Automating Concrete Construction: Digital Design of Non-Prismatic Reinforced Concrete Beams

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Abstract. The construction industry is responsible for nearly half of the UK's carbon emissions, mainly due to the large amount of concrete used. Traditional formwork methods for concrete result in prismatic building elements with a constant cross-section, but the shear forces and bending moments that beams have to withstand are far from constant along their length. Up to 40% of the concrete in a typical beam could be removed. An iterative optimisation process has been implemented in a parametric modelling framework to generate and analyse optimal forms for non-prismatic beams that take into account the constraints imposed by the fabrication process, namely the use of fabric formwork. The aim of the resulting design tool is to facilitate the adoption of non-prismatic elements by the construction industry.

Keywords: non-prismatic beam, reinforced concrete, automated design, fabric formwork, parametric modelling, structural analysis.

1 Introduction

The construction industry needs to change. The UK government has stated that the construction industry should achieve, by 2025, a 33% reduction in initial and whole life cost of assets, a 50% reduction in construction time, and a 50% reduction in greenhouse gas emissions [1].

In terms of sustainability, the construction industry is responsible for nearly half of the UK's carbon emissions [2], mainly due to the use of an extremely large volume of concrete. It is the world's most widely used man-made material, which accounts for more than 5% of global CO_2 emissions. Traditional formwork methods for concrete result in prismatic building elements (such as beams, floors and columns), not because a beam needs to be prismatic to support its load, nor because it is difficult to shape concrete to other forms (it begins life as a liquid), but because existing fabrication techniques rely on easy-to-construct prismatic moulds. 30-50% of the concrete in a typical beam is only there because of the prismatic formwork it was made in, and could be removed [3]. For too long, the industry has used "ease of construction" as an excuse to waste material.

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The authors are working on a research project, titled “Automating Concrete Construction (ACORN)”, which aims to dramatically improve whole life construction sector sustainability and productivity by defining a holistic approach to the manufacture, assembly, reuse, and deconstruction of concrete buildings, leading to a healthier, safer, built environment. This research project represents a transitional pathway for low-carbon concrete design, paving the way towards carbon neutrality. This paper shares some early results from the project, particularly its quest to ensure that just enough material is used and no more, by investigating ways of optimising beams and slabs for off-site mass-customization, with a particular focus on the use of flexible formwork for concrete manufacturing. In particular, we present the development of computational design tools with the intent of catalysing the adoption of such an approach by the construction industry. This work precedes the fabrication of 1:1, scale physical test specimens, which will be tested in parallel and reported separately.

2 Related work

Current digital design and fabrication methods enable the construction industry to produce buildings and building elements with complex and bespoke shapes, evolving from a pre-digital age when orthogonal geometries predominated [4]. Concrete in particular, being the most used construction material, shows large potential to take advantage of such shapes towards greater design freedom, and at the same time a more efficient use of material through structural optimization [5–7], leading to the adoption of non-prismatic concrete building elements.

A large part of the efforts of applying digital fabrication to concrete construction focus on additive manufacturing, commonly called 3d printing [8]. However, concrete 3d printing is relatively novel and raises a number of challenges related to issues such as reinforcement, scalability, and life cycle cost, rendering it unlikely to disrupt the industry in the short term towards a more sustainable paradigm [9, 10].

Since well before additive manufacturing was introduced in the construction industry, concrete elements were traditionally built through casting processes. Subsequently, fabric formwork has been explored as a method for casting non-prismatic concrete elements. A recent review of the state-of-the-art [11] highlights research on fabric carried out in the University of Manitoba [12, 13] and the University of Bath [14, 15], in which beams are manufactured by pouring concrete into a flexible membrane instead of a traditional orthogonal rigid panel formwork. Recent studies on flexible formwork [16, 17] illustrate the potential of combining fabric formwork with digital fabrication as well as digital modelling techniques for improving the accuracy and efficiency of concrete elements.

