A preliminary study of the strength of non-prismatic columns using fabric formwork

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Abstract

Columns are perhaps the most iconic and emblematic of architectural elements. Their functional and symbolic presence represents both order and control over gravity. In the development of flexible formwork for concrete there are many examples of tectonically interesting columns. One of the first commercially available systems to use fabric as formwork produced circular columns. Research into fabric formed concrete structures has tended to focus on optimum geometries for beams, where the fabric can be shaped to respond to the bending moments leading to expressive, organic looking shapes. Less attention has been given to the influence of form on the strength of axially loaded columns.

This paper presents some preliminary results on the influence of shape on the compressive strength of non-prismatic columns. There appears to have been relatively little research on the strength of non-prismatic columns, probably as a consequence of the difficulty in construction of the formwork using conventional planar materials. In this project using flexible textile formwork it is shown that non-prismatic columns are straightforward to construct and with no additional complexity compared to cylindrical columns.

A series of structural tests were undertaken on circular columns with diameters that vary along their axis. The columns were constructed carefully to produce non-prismatic geometries that were concave (tapered, from the top) or convex (bulging from the top). In addition prismatic control columns were constructed of constant diameter. All the columns were of the same height and all were designed to use the same volume of concrete. The columns were tested under axial compression to failure at the Engineering Laboratories of the University of Edinburgh.

The results show that the shape of the column has a marked effect on the strength of the columns. The convex columns with increased diameters at mid-point carried the least load and the concave columns with reduced diameters sustained the greatest load approximately 90 - 100% stronger in some cases. The increased load is attributed to the influence that shape has on the development of lateral tensile strains in the columns. Using fabric formwork it is possible to optimise the shape of a column to maximise the compressive strength for a given volume of concrete at no additional cost in the construction process.

Keywords: Fabric formwork, concrete, column, non-prismatic, strength, structural testing, axial loading.
1. Introduction

The column is arguably the most iconic and symbolic of architectural components. It represents both order over material and control over gravity. In the development of flexible formwork for concrete in recent years the column has been studied extensively. Many columns have been constructed that explore the design opportunities offered by flexible formwork. West [1], in a project for a private house in Puerto Rico used textiles to create 13 different concrete columns. On another project, West developed a design using fabric formwork for the raked columns for the Women’s Hospital in Manitoba, West and Araya [2]. Manelius, [3], presented the Composite Column that she used to discuss the tectonic qualities of the fabric formwork. At the University of Edinburgh a number of different studies have been undertaken on the design and construction of columns, Pedreschi, [4] and figure 1.

![Various columns cast as the University of Edinburgh](image1.png)

Figure 1: Various columns cast as the University of Edinburgh

These columns were constructed by senior architecture students as part of an extended workshop studio. They use a variety of textiles and techniques to clamp and restrain the fabric. More recent studies have considered specifically the contrast between accuracy and constraint and free-form columns, figure 2.

![Control and restraint and free-form columns](image2.png)

Figure 2: Control and restraint and free-form columns
The geometry is controlled by careful shaping of the fabric and the use of laser cut profile guides, 2(b). Figure 2(c) shows a free-form column using a variety of textiles and glass knuckle brackets used to modify and shape the form during casting. As the concrete was placed the formwork was allowed to deform and pulled into improvised shapes by the designers.

Current work at the University of Edinburgh considers the use of techniques developed from garment tailoring to provide control and restraint to form, Milne et al [5]. The research to-date on columns is largely concerned with issues of form, tectonic expression and construction process. The use of flexible formwork offers potential in the development of efficient structural elements. In recent years there has been a number of studies at the Universities of Bath, Edinburgh and Manitoba on the structural design of non-prismatic form-active beams. In these studies the geometry of the beams can be shaped more efficiently to follow the distribution of bending forces and hence reduce quantities of materials, concrete, reinforcement and formwork. The carbon footprint can be reduced by approximately 30-35% compared to an equivalent prismatic beam. Columns are subject to predominantly axial compression and the effectiveness of geometry may be less pronounced. Non-prismatic concrete columns using conventional rigid formwork are considerably more expensive to construct. It is not surprising therefore find that there is relatively little published research on the structural behaviour of non-prismatic concrete columns.

This paper presents the preliminary results of an extended programme of research into the structural behaviour of non-prismatic concrete columns. To date a total of 60 columns have been tested.

