Biaxial membrane and bending tests on reinforced concrete panels

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ABSTRACT: This paper presents the results of a series of 10 tests on large-scale reinforced concrete shell elements subjected to bending moments and in-plane normal forces. The experimental program focused on various load combinations, including biaxial tension, tension - compression, compression - compression, biaxial flexure and cyclic loads. A comparison between numerical results obtained by non-linear finite element analysis and experimental data was also done.

1 GENERAL

The use of reinforced concrete (RC) shells in large structures as hyperbolic cooling towers, off-shore platforms, nuclear reactor envelopes etc., has required the development of computing models. Much progress has been made during the last years in modelling RC. However, there is a lack of experimental data necessary to validate these refined numerical models. There are only few experimental results on plates or shell elements subjected to both in-plane and flexural loads reported in the literature [1,4,8].

An experimental investigation was undertaken involving the testing of large-scale reinforced concrete shell elements. The objectives were to observe the phenomenological behaviour of shell elements subjected to combined membrane and bending conditions and to provide data useful in checking the accuracy of non-linear finite element models.

2 EXPERIMENTAL PROGRAM

2.1 Test specimens and material properties

The test specimens are square RC panels. The overall dimensions are 2 m by 2 m and the thickness is 10 cm (Fig. 1). 48 holes of 32 mm diameter are provided in order to connect the loading devices on the specimen.

The reinforcement is composed of two layers of 6 mm diameter bars spaced at 10 cm on two orthogonal directions parallel to the edges of the panel. Supplementary reinforcement bars
are placed within a distance of 35 cm from the edges in order to prevent local failure due to the stress concentrations caused by the loading devices.

Reinforcement bars exhibited ductile behaviour, with a bilinear stress-strain curve as shown in Fig. 2. The material properties of the reinforcement, obtained from coupon tests are summarised in Table 1.

![Stress-strain curve for reinforcing steel](image)

Fig. 2 - Stress - strain curves for reinforcing steel

Normal concrete was used and the specimens were cast in the laboratory.

The properties of the concrete, as well as the loading conditions are summarised in Table 2.

The test program focused mainly on the effect of different load combinations.

Specimens 1, 2 and 6 were tested in flexure and different biaxial in-plane loads. Specimen 3 was tested to repeated in-plane load and then, under constant in-plane load and repeated bending. Specimens 5 and 8 were tested under constant in-plane load and cyclic bending. Specimens 4, 7, 9 and 10 were tested under biaxial compression and biaxial flexure. For specimens 4 and 9 curvatures were of the same sign, while for specimens 7 and 9 they were of opposite signs.

In-plane loads were first applied and maintained during the application of bending moments.

<table>
<thead>
<tr>
<th>Table 1 - Material properties of reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (GPa)</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>195</td>
</tr>
</tbody>
</table>

2.2 Test set-up

The tests were conducted using a new shell element tester facility developed at INSA Lyon (see Fig. 3). A detailed description off the test set-up is given in [6] and [7]. In the following, only a brief description is given.

Two layers of in-plane actuators are used to apply loads along the edges of the test element, allowing a wide range of loading combinations of bending moments and in-plane forces. The ratio between in-plane forces, bending moments or between in-plane forces and bending moments can be chosen freely.

The principle of the system is similar to exterior prestressing (Fig. 4). There is no need of a reaction frame. However, a support frame is used to maintain the specimen in vertical position.

Twelve steel supports are fixed with high strength bolts on the two faces of the RC panel. Loading bars and hydraulic jacks are fixed to these supports by pinned connections.

The forces in the loading bars are balanced by reaction forces in the test specimen. Pinned joints ensure that the loading bars work only in tension or compression. The prescribed axial force and bending moment is obtained by inducing suitable forces in the pairs of loading bars: equal forces produce only membrane loads, opposite forces produce only bending and two different forces produce a combination of membrane and bending.
Fig. 3 - General view of the test set-up

Fig. 4 - Principle of the test set-up
<table>
<thead>
<tr>
<th>Name</th>
<th>Loading pattern</th>
<th>Axial Load (Mpa)</th>
<th>Bending moment</th>
<th>Concrete properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fy/A</td>
<td>Fy/A</td>
<td>M_y = 0</td>
<td>f_c (MPa)</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>-1.10</td>
<td>35.4</td>
<td>3.45</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>-0.75</td>
<td>35.2</td>
<td>3.23</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>-1.50</td>
<td>35.2</td>
<td>3.25</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.00</td>
<td>45.9</td>
<td>3.14</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>+0.47</td>
<td>45.2</td>
<td>3.75</td>
</tr>
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<td>8</td>
<td></td>
<td>-1.10</td>
<td>38.6</td>
<td>3.48</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>-1.10</td>
<td>45.1</td>
<td>3.52</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>-1.10</td>
<td>44.3</td>
<td>3.30</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>-1.31</td>
<td>35.9</td>
<td>3.31</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>-1.31</td>
<td>39.0</td>
<td>2.82</td>
</tr>
</tbody>
</table>

2.3 Instrumentation

Measures are taken of the forces applied to the specimen, displacements normal to the plane of the panel and strains in the concrete and the reinforcement.
Forces are measured by 12 load sensing clevis pins (Straininsert SPA force transducers) placed in the joints connecting the loading bars to the supports (see Fig. 4).

Transversal displacements are measured by 8 LVD transducers.

Concrete strains are measured by 20 HBM 50/120 LY41 strain gauges, 10 on one face and 10 on the opposite face of the specimen. The gauges are placed in the central zone of the panel.

Steel strains are measured by 20 Vishay CEA 06-125 UN 120 strain gauges.

Concrete and steel gauges are superposed in the depth of the plate, in order to determine the curvature of the reinforced concrete section.