Digitally driven casting processes have also been successfully applied to concrete construction. In terms of digital design tools, the complex interaction amongst materials and forces in flexible formwork justifies the application of form-finding and optimization processes, integrated with manufacturing constraints. The work of Veenendaal et al. [18, 19] explores the combination of dynamic relaxation, finite element analysis and evolutionary optimization algorithms to determine optimal shapes of concrete structural elements.

As most of these examples illustrate, a formwork approach to concrete manufacturing is considered a viable alternative to additive manufacturing. However, if such methods and processes are to be used in real construction scenarios, they need to be streamlined and flexible.

3 Development of a design tool for optimized reinforced concrete beams

The first step towards manufacturing efficient concrete elements is their design. An iterative optimization process is being implemented in a parametric modelling framework to generate optimal forms for non-prismatic reinforced concrete (RC) elements that take into account the constraints imposed by the fabrication process. This work will culminate with the deployment of a design tool that can be used by professionals in the construction industry, and therefore special attention is being given to the user experience. While the research presented in this paper has focused on beams, the authors are currently exploring ways of expanding to include other building elements such as slabs and columns.

The design of non-prismatic concrete elements will be governed by a design system that articulates three modules, namely generation, analysis and optimization, and is informed by manufacturing constraints (Fig. 1), adopting the approach of previous related research [18]. Such a system allows the evaluation and optimization of the performance of the concrete elements.

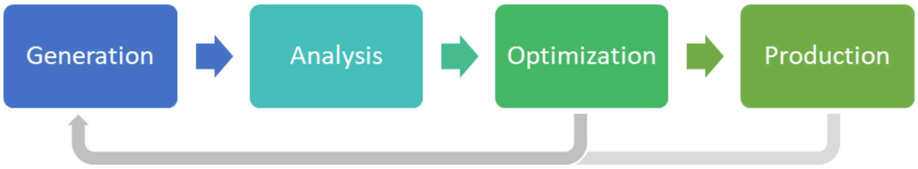

Fig. 1. Modules in ACORN design tool.

Presently, the adopted optimization approach looks for designs that use just enough material for satisfying their design requirement, and no more. In the case of beams, an element's performance is assessed in regard to serviceability, particularly in terms of deflection, as well as checking for flexural strength.

Performance is assessed by the analysis module, in which deflection is estimated using the method of integration of curves [20], as previously applied in the scope of non-prismatic RC beams [21]. This method estimates the deflected displacement of different points along the beam through double integration of curvature in those points. The analysed beam designs are provided by the generation module, which is developed towards flexibility by representing a wide spectrum of shapes and structural configurations.

Since development of the ACORN design tool (henceforth referred to as ACORN) is still in progress, this paper focuses on the first two modules, generation and analysis. Presently, the ACORN software is being developed within a parametric modelling framework supported by CAD modelling software Rhinoceros (Rhino) and visual programming interface Grasshopper (GH). The tool itself consists of a plugin for GH written in C# using RhinoCommon, a cross-platform .NET software development kit for Rhino. Existing tools for structural analysis were considered for integrating the design system, namely standalone applications such as ANSYS and Robot, or Grasshopper plugins such as Karamba3D, Kangaroo Physics, and K2Engineering. However, shortcomings in these applications to represent a non-prismatic RC beam, as well as their potential to compromise open accessibility to ACORN, pushed towards an integrated solution supported by numerical methods for structural analysis. Once prototyping is complete, the new tool may be re-written as an extension of the aforementioned existing tools to maximise dissemination of the ACORN methodology.

4 Generation module

The generation module is responsible for creating the shape of a reinforced concrete element represented by NURBS surfaces, as well as information pertaining to it. Since one of the project's research questions is to determine the most efficient manufacturing strategies for producing non-prismatic concrete elements, ACORN needs to be as flexible as possible, hence the decision to adopt NURBS as the representation of geometry.

