EXPERIMENTAL AND THEORETICAL RESULTS ON CRACKING OF CONCRETE WALLS SUBMITTED TO CYCLIC SHEAR FORCES

Philippe BISCH¹, Silvano ERLICHER², Miquel HUGUET³, Gianluca RUOCCI⁴

ABSTRACT

As part of the CEOS.fr project, four shear walls at 1/3 geometric scale have been tested and submitted to cyclic forces, in order to assess the behaviour of reinforced concrete thick walls during an earthquake. The experimental arrangement is first described and the results of the cyclic tests are presented, highlighting the crack width during the cyclic loading (earthquake) and the residual width at the end of the loading. Practical engineering methods for cracking assessment have been deducted from experimental observations and are discussed in this paper.

Keywords: seismic behaviour of RC wall; experimentation; (non-)reversing cyclic loading; maximum crack width; residual crack width.

1. INTRODUCTION

The evaluation and control of cracking in Reinforced Concrete (RC) elements of industrial buildings is an important design aspect. Most of construction design codes, e.g. Eurocode 2 (CEN, 2005) – EC2 – and the Model Code 2010 (fib, 2010) – MC10 –, require cracking control at the Serviceability Limit State (SLS). In the particular case of nuclear power plants, the limitation of cracking should also be ensured for some structures throughout extreme events like earthquakes in order to preserve the tightness, durability and confinement issues at the Ultimate Limit State (ULS) under seismic loadings. The French national research project CEOS.fr which took place over several years was intended to improve the knowledge of the phenomenon of cracking of RC elements and to provide simple and reliable cracking assessment methods for designers (CEOS.fr, 2008). The project mainly concerned beams and walls with large dimensions, for which the current evaluation methods of cracking at the early age and during operation are not suitable and not available for the ULS. The project had three axes: improvement of refined constitutive models for the structural elements by various research organisations, experimentation on different mock-ups and development of engineering methods for cracking assessment.

As part of this project, four RC shear walls at 1/3 geometric scale have been tested and submitted to cyclic forces, in order to assess the behaviour of RC thick walls during an earthquake. The tested walls are representative of the walls present in nuclear power plants. The scientific objective of this task of the CEOS.fr project was to obtain data on cracking patterns and about the mechanisms governing cracking for walls subjected to a cyclic non-reversing or reversing in-plane loading, since the membrane stresses are preponderant in seismic situation for this type of structures.

After a brief presentation of the research program and the experimental campaign carried out on the walls (experimental arrangement and instrumentation), the results of the cyclic tests are presented, highlighting the crack width during the cyclic loading (earthquake) and the residual width at the end of

¹ Expert, EGIS Industries, Montreuil, France, philippe.bisch@egis.fr
² Scientific Director, PhD, EGIS Industries, Montreuil, France, silvano.erlicher@egis.fr
³ Engineer, PhD, EGIS Industries, Montreuil, France, miquel.huguet-aguilera@egis.fr
⁴ Engineer, PhD, EGIS Industries, Montreuil, France, gianluca.ruocci@egis.fr
the loading. The latter is the most important result for industrial applications (the wall design should ensure leak-tightness and confinement).

Finally, some practical engineering methods for cracking assessment are deducted from experimental observations.

2. THE WALL EXPERIMENTS IN THE FRAME OF THE CEOS.FR PROJECT

2.1 The shear walls experimental programme

Shear-wall specimens were designed and tested in order to analyse shear cracking in thick RC walls under cyclic loading. The walls were tested at CSTB laboratory, in France.

The test campaign concerned four specimens representing a reduced-scale model of RC shear-walls commonly employed in nuclear facilities to resist horizontal seismic forces. The specimens measure 4,20 m × 1,05 m × 0,15 m (Figure 1) and, as a result of their geometrical scale of 1/3, they are equivalent to a “real” 12,6 m × 3,15 m × 0,45 m wall. These dimensions ensure a ¼ slenderness ratio that guarantees the prevailing of the diagonal shear cracking development over the bending one. This is also attained in the specimen by several vertical steel bars of 25 mm and 32 mm diameters, placed at the edges of the wall; they connect two horizontal thick concrete beams with a high reinforcement ratio. These beams, connected to the shear wall in its upper and bottom parts, aim at a as uniform distribution of the shear stresses in the wall as possible.

