, 0.6, 0.4, and 0.11 % depending on the specimen; the theoretical frequencies were equal to 4 hertz, 8 hertz or 12 hertz.

Each test has been performed with the pseudodynamic method which is a hybrid method. In this method, a step by step integration of the equation of motion is performed in the computer. In this equation a known mass is used whereas the non-linear restoring forces are experimentally obtained. To this purpose, at every time step, the computed relative displacements are statically imposed to the specimen and the existing forces at the actuators are then measured. These forces are subsequently fed back into the equation in order to compute the displacement at the next step. In order to obtain the pseudo dynamic response of the structure, the equation of motion is formulated in a discrete way in the time domain:
Ma (n) + r(n) = f(n)

Where M is the mass of the oscillator, a(n) the acceleration, r(n) the restoring force and f(n) the external force. For this seismic excitation, the external forces are calculated as seismic equivalent forces taking into account the ground acceleration and the mass. The restoring force, is experimentally measured at each step for the computed displacement. To impose this displacement quasi statically to the specimen, a servo-hydraulic control system is attached to the computer. In the same time, this equation is integrated step by step (the variation of the stiffness is taken into account by the force measurement and then injected in the calculation, in the next step). Concretely the loading device can be seen on the figure n° 2:

![ SAFE experiment loading device](image)

The main advantage of this the pseudodynamic test method is its ability to stop the experiment at any time and to fix extensometers on each new visible crack. In this way, it was possible to record the variation of the crack width during each pseudodynamic test, at each time step.

5 Analytical methods

The analytical methods are those given by the codes such as EC 2 or CEB 1990 codes: in both of them, the cracks width is expressed as follows in terms of the length \( l_{s, \text{max}} \) over which slip occurs between the steel reinforcement and the concrete (approximating crack spacing in stabilized cracking)

\[ W_k = l_{s, \text{max}} \left( e_{cm} - e_{c} - e_{b} \right) \]

The expression of EC2 \( l_{s, \text{max}} \) is relatively opaque, because of its four coefficients where there is no link to the bond characteristics excepting for the bar type. The CEB formula is more explicit but has to be corrected to take into account the real bond slip characteristics and to consider the reinforcement angle. So for stabilized cracking, we can demonstrate:

\[ l_{s, \text{max}} = 2 \times (\phi f_c / (4 \rho \tau_b)) \times \cos \theta \]

With \( \phi \), the bar diameter, \( f_c \) tensile concrete strength, \( \rho \) reinforcement ratio, \( \tau_b \) bond stress, \( \cos \theta \) factor taking into account both perpendicular reinforcement directions. The strain differential is given by the following expression which can be demonstrated by the strength transfer trough bond:

\[ (e_{cm} - e_{c} - e_{b}) = e_{c2} - \beta \left[ f_c (1 + \alpha p) / (\rho E_u) \right] \]

This expression, very similar to the EC2 expression is quite convenient for tie rods and beams in flexure. A bibliographic revue shows a lot of experimental based expressions, such as this one given by Ratnamugidgedara Piyasena in his Australian PhD thesis:

\[ w = 1.5 \left( e_s \right) x [0.6 (c-e)+ 0.1 (h/\rho)] \]

With c concrete cover, e bar spacing; in order to apply such an analytical method, we consider in a cracked section the total strength in the steel but this hypothesis leads to the incoherent stress values which can be seen on the following figure which takes into account the dowel action:
Figure n° 3  Steel stress with dowel action but with a elastic analysis

These difficulties show the necessity for other methods of analyses that can take into account a more realistic strength transmission scenario such as ties rods diagram or non linear finite elements analysis: actually compression strength pass easily throw concrete and tension mainly in the ribs; however we have to keep in mind that what we need is the mean steel strain in order to estimate the cracks width.

6 Non linear finite element methods

Presently, there are a lot of non linear models which are quite able to evaluate the mean global strains. In order to achieve a good compromise between simplicity and accuracy, a biaxial concrete model that provides acceptable representation of the cyclic inelastic behaviour of reinforced concrete under cyclic loading was used in this study. This model [ref 4], adopts the concept of a smeared fixed crack approach (with a second crack perpendicular to the first one). It is based upon the plasticity theory for uncracked concrete with isotropic hardening and associated flow rule. Two distinct criteria describe the failure surface: Nadai in compression and bi-compression and Rankine in tension. When the ultimate surface is reached in tension, a crack is created perpendicularly to the principal direction of maximum tension, and its orientation is considered as fixed subsequently. An orthotropic law whose orthotropy directions are normal and parallel to the crack then models the behaviour. Each direction is then processed independently by a cyclic uniaxial law, and the stress tensor in the local co-ordinate system defined by the direction of the cracks is completed by the shear stress, elastically calculated with a reduced shear modulus (shear retention factor) to account for the effect of interface shear transfer. This model has been implemented in both well known in Europe software codes Aster (EDF) and Cast3M (CEA).