2. Experimental programme

The results presented in this paper form part of a large programme of research into non-prismatic columns. The programme considers a variety of different geometric configurations and both reinforced and un-reinforced columns. In this paper the effect of convex and concave profiles was compared. It was important to test columns that were broadly representative of ones found in buildings. A short review of 4 recent projects in Edinburgh indicated that the ratio of height to diameter of circular prismatic columns in buildings was between 7.0 and 10.0 and therefore in this study the ratio of 10 was used. Two separate series of prototype columns were designed and constructed. The first series was based on a column of height 1220 mm and diameter of 120 mm at the top and bottom. The diameter at mid-height varied, either increasing or decreasing, to create a convex or concave profile. In the second series of prototype columns the diameters at the top and bottom of the column varied along with the diameter at mid height. These dimensions were determined to maintain a constant volume of concrete in each column, whilst varying the profile from concave to convex and hence provide insights into the influence of shape on material efficiency.

2.1. Geometry and Construction of prototype columns

The prototype columns were constructed in the Architectural Research Workshop at the University of Edinburgh. The prototypes were designed and constructed in two separate series of ten columns each. Each series comprised 5 pairs of identical columns.

All columns in both series were of the same height, 1220 mm and of circular cross section. One pair in each series included a prismatic circular column and two pairs of concave and convex columns, in which the diameter at mid-height reduced (waisted) or increased (bulged). The difference in diameter from the end of the column to the mid height of the columns was either ±20 or ±50 mm. The shape of the vertical profile of the columns in series 1 was based on a circular arc and in series 2 on a catenary curve between the two endpoints. The profiles of both series are shown in figures 3 and 4. In series 1 the diameter at the top and bottom of each column was constant at 120 mm. In series 2 as the columns were designed to use the same volume of concrete the diameter at the top and bottom varied but the
difference between the diameter at mid-height and the end was the same as series 1. The tests in series 2 were then able to indicate more directly the influence of non-prismatic shape on efficiency and strength of the columns.

Figure 3: Dimensions of series 1 prototype columns.

Figure 4: Dimensions of series 2 prototype columns.

The procedure for constructing the columns was generally the same for both series of prototypes.
All columns were 1220 mm in height and constructed using a specially designed frame to support the fabric during casting. Five columns could be cast simultaneously in the frame, thus each series of columns was cast in two stages. A woven polypropylene textile fabric was used for both series, type 3323, supplied by JD Wilkie. The fabric was stretched and the edge profile drawn carefully. This was then aligned with and then attached, using steel staples, to a series of plywood profiles that followed the dimensions shown in figures 3 and 4. The profiles were then bolted to each other and installed in the casting frame between two sheets of plywood at the top and bottom of the columns. These sheets had pre-cut holes cut to the diameters in figures 3 and 4 for each column. The fabric was drawn through the holes and stapled around the perimeter. For the columns in series 1, four sets of profiles at 90 degree intervals were used. In series 2, two sets of profiles were used. In principle a tube or cylinder of fabric should fill in a uniform radial manner due to the hydrostatic pressure of the wet concrete and a circular cross section would be obtained. The guides provided additional control over accuracy and ensured that the top and bottom of the columns aligned along a central vertical axis, Figure 5 shows series 1 columns in the casting frame.

![Figure 5 Columns in casting frame](image)

A concrete mix that had been developed from earlier studies was used in the following proportions:

<table>
<thead>
<tr>
<th>Component</th>
<th>Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>1.00</td>
</tr>
<tr>
<td>Sand</td>
<td>1.73</td>
</tr>
<tr>
<td>Aggregate (10mm maximum)</td>
<td>1.87</td>
</tr>
</tbody>
</table>

The sand and aggregate was spread on the workshop floor to dry for two days prior to casting. For series 1 a target water cement ratio of 0.46 was used. The actual added water was measured for each batch cast and varied between 0.46 and 0.51. 100mm cubes samples were taken from each batch to
determine the compressive strength of the concrete. In series 2 the same proportions of dry materials was used however the water content was reduced to 0.4 by the addition of a plasticiser.

2.2. Dimensional Accuracy
A detailed survey of the dimensions of the columns in series 2 was carried out. The circumference was measured at five positions along the length of the column: top and bottom, middle and quarter points. The measurements were compared with the target dimensions and found to be on average within 2.5%.