Figure 1. Dimensions of the specimen - origin CSTB -

Figure 2. Reinforcement and part of the formwork

RC walls 1, 2 and 3 are reinforced with two identical steel layers on each face of the wall, each one with horizontal and vertical rebars of 10 mm diameter and spaced by 100 mm (Figure 2). The cover is 10 mm for the horizontal rebars and 20 mm for the vertical ones. Wall 4 is similar, but with a different reinforcement: all rebars have 8 mm diameter and they are spaced by 80 mm, with a 0,84% total steel ratio in each direction, compared to 1,05% for the other walls (Table 1).

<table>
<thead>
<tr>
<th>Nature of test</th>
<th>Wall 1</th>
<th>Wall 2</th>
<th>Wall 3</th>
<th>Wall 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete class</td>
<td>C25</td>
<td>C40</td>
<td>C40</td>
<td>C40</td>
</tr>
<tr>
<td>Reinforcement (mm)</td>
<td>φ10@100</td>
<td>φ10@100</td>
<td>φ10@100</td>
<td>φ8@80</td>
</tr>
<tr>
<td>Steel ratio / direction</td>
<td>1,05%</td>
<td>1,05%</td>
<td>1,05%</td>
<td>0,84%</td>
</tr>
<tr>
<td>Cyclic loading</td>
<td>Reversing</td>
<td>Reversing</td>
<td>Non reversing</td>
<td>Reversing</td>
</tr>
</tbody>
</table>

Specimens 2, 3 and 4 are made of a C40 concrete mix. Wall 1 is basically the same as walls 2 and 3, but it is cast with a different concrete class C25, in order to assess the effect of concrete strength on cracking.

Each specimen is installed in a stiff steel frame to avoid large reactions on the laboratory slab (Figure
The specimen is horizontally and vertically connected at the edges of the bottom beam, the vertical support being secured by prestressed bars, in order to avoid uplift for the highest values of the loading assumed for the test. The forces are applied by actuators located between the upper beam and the frame; Figure 4 shows the links between the wall and the steel frame: they constitute together a self-balanced system. This arrangement allows a better control of the applied force and of the boundary conditions.

![Figure 3. Steel frame and face A of the specimen](image1)

![Figure 4. Section in the middle of the steel frame and of the specimen - origin CSTB -](image2)

The load is applied by two hydraulic actuators placed 100 mm above the top of the wall at both sides of the upper thick beam by means of 300 kN force increments. The applied loading history on three of these tests (1, 2 and 4) was cyclic and reversing (Figure 5), while a non-reversing loading history (without reversal of the applied force sign) was applied to wall number 3 (Figure 6). In the first case, three cycles were applied at each force amplitude, while only one was applied in the non-reversing case. No vertical load was applied except the self-weight, which is small compared with the horizontal loadings.

![Figure 5. Measured load time history (wall 2, reversing cyclic loading)](image3)

![Figure 6. Measured load time history (wall 3, non-reversing cyclic loading)](image4)

### 2.2 The measurement layout

The external face A of each wall is painted (speckle effect) for the image correlation analysis, while on the surface at face B several sensors are put and a grid is drawn, representing the rebars mesh. A total of 122 sensors are embedded in concrete and 227 placed on face B. In addition, cracks were carefully identified and mapped at each stage of the loading and LVDTs were installed when the cracks appeared to measure their widths.

Digital Image Correlation (DIC) gives a more exhaustive characterisation of the global crack pattern (Ruocci & al., 2016). This technique uses images from face A of the wall, captured by three digital...
cameras that cover the whole surface of the wall for all the test duration. The crack pattern detected by DIC analysis (face A) has been compared with the visual crack identification (face B), showing a good agreement.

