

Automated Fabrication of double curved reinforcement structures for unique concrete buildings



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HIGHLIGHTS

- Automatic planning of collision free steel reinforcement bar (rebar) bending operations.
- Rebar deflection modeling using a virtual joint model.
- Automatic planning of transportation of bended and deflecting rebars.
- Rebar binding using mechanical and sensor based adjustments.
- Integration and tests of all parts of the rebar mesh production system.

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ABSTRACT

In this paper we present research and development results that have lead to a fully automated fabrication cell with two robots, that in one integrated step can produce unique double curved steel reinforcement structures with sizes up to 2 times 2 meters. Input is a computer-aided design description of the reinforcement bar layout. The reinforcement bars are bent and transported to the structure by one robot and assembled (bound together) with the other. The paper encompasses a presentation of the design of the bending tool and the associated optimal bending strategy. Moreover, we present a method to automatically plan collision free robot motions that account for deflections of the bars, and finally a sensor based robot control method that binds the bars together while accounting for unexpected positional deviations. The paper is concluded with a set of experimental validations where we show that the bent bars accurately follow the specified shapes.

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1. Introduction

With the increased use of digitization in the architectural design of large concrete buildings in the last couple of decades, the options for interesting new shapes have become almost unlimited. However, today's concrete buildings are still often rectangular shaped such as in the left picture in Fig. 1. This is due to the complexities and in particular the costs involved in the building manufacturing phase where the usage of modern technologies is still quite limited. Due to their elegance, architecturally advanced buildings, such as in the middle picture in Fig. 1, are attractive for customers. However, currently they are highly expensive to construct, hence there is strong demand for reducing the costs, so

that the manufacturing of these becomes economically feasible in a much wider range of cases.

It has been the purpose of the European project TailorCrete under the 7th framework program to address this problem. A wide range of topics such as formwork materials and manufacturing, fiber reinforcements, modeling the casting process using self compacting concrete, and digital manufacturing has been addressed by other partners in TailorCrete [1,2].

The topic that we have studied in TailorCrete has been how to use robotic automation to reduce the price for manufacturing the steel reinforcement associated with these advanced constructions. The steel reinforcement constructions ensure that the concrete structures can withstand the tensile stresses as the concrete material can itself resist compressive stresses. In the right picture in Fig. 1, we show an example of the manually manufactured reinforcement for the shape in the middle picture. As should be obvious, the manufacturing of such a structure is a cumbersome process involving a large amount of man hours on-site.

To illustrate the requirements for reinforcement in a more simple context, consider the concrete element in Fig. 2. Before

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Fig. 1. Left: dominating geometry of today's urban landscape. Center: a prestige unique concrete structure. Right: handmade formwork for producing the unique concrete structure shown at the center photo.

Source: www.tailorcrete.com.

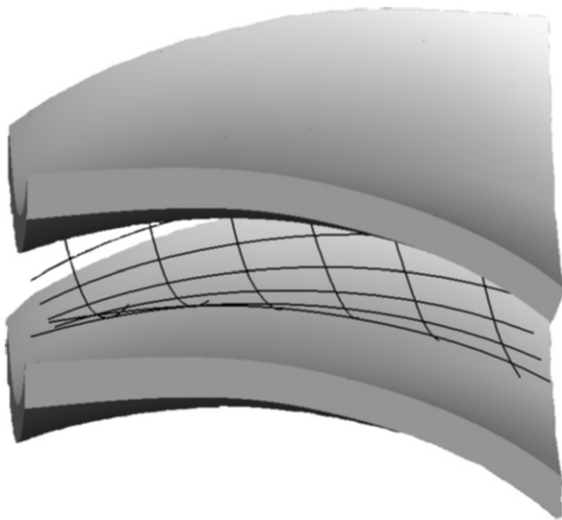


Fig. 2. Exploded drawing of element, concrete–steel reinforcement–concrete.

casting, the element consists of the formwork (shells into which the concrete is casted) and the reinforcement. To avoid cracks, minimize usage of reinforcement, and enable a better flow of the (self-compacting) concrete, the reinforcement structure (illustrated on the figure with the grid inside the element) must be manufactured according to Computer-aided design (CAD) descriptions computed by construction experts, which among other things impose that the shape of the reinforcement should be aligned with the shape of the element.

As mentioned, an option for reducing the costs for making such non-standard reinforcement structures would be automation. There are existing machines for manufacturing reinforcement cages from e.g. Pedax,¹ Schnell,² Progress³ and MEP.⁴ However, the generated cages are for standard structures such as for planar surfaces and circular columns and therefore rely heavily on fixtures for exactly these types of shapes. There are therefore no integrated solutions for arbitrary double curved structures.

Apart from the complexity in the manufacturing procedure, due to logistic reasons unique double curved shapes will often be unsuitable to produce in large scale installations such as the above mentioned. Consider as an example that a new building requires thousands of different double curved reinforcement substructures,

then transporting these from a central production facility would yield substantial additional costs. We therefore propose a solution that can be ported to the construction site.

Our solution comprises a relative cheap and small fully automated robotic system for manufacturing of unique double curved reinforcement structures. The solution involves integration of 3D-bending of the steel reinforcement bars (from now on we use the phrase “rebar” for these), picking the rebars and move them to the rebar structure, and finally placement and binding of the rebars. Rather than developing an expensive system for manufacturing complete rebar structures, we have focused on developing a cheap system for manufacturing pieces of double curved mono-layer reinforcement grids that can then quickly be manually assembled. The system involves two robots. The first robot performs the bending operations and transports the rebars to their correct locations at the structure. The second robot performs the binding operations. We studied options of using only one robot, but it turned out to be infeasible, because of the requirement to fixate arbitrarily shaped rebars while binding them together.

The contribution presented in the paper is a complete integrated system for automatic bending and binding of rebars. The system comprised off-line planning methods for bending and transporting the rebar using a model of the deformation due to gravity and a binding method with online sensor based adjustments. For planning bending and transporting, a hybrid approach is applied, where the robot links are modeled as rigid, whereas the rebars are modeled as dynamically deflecting beams. The shape of the rebars is shown to be precisely modeled by a structure consisting of rigid parts connected by “deflection joints”. The advantage of using this beam model is that it can be directly integrated into existing physics simulation engines such as the Open Dynamics Engine (ODE) and embedded into motion planning algorithms for computing collision free robot movements. The method is an essential tool to avoid undesired contacts between robots, rebars and the environment both during the 3D bending of the rebars and when the robot moves the rebars from the bending station to the reinforcement structure.

In order to derive a complete solution, some additional contributions had to be derived such as the design of a bending tool and an associated method for computing the tool trajectory during bends and a method for approximating the shape of spatially curved rebars with a set of bends separated by a minimal distance. Finally, we have designed and programmed a sensor based binding tool that robustly handles inaccuracies in the rebar positions at the binding location.

The paper is organized in the following way: first we describe related work in Section 2. In Section 3, we outline the overall system by providing a short introduction to the three main processes: bending, transporting and binding and how they are integrated into a system, where model and simulation based automatic off-line programming accounting for deflections and deviations has

¹ www.pedax.com.

² <http://www.schnell.it/?lang=en>.

³ www.progress-m.com/en/produkte/.

⁴ www.mepgroup.com/en/products/.

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