3. Structural Tests
The columns were transferred to the Structures Laboratory at the School of Engineering. The columns were tested to destruction in an Avery 7104 Universal Testing Machine. Prior to testing, the columns were prepared by applying a levelling layer of rapid setting plaster to each end. Demec points were applied at four points around the circumference of the column at mid-height and used to monitor the strains in the columns during loading. The Demec points were also used to accurately position the samples. An initial load was applied and the strains were recorded. If the readings indicated uneven strains then the load was removed and the column re-adjusted to obtain more uniform strains. In series 2 digital image correlation (DIC) was also used. This technique uses high-resolution cameras and pattern recognition software to record small changes in the surface of a structure when subjected to loading. The central sections of the columns were painted black and then speckled with white paint to created more easily recognised patterns. The load was applied in equal increments to failure. At each increment strains were recorded and images for the DIC taken.

3.1. Results for series 1 prototype columns
The results for series 1 are summarised in table 1.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Shape</th>
<th>Failure load kN</th>
<th>Compressive strength of concrete MPa</th>
<th>Compressive stress at mid-height MPa</th>
<th>Compressive stress at top MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>25 mm concave</td>
<td>112.5</td>
<td>23.4</td>
<td>29.2</td>
<td>9.9</td>
</tr>
<tr>
<td>1.2</td>
<td>25 mm concave</td>
<td>116.5</td>
<td>21.2</td>
<td>30.3</td>
<td>10.3</td>
</tr>
<tr>
<td>1.3</td>
<td>10 mm concave</td>
<td>142.5</td>
<td>27.9</td>
<td>18.1</td>
<td>12.6</td>
</tr>
<tr>
<td>1.4</td>
<td>10 mm concave</td>
<td>177.0</td>
<td>21.3</td>
<td>22.5</td>
<td>15.6</td>
</tr>
<tr>
<td>1.5</td>
<td>straight</td>
<td>139.5</td>
<td>22.2</td>
<td>12.3</td>
<td>12.3</td>
</tr>
<tr>
<td>1.6</td>
<td>straight</td>
<td>171.0</td>
<td>21.2</td>
<td>15.1</td>
<td>15.1</td>
</tr>
<tr>
<td>1.7</td>
<td>10 mm convex</td>
<td>181.0</td>
<td>27.9</td>
<td>11.8</td>
<td>16.0</td>
</tr>
<tr>
<td>1.8</td>
<td>10 mm convex</td>
<td>165.0</td>
<td>22.1</td>
<td>10.7</td>
<td>14.6</td>
</tr>
<tr>
<td>1.9</td>
<td>25 mm convex</td>
<td>179.4</td>
<td>22.1</td>
<td>7.9</td>
<td>15.9</td>
</tr>
<tr>
<td>1.10</td>
<td>25 mm convex</td>
<td>184.5</td>
<td>23.4</td>
<td>8.1</td>
<td>16.3</td>
</tr>
</tbody>
</table>

Table 1 Summary of the series 1 tests
The columns failed with the onset of cracking along the vertical axis and then crushing. The location varied depending on the shape of the column. For example column 1.1 with a concave profile failed at
mid-height, column 1.8 with a convex profile failed by crushing at the base, figures 6 and 7. Comparing the 25 mm concave columns with the 25 mm convex columns the concave columns are on average 37% weaker that the convex columns although they use approximately 43% less concrete.

Figure 6: Failure of column 1.1
Figure 7: Failure of column 1.8

3.2. Results for series 2 prototype columns

The results for series 2 are summarised in table 2. Column 2.1 was damaged in transit to the structures laboratory and could not be tested.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Shape of column</th>
<th>Failure load kN</th>
<th>Compressive strength of concrete MPa</th>
<th>Compressive stress at mid-height MPa</th>
<th>Average compressive stress at end MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>25 mm concave</td>
<td>-</td>
<td>38.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2.2</td>
<td>25 mm concave</td>
<td>214.5</td>
<td>42.6</td>
<td>25.4</td>
<td>12.3</td>
</tr>
<tr>
<td>2.3</td>
<td>10 mm concave</td>
<td>213</td>
<td>34.3</td>
<td>19.6</td>
<td>15.7</td>
</tr>
<tr>
<td>2.4</td>
<td>10 mm concave</td>
<td>219</td>
<td>40.6</td>
<td>20.1</td>
<td>15.5</td>
</tr>
<tr>
<td>2.5</td>
<td>straight</td>
<td>144</td>
<td>42</td>
<td>12.3</td>
<td>12.7</td>
</tr>
<tr>
<td>2.6</td>
<td>straight</td>
<td>216.5</td>
<td>43.5</td>
<td>18.3</td>
<td>16.9</td>
</tr>
<tr>
<td>2.7</td>
<td>10 mm convex</td>
<td>135</td>
<td>42</td>
<td>10.6</td>
<td>14.2</td>
</tr>
<tr>
<td>2.8</td>
<td>10 mm convex</td>
<td>188</td>
<td>43.5</td>
<td>14.7</td>
<td>19.5</td>
</tr>
<tr>
<td>2.9</td>
<td>25 mm convex</td>
<td>77</td>
<td>38.4</td>
<td>5.2</td>
<td>11.2</td>
</tr>
<tr>
<td>2.10</td>
<td>25 mm convex</td>
<td>102</td>
<td>42.6</td>
<td>6.9</td>
<td>14.8</td>
</tr>
</tbody>
</table>