3. REPRESENTATIVE OUTPUTS FROM THE EXPERIMENT

The large amount of data obtained from the measurements is an outstanding basis for a further interpretation of the behaviour of the RC walls. It is only possible to deliver here part of these results and this is done in this section mainly for wall 3 (easier to illustrate because of the non-reversing loading) and for wall 2. The results presented here are only related to the cyclic aspect, the other aspects (e.g. crack spacing) have been presented in other publications (CEOS, 2016).

3.1 Global behaviour

Each cycle causes skew cracking depending on the direction of the applied force; when the force direction is reversed, this set of cracks closes and another family of cracks opens symmetrically with respect to the vertical direction. Walls 2 (cyclic reversing) and 3 (cyclic non-reversing) are identical (except the loading history) and the results only differ due to the reversing character or not of the applied force. Crack pattern of walls 2 and 3 are shown in Figure 7. The analysis of the results shows that the average inclination angle and spacing between cracks are not significantly affected by the direction of thrust.

![Figure 7. Stabilised cracking pattern at 4200 KN for walls 2 (left) and 3 (right) – origin CSTB –](image)

The global behaviour is apprehended by the curves showing the horizontal distortion of the wall between the top and bottom beams vs. the force applied, for the reversing and the non-reversing cyclic loadings (Figure 8).

![Figure 8. Relative horizontal displacement between top and bottom of the specimen vs. applied force for: (a) wall 2 and (b) wall 3](image)

These curves show a fairly classical behaviour, including:

- a progressive softening with the development of cracking;
- pinched hysteresis cycles reflecting the predominance of cracking in damage, with the materials remaining quasi-elastic;
- at each level of loading, three cycles are applied (wall 2); they are almost superimposed, which means that concrete is mainly damaged by cracking, except when near to rupture;
– for the non-reversing loading (wall 3), cracks do not close completely when unloading;
– for the reversing loading (wall 2), the shape of the cycles at small loading shows a full crack re-closing when the sense of the thrust is reversed.

### 3.2 Crack width

LVDT extensometers have recorded crack widths. In the case of reversing cycles, there are two patterns of cracks, approximately symmetric with respect to the vertical direction (Figure 7). Figure 9 shows the evolution of the width of several cracks in a time range; note that (only on this figure), resulting from gross exploitation of the measures, the sign convention for crack widths is negative when open. D2 and D4 sensors measure the cracks widths for the right thrust, D10 and D11 for the left thrust. No significant differences appear between these two sets of cycles, which are shifted depending on the direction of the thrust. The shapes and amplitudes of the records are comparable.

Figure 9. Cycles of cracks width in wall 2

Figure 10. Envelope curves of cycles for walls 1 to 4

Figure 10 shows the envelope curves of the cycles for the four walls. The resistance (or capacity) is essentially determined by the concrete strength: with a lower concrete strength, wall 1 appears as less resistant, softer and more ductile than walls 2 and 3, although the reinforcement is the same. This shows, if a proof was needed, that concrete plays an important role in the wall resistance to shear. Wall 4, less reinforced than the others, shows a particular behaviour with a rapid decrease of resistance after the peak followed by a stabilisation.

Figure 11 shows representative cycles of opening and closing of cracks in the case of reversing (wall 2) and non-reversing (wall 3) loadings.

Figure 11. Crack width vs. force for: (a) sensor D4 on wall 2 and (b) sensor D5 on wall 3
4. INTERPRETATION OF EXPERIMENTAL RESULTS

4.1 Residual crack width

The maximum crack width increases with the applied force. In the case of wall 3 (non-reversing loading), it is observed that the residual width increases when increasing the applied load. In the case of wall 2 (reversing loading), the cracks close at each cycle when the thrust is reversed, for a value of the force depending on the amplitude of the cycle.