Presently, two templates are implemented, capable of generating T-shaped, and fabric-formed beams. T-shaped beams were selected as they are fairly common, typically studied in structural design textbooks, while the choice for fabric-formed beams derives from the project team members' expertise in the subject. Note that standard rectangular beams can also be generated using the T-beam template. Moreover, the generation module currently supports point loads and uniformly distributed loads (UDL) along the whole beam, and is limited to simply supported beams. Naturally, as research progresses, the module's capability will be extended to different types (slabs, columns, walls) and sub-types of concrete elements, as well as to additional load cases and support conditions. Defining such elements will build upon the previous work, further enrichening the generation module.

In existing structural design tools, structural elements are represented under the assumption that they will be prismatic, or tapered at best, whereas ACORN requires a more flexible representation of non-prismatic elements. Therefore, an effective implementation required the representation of all the elements of the RC beam into a number of classes, enabled by C# being an object-oriented programming language. So far, three main classes have been implemented, corresponding to Beam, CrossSection, and DistributionDiagram. Complying with the Euler-Bernoulli beam theory, according to which the cross-section of a beam remains plane after deformation [22], a Beam object is described in ACORN by a number of CrossSection objects, each of which is in turn associated with a number of calculated DistributionDiagram objects. Additional classes, such as Rebar, help better represent the aforementioned entities.

The representation of T-shaped beams is relatively straight-forward. Given the required parameters, the corresponding T-shaped cross sections are determined, which in turn are used to generate the beam's shape. Such parameters include flange breadth and depth, web breadth, effective depth, cover thickness, and inset distance. In order to represent a non-prismatic beam, each of these parameters can vary along its length, since they associated to cross sections. Additional parameters pertain to the beam itself and remain constant, namely its span, material properties and number, diameter and type of reinforcement bars used.

While the geometric representation of a T-shaped beam is fairly simple, the generation of a fabric-formed beam implied simulating the behaviour of poured concrete inside fabric formwork. While this can be achieved using physics simulation provided by third-party software, we again opted for a numerical approach. In a first iteration, empirically determined equations were used to approximate the hydrostatic shape as a truncated ellipse [14, 23]. Subsequently, an iterative method was used to form-find the section shape using its top breadth and depth as inputs, corresponding to a variation of the 'elastica' curve, which takes into account the effects of both gravity and the hydrostatic pressure of the poured concrete [21, 24]. The form-finding procedure was further extended to determine the shape of fabric formwork when restrained at a defined depth level with internal ties [25], hence expanding the design space of the beam's shape (Fig. 2). Note that computing the equilibrium shape of two-dimensional sections of the fabric formwork is a simplification of form-finding the doubly curved shape that describes it. However, such simplification has been shown as acceptable [24], and justified since it reduces computation time.

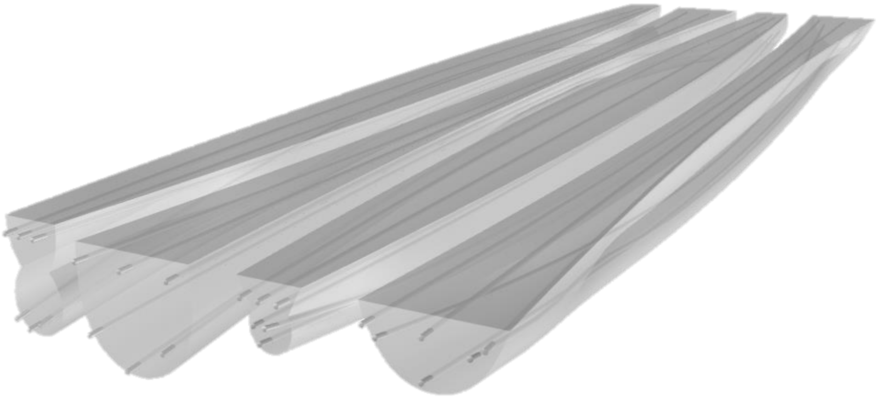

Fig. 2. RC beam designs generated by the ACORN design tool.