Table 2 Summary of series 2 tests

The compressive strength of the concrete columns in series 2 is markedly greater than series 1 showing the effects of the plasticiser used to reduce the water content. Column 2.2 with a concave
profile failed near mid-height. Again the nature of the failure varied largely depending on the geometry of the column. The concave columns tended to fail at or near the mid-height position. The prismatic and convex columns demonstrated failure at or near the top or bottom of the columns. The convex columns tended to develop vertical cracks prior to failure, developing and growing as the load approached ultimate. The failure of the concave columns on the other hand was more sudden with less early cracking and was quite explosive in some cases. Typical failures are shown in figures 8 and 9.

Figure 8: Failure of column 2.2
Figure 9: Failure of column 2.10

The results of series 2 show a marked difference in trend with series 1. The difference in behaviour due to the effects of geometry in more pronounced with the concave columns carrying significantly larger loads at failure than the convex columns. All the columns tested used approximately the same quantity of concrete and therefore a clear understanding of the influence of geometry can be seen. Column 2.2 demonstrated over twice the strength of columns 2.9 and 2.10 with comparable degrees of concavity and convexity.

3. Analysis

Tables 1 and 2 include the compressive strength of the concrete used in each of the columns and the stresses at the ends of the columns and at mid height. From table 1, it is noted that the stresses at mid height for the concave columns, 1.1 and 1.2, although they carried the lowest failure loads, are considerably higher than the crushing strength obtained from the concrete cube tests. They also experienced approximately twice the stresses at failure than the comparable convex columns 1.9 and 1.10. Another interesting observation is the ratio between the maximum and minimum stresses in the columns, again looking at 1.1 and 1.2 the stresses at the mid height are approximately three times the stress at the ends of the column. For the convex columns maximum stress is approximately twice the minimum. Figure 10 illustrates the influence of geometry on the stresses in the columns. As concrete is an inherently variable material, to aid comparison the stresses have been normalised in relation to the notional compressive cylinder strength. The strength of concrete in compression is normally determined from cubes or cylinders. The strength of cylinders is generally considered more representative of the in-situ strength of concrete. Although concrete cubes are the simplest form of test specimen the aspect ratio and the influence of platen friction from the test machine tends to result in higher strengths than the cylinder. There are various expressions that relate the cube strength to the
cylinder strength. The Euro-code, British Standards [6], for concrete presents this in tabular form according to strength, which for the range of strengths herein the cylinder strength is approximately 80% of the cube strength. The stresses at failure have been normalised as follows:

\[ f_{cn} = f_u / 0.8 f_{ck} \]

where \( f_{cn} \) is the normalised stress at failure
\( f_u \) is the compressive stress at failure
\( f_{ck} \) is the average compressive strength from the concrete cube tests.

In figure 10 the normalised stress at failure is compared with the convexity or concavity of the prototypes. The concavity and convexity is taken simply as the ratio of the end diameter to the diameter at mid-height. Below a ratio of 1 the column is convex above the column is concave. The figure shows a strong trend towards increasing compressive stress at mid-height as the geometry changes from convex to concave. The stresses at the ends of the column increase at a much slower rate as the geometry changes from concave to convex.