Table 2 shows the maximum and the residual crack width for some cycles. It is noted that the residual width is not constantly proportional to the maximum width; the ratio tends to increase for the highest values of loading. In any case, the residual value remains very low. However, it should be kept in mind that the measure of the residual width does not include the “zero point” value at which the LVDT sensor has been installed. Assuming that this value is 50 µm (approximate value depending on the surface lightning and on the human eye) and adding it to both values, the ratio is more stable and stands generally between 30% and 40%; the mean corrected ratio is 34%. It can be observed that the individual ratios slightly decrease when the force increases, which accounts to the fact that part of the residual width is acquired during the first cycles after crack onset.

Table 2. Maximum and residual crack widths / cycles (wall 3)

<table>
<thead>
<tr>
<th>Force (kN)</th>
<th>2372</th>
<th>3040</th>
<th>3380</th>
<th>3689</th>
<th>3947</th>
<th>4289</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max width $w_m$ (µm)</td>
<td>85</td>
<td>125</td>
<td>136</td>
<td>126</td>
<td>138</td>
<td>159</td>
</tr>
<tr>
<td>Ratio force/width (MN/m)</td>
<td>27906</td>
<td>24320</td>
<td>24853</td>
<td>29278</td>
<td>28601</td>
<td>26975</td>
</tr>
<tr>
<td>Max width $w_r$ (µm)</td>
<td>5</td>
<td>15</td>
<td>8</td>
<td>9</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>Ratio $w_r/w_m$ (%)</td>
<td>5.9</td>
<td>12</td>
<td>5.9</td>
<td>7.1</td>
<td>6.5</td>
<td>6.9</td>
</tr>
<tr>
<td>Corrected ratio $w_r/w_m$ (%)</td>
<td>41</td>
<td>37</td>
<td>31</td>
<td>34</td>
<td>31</td>
<td>29</td>
</tr>
</tbody>
</table>

These results are complemented with a different approach below.

4.2 Crack width, non-reversing cycles

Figure 12 shows the evolution of the crack width by two sensors placed on two different cracks on wall 3 with the evolution of the applied force. After the initial crack width discontinuity, there is a clear correlation between the magnitude of the force and the maximum width. The cracks are not completely closed when the force vanishes: measures show also the progress of the residual crack width.

Figure 13 is a further analysis of the behaviour of the same cracks in the vicinity of the same sensors. It shows the envelopes of the curves of maximum crack width and residual crack width when the force vanishes. For comparison, the same values obtained by the DIC on the same cracks are also drawn; they differ by the fact that these are average values along the crack, while the values measured by the
sensors are at precise locations. This may explain the observed differences, which are insignificant in the case of the D5 sensor, a little stronger for D7. In both cases, the trends are the same. In particular, the residual width remains less or about equal to the measurement accuracy thresholds (20 µm for sensors LVDT and 50 µm for the DIC).

Figure 12. Evolution of the force and of the crack width (sensors D5 and D7, wall 3)

Figure 13. Evolution of maximum values on two cracks (sensors D5 and D7, wall 3)

An additional observation can be made from DIC measurements. Figure 14 shows the results averaged along the cracks observed in the central area of the wall.

Figure 14. Evolution of extreme values obtained by the DIC in the central zone of wall 3
− The maximum width undergoes a discontinuity at the creation of the crack, followed by an increase according to the increase of the force. The average slope of this progression is quite low.
− The mean residual width increases in parallel with the maximum value, but remains below the threshold of accuracy of measurement (50 µm). Its ratio to the mean maximum width stabilises and remains below 50%. This confirms (approximately) the observation made with the LVDTs.
− The mean tangent displacement is less than the mean maximum width, although they are of the same order of magnitude. A more detailed analysis crack by crack shows that it is difficult to draw a stable relationship between the two quantities; the tangent displacement can be larger than the width in a limited number of cases, or much smaller in other cases, although all the observed cracks are in the same area of the wall. In addition, the ratio between these two quantities can vary greatly during loading.