This kind of model is a “local” one, that is to say strain localisation and bond slip are not treated in a realistic way. Discontinuousness at the crack is not explicitly represented, so we have to introduce it as a hypothesis. This hypothesis concerns the cracks spacing which is a value we can asse to with an independent analytical method as we have seen in the previous chapter. Actually we do not need to access to the exact location of the cracks, but we need to evaluate the cracks width which corresponds to the concrete damage level. It is necessary to consider this procedure as an artifice, doing the transition between local crack damage characteristic and the need to access only to a quantitative value.

As this kind of model is a “local” one, crack band width depends on the mesh size and it is necessary to be careful and to adapt the post-pic slope in the strain softening area. Actually crack energy has to be dissipated on a band width corresponding to the mesh size. It is clear that this approach is to be criticized if compared to “non local” models which introduce a length scale through higher-order strain-rate or strain-gradient terms. However, these later approaches, even if they seem to provide a better insight into the problem, they are presently not very well suited for treating the cyclic type of loading.

Based on the results obtained with the “local” model, we calculate the mean strain value between the four integration Gauss points belonging to a finite element. Then, we evaluate the crack opening by multiplying the
mean value by the slip length. So we have a crack opening value at each time step and we can compare this value to the measured one, as can be seen on the figure n°4 for the T3 specimen:

![Graph](image1.png)

Figure n° 4: INSA model computed and experimental crack width comparison (T3 specimen)

In order to test a « non local » model, we have chosen the one developed at Lyon INSA which is a damage visco-plastic one as described in ref [3] and ref [11]. The introduced viscosity allows to treat a well posed equations set when reaching the softening area of the concrete in tension. This sophisticated model gives good informations about the cracks spacing and the mesh size dependence problem is solved. Figure n°5 presents the computed results which can be compared to the experimental crack pattern.

![Graph](image2.png)

Figure 5: damage visco-plastic model computed strain compared to experiment photography

7 Alternative Engineering methods

Because of the complex phenomena and the difficulty to represent them in a realistic way, we have looked for alternative methods. The general idea of these alternative methods is to find a damage index which could indirectly represent the crack openings. The SAFE program constitutes a relevant opportunity to test this index and to compare its value to the cracks width. The index that seems to be the most suitable for this purpose is the drift: this conclusion has been done also by a lot of researcher such as Michael Brun in France in its thesis ref [5].This criteria is also widely used in codifications such as the Japanese Guidelines for Performance Evaluation of Earthquake Resistant Reinforced Concrete Buildings ref [8] or in the FEMA 356 Seismic Rehabilitation Prestandard ref [9]: in these standards, the criteria values are 0.4 % for immediate occupation and 0.25% for functional requirement during earthquake. So because of the large instrumentation of the SAFE program, objective comparison could be done with each specimen.
For this example a 0.4% criteria seems to be convenient, but we have to keep in mind that reinforcement ratio and bars diameter may have an influence on crack opening. This is the reason why we have done an assessment concerning the opening – drift variation tacking into account every specimen which has various reinforcement ratio and bar diameters: this one can be seen on the figure n°8.

The figure shows a good stability of the opening values until an average drift value of 0.6%, and confirms that the drift index is a relevant alternative damage index to control cracking in reinforced concrete shear walls. However, giving a suitable damage criteria based on global strain is not sufficient because seismic displacement can vary a lot with the chosen rigidity hypotheses: consequently we have to focus on the variation of the shear rigidity during an earthquake. This issue has already largely been studied for ordinary buildings, where flexure dominates. So we have analysed the SAFE program which was dedicated to low-rise shear walls, subjected to pure shear. During this program, the wall rigidity was recorded at each time step as both strength and displacement were measured (without any speed effect, dynamic behaviour being computed). So the rigidity can be clearly expressed as a function of the drift for each specimen. The fact that the reinforcement ratio has a low influence on the rigidity is already well known, but this program brought to light the brutal drop of the wall rigidity at the beginning of the loading in an area corresponding to concrete cracking, and then a relative stability of the rigidity till the end of the test. This “S” shape curve has already been seen by M Brun, ref [5] who developed a simplified model to represent the behaviour of a low-rise reinforced concrete shear wall subjected to dynamic loading. So to summarise this phenomena we have put on the figure n°8 the frequency shift as a drift function obtained by the numerical model (ref [5]) and obtained by experiments.

Figure 6: crack opening compared with drift for T3 specimen

Figure 7: crack opening (mm) as a drift function (drift maximum drift and opening maximum)
8 conclusion

The SAFE program has brought to light a relevant bond stress value equal to 10 MPa for reinforced concrete shear wall: this value much higher than the codified ones allows us to evaluate more realistic the cracks width. These cracks openings calculation may be based on the mean concrete strains, obtained by basic non linear cyclic models. We also have shown that drift is a suitable damage index for cracks openings criteria but the remaining difficulty of the rigidity shift has to be carefully analysed taking into account in local areas 1/4 initial uncracked modulus. To conclude, we can say that finite element methods and analytical ones are not in competition, we need both of them: non linear finite element methods give quite relevant information about mean strains and analytical ones give information about the slip lengths so that we can access to the crack widths.

references

[6] T1 à T13 SAFE program reports –technical reports Excel associés ISPRA
[9] FEMA 356 Seismic Rehabilitation Prestandard USA