The algorithm was tested to replicate the shape of an existing fabric-formed beam, by comparing a model generated by ACORN with a mesh that resulted from 3D-scanning a physical model of a 60-cm long fabric-formed beam [26]. The average deviation between the generated surface and the scanned mesh is 8.6 mm, measured between sampled points in the NURBS surface generated by ACORN and the corresponding closest point in the original mesh. The maximum deviation being is 28.8 mm, and the largest deviations (circled in black) are found at the beam's ends and at imperfections in the concrete (Fig. 3). While the maximum deviation can be attributed to imperfections in the physical model, the average deviation of 8.6 mm was considered small when compared with the beam's dimensions, namely 1.43% of its 60-cm span and 8.60% of its 10-cm breadth. Nevertheless, an increase in deviation is identified towards the bottom and the ends of the beam (Fig. 3) and should therefore be addressed further afield.

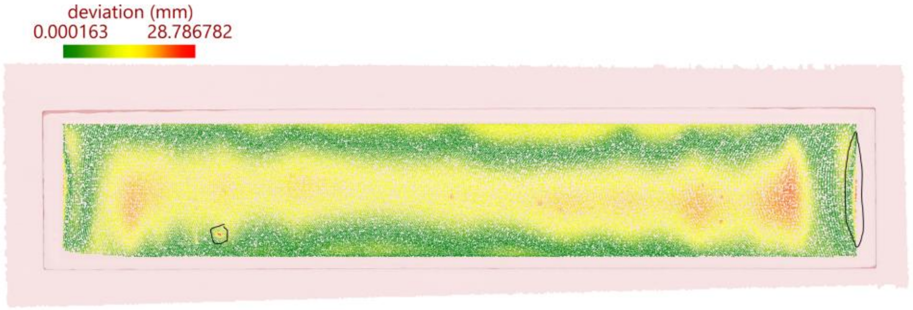

Fig. 3. Geometric deviation between fabric-formed beams produced in [26] and shape generated by ACORN design tool (plan view)

5 Analysis module

The main purpose of the analysis module is to estimate the maximum deflection for a given beam design. Deflection is targeted over strength since, in the case of buildings, serviceability is often the limiting factor. This is calculated through the method of integration of curves [20]. The main advantage of the implemented module over existing plugin solutions is its capability to analyse non-prismatic geometry, as well as take reinforcement steel into account. The estimation procedure consists of the following:

- divide the beam into a number of equally spaced planar sections;
- for each section,
  - for each strain value within an increasing range of strain values between zero and the ultimate strain value for concrete (0.0035);
    - iteratively determine neutral axis by plotting a hypothetical strain diagram and balancing compression and tension forces both in concrete and reinforcement steel;
    - calculate resisting moment (currently around the centroid of the tension rebar's cross section);
  - plot a graph of resisting moments against curvatures (calculated from slope of strain diagrams);
  - determine curvature from bending moment;
- integrate curvature over beam's length to determine slope;
- integrate slope over beam's length to determine deflection.

One intent in developing the analysis module was to provide as much visual feedback on the analysed parameters as possible, primarily to support validation during development of the tool, and eventually to help designers make informed decisions on the design of a beam based on its performance. Therefore, the beam design is complemented with information on bending moment values, tension and compression forces for each strain value, moment-curvature plots, curvature, slope and deflection values for each section, as well as a summarizing analysis table and key parameters used in generating the beam.