4.3 Crack width, reversing cycles

Figure 15 shows the simultaneous evolution of force and crack width measured by sensor D4 on wall 2. As in the case of wall 3, there is a clear correlation between the maximum crack width and the magnitude of the force during cycles where the thrust is in the direction of the crack opening. On the other hand, when the thrust is reversed, the crack closes and is compressed; the compression deformation slightly increases with the amplitude of the thrust. The measurement is originated by the compensation of the crack width existing when the sensor is placed (this explains *inter alia* the negative values of the measure), and by the compression of concrete when the crack is closed. In principle, it is the evolution of this compression and the fact that the crack probably better closes when the compression increases which explain this evolution (see also Figure 9).

Figure 16 shows an analysis of the same type than Figure 13, for both sensors D4 and D11 which are on cracks with opposite angles on wall 2. Similar observations to those in the case of wall 3 can be made. Here the crack width at the reversing of the thrust is also plotted; as already mentioned, these values progress very slightly. Crossings of the axis (force = 0), in the direction of closure and the ones in the direction of crack opening are different; the gap is due to the fact that the compression 'crushes' the crack and the latter is therefore less open in the direction of the opening than that of closing. Nevertheless, for both measures, the evolution is low and reflects the fact that residual crack width evolves with the increase of the force. The maximum (negative) deformation under compression is also plotted.
Residual crack width is difficult to assess because the measures contain the value at the origin of measurement. Nevertheless, the latter can be evaluated by considering that it is roughly equal to the minimum value at the crack onset. By subtracting this value from measures at 0-force crossings, the residual width can be assessed and it can be seen that it is low. Similar conclusions are found at other points of measurement.

Figure 17 is equivalent to Figure 14, but for wall 2. It shows the results obtained by the DIC, averaged along the cracks observed in the central area of the wall, for each direction of thrust. Although the mean maximum width is slightly larger in the case of the left thrust, there is no essential difference between the values of the two senses of thrust. For the left thrust, the mean residual width develops with the increase of the force only in the latest steps of loading, close to the rupture; it evolves much more in the case of the right thrust. However, it remains limited to values slightly greater than 50 µm, which is the measurement accuracy. Mean residual width / mean maximum width ratio for a given loading level evolves little depending on the level of loading beyond a certain threshold, about 50% for the right thrust, a little more than for the left thrust and wall 3.

4.4 Summary of crack width values

Table 3 shows mean values characterising the cracking at the last load cycle, obtained by DIC for the four walls.
Table 3. Crack width during the last cycle of loading

<table>
<thead>
<tr>
<th>Test number</th>
<th>Mean crack width [mm]</th>
<th>Maximum crack width [mm]</th>
<th>Fractile 95% of crack width [mm]</th>
<th>Standard deviation of crack width [mm]</th>
<th>Residual crack width [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left thrust Right thrust</td>
<td>Left thrust Right thrust</td>
<td>Left thrust Right thrust</td>
<td>Left thrust Right thrust</td>
<td>Left thrust Right thrust</td>
</tr>
<tr>
<td>1</td>
<td>0.137 0.180</td>
<td>0.332 0.498</td>
<td>0.268 0.389</td>
<td>0.047 0.075</td>
<td>0.052 0.090</td>
</tr>
<tr>
<td>2</td>
<td>0.144 0.132</td>
<td>0.370 0.400</td>
<td>0.227 0.237</td>
<td>0.078 0.056</td>
<td>0.075 0.065</td>
</tr>
<tr>
<td>3</td>
<td>0.118 -</td>
<td>0.364 -</td>
<td>0.222 -</td>
<td>0.027 -</td>
<td>0.049 -</td>
</tr>
<tr>
<td>4</td>
<td>0.147 0.207</td>
<td>0.377 0.475</td>
<td>0.263 0.359</td>
<td>0.045 0.055</td>
<td>0.044 0.089</td>
</tr>
</tbody>
</table>

5. ENGINEERING PROCEDURES

5.1 Crack pattern and spacing

Experimental results concerning cracks spacing have been analysed in detail and conclusions drawn in (Ruocci & al., 2012), (Ruocci & al., 2013), (CEOS, 2016). The main conclusion is that the relation given by Vecchio & Collins (1986) is acceptable within a domain of crack angles determined by the ratio between the horizontal and the vertical bars sections. Also, the crack angle is determined with a good precision from the principle direction of tensile stress.