There is a total of 60 channels connected to a Centralp data acquisition unit. This unit is connected to the same computer which is used to control the test.

4 TEST RESULTS

4.1 Biaxial in-plane load and monaxial flexure

Flexural behaviour in the presence of biaxial in-plane loads was investigated in tests 1, 2 and 6 and partly in tests 3, 5 and 8. The applied moment, curvature and deflection at cracking of concrete and yielding of reinforcement are given in Table 3.

The cracks appeared at deflections of about 1/1000 of the span, and the tension strain in the concrete was about 150-200x10^{-6}.

Cracks were parallel, regularly spaced at about 10 cm and developed deeply in the depth of the plate above the upper reinforcement.

The stiffness of the cracked panel is only 10-15% of the uncracked one.

After yielding, the stiffness diminished to 2-3% of the uncracked value. The maximum measured deflections ranged between 1/150 and 1/50 of the span.

Failure was generally due to instability by P-Δ effect followed by crushing of concrete in compression.

The in-plane force parallel to the bending stresses has a great influence on the behaviour of the specimen, at the cross-section level by modifying the cracking and yielding moments and at the structure level by the second-order effect. The in-plane force perpendicular to bending has very little influence.

The behaviour of the test specimens was modelled using the non-linear finite element program CASTEM with a multi-layered RC shell element. Numerical and experimental results show good agreement (see Fig. 5). Details concerning the numerical model are given in [3].
As the number of tests was limited, a parametrical study of the influence of in-plane loads using the above mentioned finite element model was performed [6]. The finite element analysis confirmed the experimentally observed behaviour.

Table 3 - Summary of the flexural response of test specimens

<table>
<thead>
<tr>
<th>Test</th>
<th>Moment (kN/m)</th>
<th>Curvature (cm⁻¹)</th>
<th>Deflection (mm)</th>
<th>Moment (kN/m)</th>
<th>Curvature (cm⁻¹)</th>
<th>Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>02</td>
<td>6.0</td>
<td>44x10⁻⁶</td>
<td>0.9</td>
<td>15.85</td>
<td>440x10⁻⁶</td>
<td>10.9</td>
</tr>
<tr>
<td>03a</td>
<td>17.8</td>
<td>64x10⁻⁶</td>
<td>1.8</td>
<td>35x10⁻⁶</td>
<td>58x10⁻⁶</td>
<td>2.8</td>
</tr>
<tr>
<td>05a</td>
<td>7.6</td>
<td>35x10⁻⁶</td>
<td>0.6</td>
<td>13.94</td>
<td>335x10⁻⁶</td>
<td>9.4</td>
</tr>
<tr>
<td>06</td>
<td>5.4</td>
<td>18x10⁻⁶</td>
<td>0.8</td>
<td>14.00</td>
<td>385x10⁻⁶</td>
<td>9.5</td>
</tr>
<tr>
<td>08a</td>
<td>9.25</td>
<td>43x10⁻⁶</td>
<td>1.1</td>
<td>19.98</td>
<td>520x10⁻⁶</td>
<td>10.3</td>
</tr>
</tbody>
</table>

4.2 Biaxial in-plane load and biaxial flexure

During this tests the specimens were subjected to biaxial compression and to biaxial flexure with Mxy/Mz = 1 (same sign curvatures) or Mxy/Mz = -1 (opposite curvatures).

![Graph showing comparison between monoaxial and biaxial bending](image)

In both cases, cracks appeared first and failure occurred in the X direction, where in-plane compression was lower. Cracks were parallel and spaced at about 10 cm. For the specimens subjected to moments of the same sign, the cracks formed a rectangular grid on the tensioned face of the panel. For the specimens subjected to moments of opposite sign, a pattern of parallel cracks developed on each face, perpendicular to the bending stresses. However, the global behaviour of the specimens in the direction in which failure occurred was very similar and close to that of a specimen subjected to the same in-plane loads but only to uniaxial bending (see Fig. 6). In the other direction, some slight differences were noted.

These led to the conclusion that there is very little interaction between bending on two orthogonal directions, at least when the directions of bending coincide with those of the reinforcement. In fact, when reinforcement and bending directions are not identical, an important interaction effect was reported in [8].

4.3 Cyclic flexure

Two types of loading were applied: repeated bending (test 3) and cyclic alternate bending (tests 6 and 8).

In the first case (Fig. 7), the bending moment varied between 0 and a value below the yielding point of the reinforcement.
In the second case (Fig. 8) a full reversal of the bending moment was applied and the load exceeded the yield moment.

For the repeated loading, the specimen showed no diminution of the stiffness or strength. The hysteresis loop is closed.

The relationship between the moment and the crack opening is identical to that between moment and deflection.

The behaviour in the case of full reversed cycles is very different. Either the stiffness and the strength diminish quickly, as it can be seen in Fig. 8.

The cause of these is the accumulation of plastic strain in the reinforcement. In fact, after yielding in one direction, the reinforcement recovers only partially the previous plastic strain (see Fig. 9).

5 CONCLUSIONS

The results of a series of large scale tests on shell elements are presented. The experimental program focused on the effect of different biaxial in-plane and flexural loads.

The in-plane load parallel to the bending direction influences the behaviour at the cross-section level and at the structural level.

The in-plane load perpendicular to the bending direction has only little influence.

There is little interaction between bending in two orthogonal directions when bending and reinforcement directions coincide.
Repeated bending below the yield moment is perfectly reversible. Cyclic bending beyond the yield moment results in rapid drop of stiffness and strength. An experimental database was obtained which can be used to check theoretical models. Further experimental work could be done, investigating other load combinations and reinforcement arrangements.

ACKNOWLEDGEMENT

This research investigation was supported by EDF-SEPTEN, for which the authors are grateful.

REFERENCES