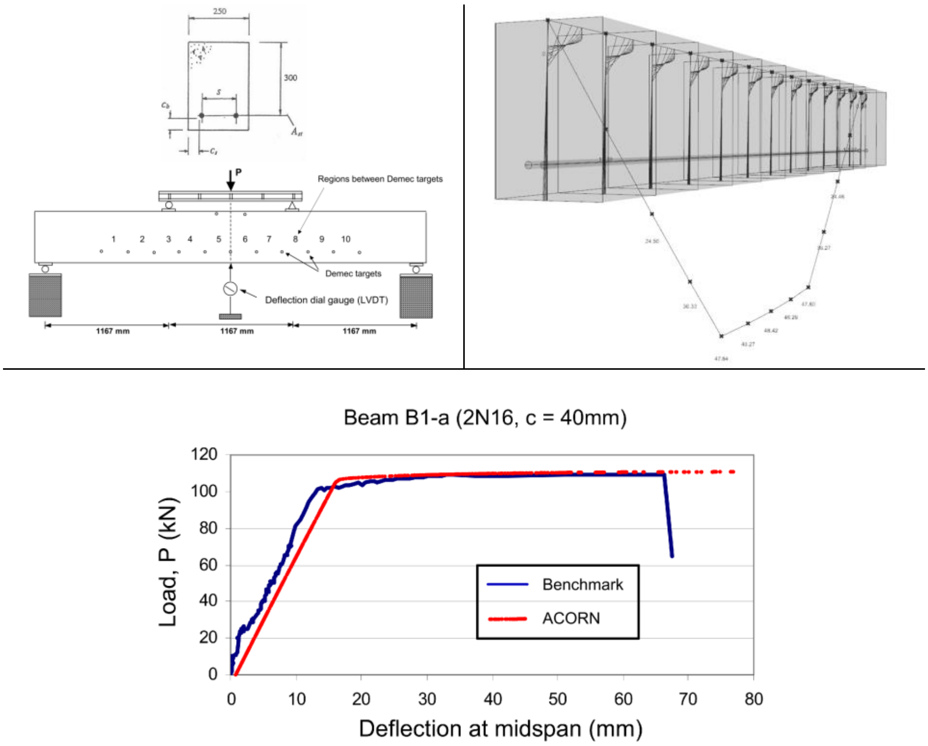

Fig. 4. Analysis module validation – Top left: geometry of benchmark beam (source: [27]); top right: geometry of ACORN beam; bottom: load-deflection plots of benchmark beam and of ACORN beam (adapted from [27]).

The analysis module was validated by comparing its results with published experimental data (Fig. 4), consisting of a series of short-term load tests on reinforced concrete flexural members, to study the development of flexural cracking under increasing loads [27]. Considering these as benchmarks prismatic beams, a beam was modelled in ACORN, replicating the dimensions, support conditions and load case of benchmark beam B1-a. The beam model was then run through the analysis module, generating the corresponding moment-curvature and deflection plots. While not stated in the benchmark study, the simulation considered a yield strength value (Fy) for the rebar steel of 590N/mm^2. A load-deflection plot was then generated in Grasshopper by varying the applied load and comparing the results with the benchmark beams.

Comparing both load-deflection plots shows that their shape is similar: the curves' inflections occur in the same Deflection range, between 10 and 20 mm, and maximum load values are between 100 and 120 kN in both curves. The two plots are fairly approximate, particularly when considering that the benchmark plot results from physical tests and the ACORN plot results from a simulated beam, and therefore we consider the analysis module valid.

Furthermore, parametric studies are being performed in order to a) further validate the analysis module and b) assess the sensitivity of parameters in the generation module. Although the results of these studies will be useful for further developing the design tool, they were not included in this paper due to space restrictions.

6 Conclusions

This paper introduces the ACORN project and presents the ACORN design tool as a work in progress, documenting its current status. As a tool to facilitate the design of sustainable non-prismatic reinforced concrete elements, ACORN is being developed towards three main objectives: flexibility, rigour and usability. Building on previous research on non-prismatic beams, the tool aims at rendering such approach available to current design practices, thus enabling structural designers to design non-prismatic concrete elements with confidence, rigour and speed, and therefore mitigating the obstacles that prevent them from using just enough material. Currently under development, we realize the challenge of honouring those three objectives. Therefore, further development will include the following actions:

- adding beam cross section templates (I beam, girder, generic);
- improve speed until suitable for real-time optimization;
- assess embodied carbon beyond quantity of concrete, including from fabrication transport and assembly strategy.

Subsequently, a full exploration of the optimization module will begin by experimenting with existing optimization plugins for Grasshopper, later looking at additional existing solutions such as topology optimization and, if necessary, developing a custom approach.

As the project advances beyond beams, non-prismatic concrete slabs will be addressed, particularly looking at thin shells, due to their structural efficiency and reduced material. Looking at a wider horizon, it is crucial that our tool is tested in practice, which will be carried out with the support of the dozen Project Partners and growing list of Project Affiliates.

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