In table 2 the results for series 2 tests indicate more clearly the effects of geometry on failure load. This is perhaps a more accurate comparison as the volume of the concrete in the columns is kept constant. The dimensions at both the end and mid section vary to provide the same degree of concavity or convexity as columns in series 1. In these tests the stresses are calculated using the actual measured dimensions at each section. Interestingly the compressive stresses at failure are not higher than the stresses in series 1 despite the higher strengths in the concrete cubes. The failure stresses in the convex columns are significantly less than suggested by the cube test results. Figure 11 presents the normalised stresses in relation to the degree of convexity and concavity. A similar trend to series 1 is evident with increasing compressive stress at mid-height in columns with concave profiles. The stresses at the ends of the column show little or no influence on the stress at failure.
The position of the failure in the column is affected by geometry. Although the trend-line for stress at failure at the ends of the column does not appear to be influenced by the geometry it is represents the maximum stress in the convex columns and minimum in the concave columns, further emphasising the importance of geometry on strength.

![Diagram](image)

**Figure 11**: The relationship between normalised stress at failure and the degree of non-prismatic form, series 2

To some extent these findings may appear counter-intuitive, normally increasing the cross-section of a column at the midpoint would be thought to increase the load carrying capacity. This applies in applications where the slenderness of the column is such that buckling will be the pre-dominant mode of failure. Buckling was not in evidence and failure was observed due to crushing. As a brittle material is loaded the Poisson effect gives rise to transverse tensile strains. The tensile strength of concrete is approximately 10% of its compressive strength and failure is often initiated by the development of cracks perpendicular to the tensile stress, following the direction of axial compressive force. The difference in strength commonly recognised between cylinder and cube tests is attributed to the ‘platen friction’ effect in the cubes that restrains the development of transverse tensile strains. The longer aspect ratio of the cylinder allows development of transverse cracks and hence lower failure loads.

The convex and straight columns in series 2 clearly showed the development of vertical, axial cracks prior to failure. Failure of the concave columns was more sudden with less cracking prior to failure. It was anticipated that the use of DIC would provide some additional insights into the transverse strains but these have been inconclusive thus far and further studies using this technique are underway.

The explanation for the higher stresses and increased load capacity of the concave columns and lower stresses and loads in the convex columns is most likely due to the effect that the geometry has on the development of transverse strains. Figure 12 presents a simplified conceptual diagram to explain the behaviour. In the concave samples the taper towards the centre of the column directs the resultant compressive force inwards toward the central axis of the column. This in turns serves to counteract the
transverse tensile strains that develop due to the effect of the Poisson ratio, delaying the development of the axial cracks that initiate compressive failure. Following this model then the reverse would occur in the convex column. The resultant forces induce additional tensile strains in the column that hasten the development of transverse cracks, leading to a reduction in strength.

Figure 12: Simplified diagram representing forces at mid height in the columns

4. Summary and conclusions
This paper has presented some of the initial findings from an extended study into the use of flexible fabric formwork to produce non-prismatic columns. Although there has been many studies of columns using fabric formwork that demonstrate the great variety of geometry and complexity of form there does not appear to have been any prior research on the structural behaviour of non-prismatic columns. This is probably due to the difficulty and effort required to produce non-prismatic formwork using rigid materials. In addition as the forces are axial and hence do not vary with length there is not the same perceived opportunity to improve efficiency in columns and therefore to date most of the research on the performance of form-active structures has focussed on flexural elements such as beams.

The prototypes considered in the present study comprised simple variations in geometry from a prismatic cylindrical form to create either concave or convex profiles. The overall proportions of the columns were chosen from a study of existing building structures. The project would not have been considered had it not been the ease with which the non-prismatic forms can be constructed using flexible formwork. The aim therefore was to determine if there is a structural advantage, through increased efficiency without a corresponding increase in the complexity of construction. Careful measurements have also demonstrated that the construction process can produce dimensionally accurate geometry.

The structural tests on 19 prototype columns have revealed that the strength of columns is influenced considerably by form of the column. Two series of tests have been carried out and both indicate that higher stresses and loads at failure are obtained by columns with concave profiles and that convex profiles produce weaker columns. This behaviour is most clearly demonstrated in series 2, where the total volume of concrete used was constant irrespective of form. The concave columns carried approximately twice the load of equivalent convex columns. Thus the material is used more efficiently
To some extent this result may appear counter-intuitive as columns for which the dimensions are greater at mid-height have greater resistance to buckling. However for the proportions of the columns tested in this study failure occurs due to material crushing, initiated by the formation of vertical cracks. It is considered that the concave form creates transverse compressive stresses that actively resist the development of vertical cracks whilst the convex form create additional tensile strains that hasten the development of vertical cracking.

A further 40 prototype columns have been tested and the results are currently under analysis including more detailed investigations using Digital Image Correlation and finite element modelling.

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References