The fact that the limit state is a ULS instead of a SLS should not, in principle, change the crack spacing. Indeed, the only parameter that can be affected by the stress level is the bond between reinforcement and concrete. The value of the bond stress given in codes matches to that which produces cracking up to its stabilisation. If the load increases the bond stress increases, but if cracking has stabilized, there is a full slip between the bar and the surrounding concrete and therefore the crack spacing is not affected.

In the case of walls subjected to a variable and reversing shear because of an earthquake, each cycle causes a skew cracking associated with the direction of the seismic action; then, when there is a reversal of the seismic action, this series of cracks closes and another family of cracks opens roughly symmetrically to the vertical. Walls 2 (cyclic reversing) and 3 (cyclic non-reversing) are assumed identical and the results differ only because of the alternation of the applied force. Crack patterns of walls 2 and 3 are shown in Figure 7. It shows that the cracks angle and spacings are not significantly affected by the direction of the thrust.

It is concluded that reversing cycles of shear create two symmetric families of parallel cracks, with a little affectionation on the stiffness and the resistance of the wall.

5.2 Mean deformation and crack width

The CEOS project has made possible to propose a procedure to predict the crack width in shear walls from the elongation of the bars. Also an analytical relationship between the wall drift and the cracks width has been established. This aspect is developed in (Bisch et al., 2014) and (CEOS, 2016) and is not recalled here. Other approaches may be found in (Kaufmann and Marti, 1998) or (Pimentel & al., 2010).

The mean differential deformation is affected by the value of the tension stiffening which has to be reduced by correcting the MC10 $\beta$ factor, where it is given for a SLS situation, with a reduction factor $\alpha (\alpha \leq 1)$, which is of the order of 2/3 at ULS.

5.3 Residual crack width

In order to determine the physical phenomenon of diffusion (gas or liquid) through cracks, it is interesting to characterise the mean residual crack width in a structural element relative to the maximum width attained during an earthquake; the latter may be evaluated either by its mean value (as in the previous figures), or by its highest characteristic value (as in the codes). In table 3, the mean ratio to the mean width is 43%; the ratio to the characteristic width is 24%. CEOS.fr tests do not fully
conclude on the residual width after an earthquake, because the ULS is not reached in the central part of the wall: it has been observed that the level of stress in the reinforcement fits more to a SLS. However there is no evidence that these ratios increase with the maximum crack width, as long as the reinforcement remains elastic. It is concluded that the average residual crack width after an earthquake can be evaluated, as a first approximation, as a proportion of the maximum crack width attained during the earthquake.

6. CONCLUSIONS

The tests of RC walls performed in the frame of the French national project CEOS.fr have provided interesting results for the assessment of cracking in both static and seismic situations. Among these results, those presented in the present paper lead to the following conclusions:

- the development of cracking and the global behaviour are approximately symmetrical for the two senses of thrust;
- a reversing cyclic loading creates a symmetrical bidirectional crack pattern, which slightly affects the stiffness and the maximum strength of the wall, of the order of 10% both;
- the cracking pattern and the maximum crack widths in case of earthquake can be evaluated on the basis of the procedure developed in (CEOS, 2016) taking into account the decrease of tension stiffening at ULS; neglecting tension stiffening at ULS seems to be a conservative but acceptable practice;
- the tangential displacement at the crack is of the same order of magnitude as the width, but cannot be expressed by a simple and constant ratio to the latter;
- the residual crack width remaining after the end of the earthquake is soon established after crack onset, mainly due to interlock effect, and may be evaluated as lower than 30% of the maximum crack width. However, the residual crack width values observed during the experiment rarely exceeded 0,1 mm.

7. ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of the French National Program CEOS.fr sponsored by the French ministry of sustainable development (MEEDDM-DRI).

8. REFERENCES


CEOS collective work (2016). “Control of cracking in Reinforced Concrete Structures”. ISTE (UK) & WILEY (USA).


Web site from where data of the experiment can be downloaded: https://cheops.necs.fr/